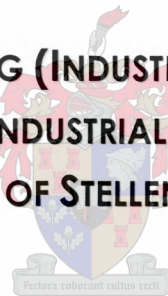


**THE APPLICATION OF THE SIX SIGMA QUALITY CONCEPT TO
IMPROVE PROCESS PERFORMANCE IN A CONTINUOUS
PROCESSING PLANT**

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DECLARATION

“I, the undersigned, hereby declare that the work contained in this thesis is my original work and that I have not previously in its entirety or in part submitted it at any university for a degree”.

Signature:

Date:

SYNOPSIS

This report presents the application of the six sigma quality concept in solving a true business problem. Six sigma is a quality improvement and business strategy/tool developed by Motorola in the mid 1980s. It aims at delivering products and services that approach levels of near perfection. To achieve this objective a six sigma process must not produce more than 3.4 defects per million opportunities, meaning the process should be at least 99.9997% perfect [Berdebes, 2003]. Motorola's success with six sigma popularised the concept and it has now been adopted by many of the world's top companies e.g. General Electric, Allied Signal-Honeywell, etc. All the six sigma companies report big financial returns as a result of increased quality levels due to the reduction in the number of defects. 'General Electric reports annual benefits of over \$2.5 billion across the organisation from six sigma' [Huang, 2003].

The six sigma concept follows a five step problem-solving methodology known as DMAIC (Define, Measure, Analyse, Improve, Control) to improve existing processes. Each of these steps makes use of a range of tools, which include quality, statistical, engineering, and business tools.

This report first gives a theoretical presentation on quality and six sigma, attempting to answer the question 'What is six sigma'. A step-by-step guide on how to go through the DMAIC problem solving cycle is also presented.

The six sigma concept was demonstrated by application to the colour removal process of a continuous processing plant manufacturing refined sugar. Colour removal is a very important process in sugar refining since the purpose of a refinery is to remove colour and other impurities from the raw sugar crystals. The colour removal process consists of three unit operations; liming, carbonation and sulphitation. Liming involves the addition of lime (calcium hydroxide) required for the formation of a calcium precipitate in the next unit operations. Carbonation is carried out in two stages; primary and secondary carbonation. Both stages involve the formation of a calcium carbonate precipitate, which

traps colour bodies and other impurities. Sulphitation occurs in a single step and involve the formation of a calcium sulphite precipitate which also traps impurities. The pH and colour are the main variables that are being monitored throughout the colour removal process.

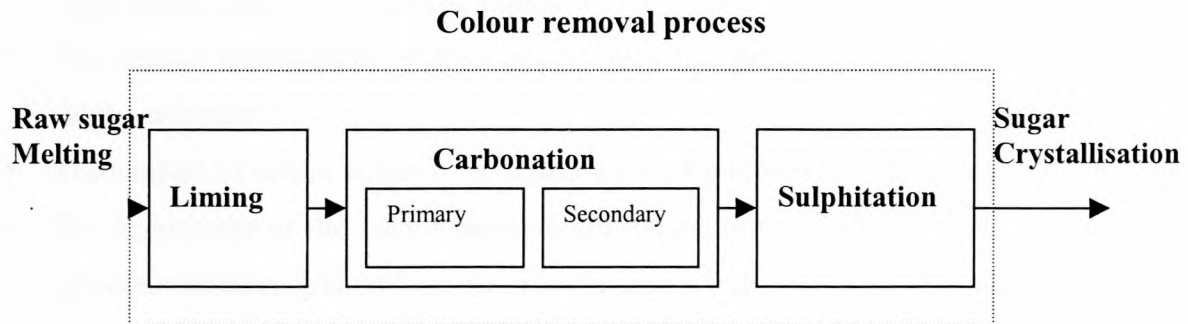


Figure 1: Colour removal process

The pH control of the two colour removal unit operations; carbonation and sulphitation, is very poor and as a result the colour removal achieved is below expectation. This compromises the final refined sugar quality since colour not removed in the colour removal processes ends up in the sugar. The first carbonation stage (primary) fails to lower the pH to the required specification and the second carbonation stage (secondary) is highly erratic, the pH fluctuating between too high and too low. The sulphitation process adds more sulphur dioxide than required and hence the pH is lowered below the lower specification limit.

The six sigma DMAIC cycle was implemented in order to solve the problem of poor pH control. The Define phase defined the project and identified the process to be improved. The Measure phase measured the current performance of the process by collecting past laboratory data with the corresponding field instruments data. The data was used to draw frequency distribution plots that displayed the actual variation of the process relative to the natural variation of the process (specification width) and to calculate process capability indices. The Analyse phase analysed the data so as to determine the key sources of variation. The Improve phase used the findings of the analyse phase to propose

solutions to improve the colour removal processes. The Control phase proposed a control plan so as to monitor and sustain the improvement gained.

The key findings of the study are presented below:

- Failure of the first carbonation stage to lower the pH to the required level is due to insufficient carbon dioxide gas supply.
- The second carbonation reaction occurs very fast hence poor control will result in high variability.
- The amount of colour removed is dependent on the input raw melt colour.
- The histograms of the colour removal unit operations are off-centered and display a process variation greater than the specification width and hence a large proportion of the data falls outside the specification limits.
- The % CaO and CO₂ gas addition were found to be the key variables that control the processes centering on target. The % CaO having a stronger effect in the liming process and CO₂ gas addition on the carbonation process.
- The variation between the field instrument's pH and laboratory pH is the key variable that control the processes spread (standard deviation of the processes).
- The processes C_{pk} values are less than C_p ($C_{pk} < C_p$) meaning the processes can be improved by controlling the key variables that control centering (% CaO, CO₂ gas addition).
- The processes capability indices are low, $C_p < 1$ meaning the processes are not statistically capable of meeting the required specifications at the current conditions.

Based on the findings of the study, the following deductions are made for the improvement of the colour removal processes in better meeting the required specifications.

- Increase the CO₂ gas supply to at least 4900 m³/hr, calculated based on the fact that at least 140 m³ gas is required per ton of solids in melt [Sugar Milling Research Institute Course Notes, 2002].

- Control the key variables identified to be the key sources of variation; % CaO, CO₂ gas addition and variation between the field instrument's pH and laboratory pH. Reducing variation in the % CaO and increasing CO₂ gas supply will improve the processes ability to maintain centering at the target specification. Maintaining a consistent correlation between the two pH readings; field instruments pH and laboratory pH will reduce the processes standard deviation and hence the processes spread. Reduction in the processes spread will minimize the total losses outside the specification limits. This will allow better control of the pH by getting rid of high fluctuations.
- Control of the input raw melt colour is essential since it has an impact on the degree of decolourisation. The higher the input colour, the more work required in removing the colour.

In improving the colour removal processes the starting point should be in ensuring process stability. Only once this is achieved, the above adjustments may be made to improve the processes capability. The processes capability will only improve to a certain extent since from the capability studies it is evident that the processes are not capable of meeting specifications.

To provide better control and to ensure continuous improvement of the processes the following recommendations are made:

- **Statistical process control charts**

The colour removal processes are highly unstable, the use of control charts will help in detecting any out of control conditions. Once an out of control condition has been detected, necessary investigations may be made to determine the source of instability so as to remove its influence. Being able to monitor the processes for out of control situations will help in rectifying any problems before they affect the processes outputs.

▪ Evaluation of capability indices- ISO 9000 internal audits

Consider incorporating the assessment of the capability indices as part of the ISO 9000 internal audits so as to measure process improvement. It is good practice to set a target for C_p , the six sigma standard is $C_p=2$, this however does not mean the goal should be $C_p=2$ since this depends on the robustness of the process against variation. For instance the colour removal processes at the current operating conditions can never reach $C_p=2$. This however is not a constraint since for the colour removal processes to better meet pH specifications it is not critical that they achieve six sigma quality. A visible improvement may be seen in aiming for $C_p=1$.

On studying the effects of CO₂ gas addition the total data points outside specification limits reduced from 84 % to 33 % and by reducing the variation between field instruments pH and laboratory pH for the secondary pH the total data points out of specification reduced from 55 % to 48 %. These results indicate that by improving C_p to be at least equal to one ($C_p=1$) the total data points outside specification can reduce significantly, indicating a high ability of the processes to meet specifications. Thus even if six sigma quality is not achieved, by focussing on process improvement using six sigma tools visible benefits can be achieved.

OPSOMMING

Hierdie tesis kyk na die toepassing van die ses sigma kwaliteitskonsep om 'n praktiese probleem op te los. Ses sigma soos dit algemeen bekend staan is nie slegs 'n kwaliteitverbeteringstegniek nie maar ook 'n strategiese besigheidsbenadering wat in die middel 1980s deur Motorola ontwikkel en bekend gestel is. Die doelstelling is om produkte en dienste perfek af te lewer. Om die doelwit te kan bereik poog die tegniek om die proses so te ontwerp dat daar nie meer as 3.4 defekte per miljoen mag wees nie – dit wil sê die proses is 99,9997% perfek [Berdebes, 2003]. As gevolg van die sukses wat Motorola met die konsep behaal het, het dit algemene bekendheid verwerf, en word dit intussen deur baie van die wêreld se voorste maatskappye gebruik, o.a. General Electric, Allied Signal-Honeywell, ens. Al dié maatskappye toon groot finansële voordele as gevolg van die vermindering in defekte wat teweeg gebring is. So bv. beloop die jaarlikse voordele vir General Electric meer as \$2.5 biljoen [Huang, 2003].

Die ses sigma konsep volg 'n vyf-stap probleem oplossings proses (in Engels bekend as DMAIC: Define, Measure, Analyse, Improve, Control), naamlik definiëer, meet, analiseer, verbeter, en beheer om bestaande prosesse te verbeter. In elkeen van die stappe is daar spesifieke gereedskap of tegnieke wat aangewend kan word, soos bv. kwaliteits-, statistiese-, ingenieurs- en besigheids tegnieke.

Die verslag begin met 'n teoretiese oorsig oor kwaliteit en die ses sigma proses, waardeur die vraag “wat is ses sigma” beantwoord word. Daarna volg 'n gedetailleerde stap-vir-stap beskrywing van die DMAIC probleem oplossingsiklus.

Die toepassing van die ses sigma konsep word dan gedoen aan die hand van 'n spesifieke proses in die kontinue suiker prosesserings aanleg, naamlik die kleurverwyderingsproses. Hierdie proses is baie belangrik omdat die doelstelling daarvan juis draai rondom die verwydering van nie net kleur nie maar ook alle ander vreemde bestanddele van die rou suiker kristalle. Die proses bestaan uit drie onafhanklike maar sekwensiële aktiwiteite waardeur verseker word dat die regte gehalte suiker uiteindelik verkry word.

Tydens die eerste twee stappe is veral die pH-beheer onder verdenking, sodat die kleur verwydering nie die gewenste kwaliteit lewer nie. Dit beïnvloed op sy beurt die gehalte van die finale produk, omdat die ongewenste kleur uiteindelik deel is van die suiker. Die pH inhoud is nie net nie laag genoeg nie, maar ook hoogs veranderlik – in beginsel dus buite beheer.

Die DMAIC siklus is toegepas ten einde die pH beter te kan beheer. Tydens die definisiefase is die projek beskryf en die proses wat verbeter moet word identifiseer. In die meetfase is die nodige data versamel om sodoende die inherente prosesveranderlikheid te bepaal. Die belangrikste bronne of veranderlikes wat bydra tot die prosesveranderlikheid is in die derde~ of analisefase bepaal. Hierdie bevindings is gebruik tydens die verbeteringsfase om voorstelle ter verbetering van die proses te maak. Die voorstelle is implementeer en in die laaste fase, naamlik die beheerfase, is 'n plan opgestel ten einde te verseker dat die proses deurentyd gemonitor word sodat die verbeterings volhoubaar bly.

'n Hele aantal veranderlikes wat elk bygedra het tot die prosesvariasie is identifiseer, en word in detail in die verslag beskryf. Gebaseer op die analise en bevindings van die ondersoek kon logiese aanbevelings gemaak word sodat die proses 'n groot verbetering in kleurverwydering getoon het. Die belangrikste bevinding was dat die huidige proses nie die vermoë het om 100% te voldoen aan die spesifikasies of vereistes nie. Die hoofdoel van die voorstelle is dus om te begin om die prosesveranderlikheid te minimeer of ten minste te stabiliseer – eers nadat die doel bereik is kan daar voortgegaan word om verbeteringe te implementeer wat die prosesvermoë aanspreek.

Ten einde hierdie beheer te kan uitoefen en variasie te verminder is die volgende voorstelle gemaak:

▪ **Statistiese beheer kaarte**

Die kleurverwyderingsproses is hoogs onstabiel. Met behulp van statistiese beheer kaarte is daar 'n vroegtydige waarskuwing van moontlike buite beheer situasies. Die proses kan dus ondersoek en aangepas word voordat die finale produkkwaliteit te swak word.

▪ **Evaluering van proses vermoë – ISO 9000 interne audit**

Die assesering van die prosesvermoë behoort deel te word van die interne ISO audit proses, om sodoende prosesverbeteringe gereeld en amptelik te meet. Die standaard gestel vir C_p behoort gedurig aandag te kry – dit is nie goeie praktyk om bv. slegs 'n doelwit van $C_p = 2$ soos voorgestel in ses sigma te gebruik nie, maar om dit aan te pas na gelang van die robuustheid van die proses wat bereik is.

Daar is beduidende voordele bereik deur die toepassing van die DMAIC siklus. So het byvoorbeeld die persentasie datapunte buite spesifikasie verminder van 84% tot 33%, bloot deur te kyk na die effek wat die toevoeging van CO₂ gas tydens die proses het. Dit toon dus duidelik dat, alhoewel die proses huidiglik nie die vermoë het om te voldoen aan die vereistes van ses sigma nie, dit wel die moeite werd is om die beginsels en tegnieke toe te pas.

ACKNOWLEDGEMENTS / DEDICATIONS

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This piece of work is dedicated to my late mother, K. Nxumalo, my two children, Vukani and Vumile, and to all who have made a positive contribution to my life.

TERMS OF REFERENCE

This project was completed as part of the requirements for the degree of Master of Science in Industrial Engineering at the University of Stellenbosch. The project has to contain both a research and a practical component as per the requirements of a thesis. This is to give the student an opportunity to demonstrate her understanding of the topic by applying the acquired knowledge to solve a true business problem. Thus, on completion of the project, the student is expected to be a master of the chosen field.

2.1 The discipline of quality engineering

2.2 Quality development

2.3 History of six sigma

2.4 Statistical process control

2.5 Statistical definition of six sigma

2.6 The focus of six sigma

2.7 Definitions of terms used in six sigma

2.8 Calculation of sigma of a process

2.9 Benefits of implementing Six Sigma

2.10 Limitations of Six Sigma

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3.3 Measure phase

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3.5 Improve phase

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GLOSSARY

DEFINITIONS

- Brix:** Total dissolved solids in a solution expressed as a percentage by mass.
- Blending:** Mixing together of different grades of sugar to form a single grade.
- Carbonation:** The reaction between carbon dioxide gas and lime to form a calcium carbonate precipitate on which colour and ash (impurities) in sugar are absorbed.
- Centrifuging:** Separation of sugar crystal from mother liquor (runoff) using centrifugals.
- Clarified Liquor:** The resultant liquor after filtering the calcium carbonate precipitate formed during carbonation (output of the carbonation process).
- Colour:** Measure of the level of non sugars (impurities) of a sugar solution.
- Conditioning:** Drying of refined sugar using hot dry air.
- Fine Liquor:** The resultant liquor after filtering the calcium sulphite precipitate formed during sulphitation (output of the sulphitation process).
- Field instrument pH:** The pH reading measured under process operating conditions (80- 85 °C).

- ICUMSA:** Units for colour measurement.
- Liming:** The addition of calcium hydroxide in a sugar solution.
- Limed melt:** The output of the liming process, a sugar solution containing lime.
- Lime ratio:** The ratio of total solids in raw melt (Tons Brix in melt) to lime flow (Tons Lime).
- Massecuite:** Mixture of sugar crystals and mother liquor (runoff).
- pH:** Measure of the concentration of hydrogen ions in a solution, or simply the acidity of a solution.
- Primary saturator:** The reaction vessel in which the first carbonation reaction occurs.
- Raw sugar:** Brown sugar (low pol).
- Rawhouse:** The process house which manufactures raw and VHP sugar from cane juice.
- Raw melt:** The liquor formed when VHP sugar crystals are melted in water.
- Refined sugar:** White sugar.
- Sulphitation:** The reaction between sulphur dioxide gas and lime to form a calcium sulphite precipitate on which colour and ash in sugar are absorbed.
- Secondary saturator:** The reaction vessel in which the second carbonation reaction occurs.

Thick Liquor:	The resultant liquor after evaporating some water in Fine Liquor.
V1 steam:	Saturated steam at a pressure of 150 kPa and temperature of 112 degrees celsius.
VHP sugar:	Brown sugar used for making refined sugar (very high pol).
Sugar refining:	The removal of impurities in VHP sugar to form refined sugar.
Runoff:	Resultant mother liquor after the separation of sugar crystals from a massecuite.

ABBREVIATIONS

CaO:	Calcium oxide
% CaO:	Percentage by mass of CaO in solution
CaCO₃:	Calcium carbonate precipitate
CaSO₃:	Calcium sulphite precipitate
Ca(OH)₂:	Calcium hydroxide
CO₂:	Carbon dioxide gas
% CO₂:	Percentage of carbon dioxide gas
C_p:	Potential capability
C_{pk}:	Actual capability
CTQ:	Critical to Quality
DMAIC:	Define, Measure, Analyse, Improve, Control
DMADV:	Define, Measure, Analyse, Design, Verify
DPU:	Defects per unit
DPO:	Defects per unit opportunity
DPMO:	Defects per million opportunities
ISO:	International Standards Organisation

LCL:	Lower control limit
LSL:	Lower specification limit
SASTA:	Southern Africa Sugar Technologist Association
SIPOC:	Suppliers, Inputs, Process, Outputs, Customers
SO₂:	Sulphur dioxide gas
T:	Target specification
TQM:	Total Quality Management
UCL:	Upper control limit
USL:	Upper specification limit
VOC:	Voice of the customer
Z:	Standard normal distribution
Z_{ST}:	Potential sigma value
Z_{st}:	Actual sigma value

CHAPTER 1

1.1 INTRODUCTION

This study aims to narrow the gap between theory and practice by studying the six sigma quality concept and using the knowledge gained to improve process performance. This concept is demonstrated by applying it to the colour removal processes of Mhlume Sugar Estate refining operation. Mhlume Sugar Estate is a continuous processing plant manufacturing raw and refined sugar from sugar cane.

Quality improvement concepts started with the focus on the outgoing product quality, while little attention was paid to the processes used to make the product. In order to ensure that product quality met customer requirements, the manufacturers relied on sorting the non-conforming product from the good product. This technique ensured that only quality products reached the customer. This however was not the best system since large volumes of non-conforming products were produced which had to be re-processed. This was bad for both the manufacturer and customer, since it resulted in higher production costs which automatically translated to higher selling prices. It was clear, therefore, that inspection alone was failing to address the needs of the manufacturer. The birth of statistical control led to the development of better techniques, which focused on the control of the process such that the process only produces quality products. The focus therefore changed from inspection to defect prevention by focusing on the process.

Numerous quality management programs have been developed over the years. They all focus on the process for defect prevention with the inclusion of the concepts of continuous improvement and customer focus. **Six sigma**, founded by Motorola in the mid 1980s, is one of many quality management programs. Six sigma focuses on the measurement, controlling and improvement of processes such that they are so good that virtually no defective products would be produced. A true six sigma process has a defect rate of 3.4 parts per million.

The six sigma concept follows a five-step problem solving approach commonly known as DMAIC, which is based on the use of statistical tools. The concept is data driven and strongly based on the measurement of the process for continuous improvement. The six sigma philosophy is 'you cannot control what you cannot measure'. Most organizations willing to implement the concept experience difficulty in measurement, as they are uncertain on what to measure, how to measure and how to use the measurement result.

The six sigma concept does not give guidelines on what to measure or how to use the measurement, as it assumes its users are familiar with the measurement concept. The lack of experience in measurement becomes a barrier in the implementation of the six sigma DMAIC problem-solving methodology and hence the true benefits of six sigma cannot be realized.

Six sigma is a results-oriented concept and requires the use of process data to identify the key sources of variation that limit process performance. This project was considered successful and in line with six sigma objectives since it used process data to identify the key causes of poor pH control for the refinery colour removal processes. The critical variables that cause the variation were identified. Control of these critical variables will improve the ability of the processes to meet specifications and reduce data variability. The improvements however were not actually implemented in the production process since these would require some time and therefore could hinder the completion of the project. In order to ensure that the study has identified the right variables statistical tests were done to verify the results.

The document chapters are structured as follows

- Chapters 2 and 3 review the relevant literature on the concept of quality, statistical process control (SPC) and the six sigma problem solving method (DMAIC).
- Chapter 4 gives an explanation of the problem and relevant background information on the company and the process to be improved.

- Chapter 5 demonstrates the actual implementation of six sigma on the selected processes, going through the five-step problem solving methodology. The problem is defined, and using relevant data, solutions to the problem are proposed.
- Based on the findings of the study conclusions and recommendations are presented in Chapter 6.
- A summary is presented in Chapter 7, which gives an overall discussion of the project in terms of meeting its objectives as well as the relevance of the topic to the industrial engineering field.

A flow diagram is presented below which gives a simplified look of the thesis layout.

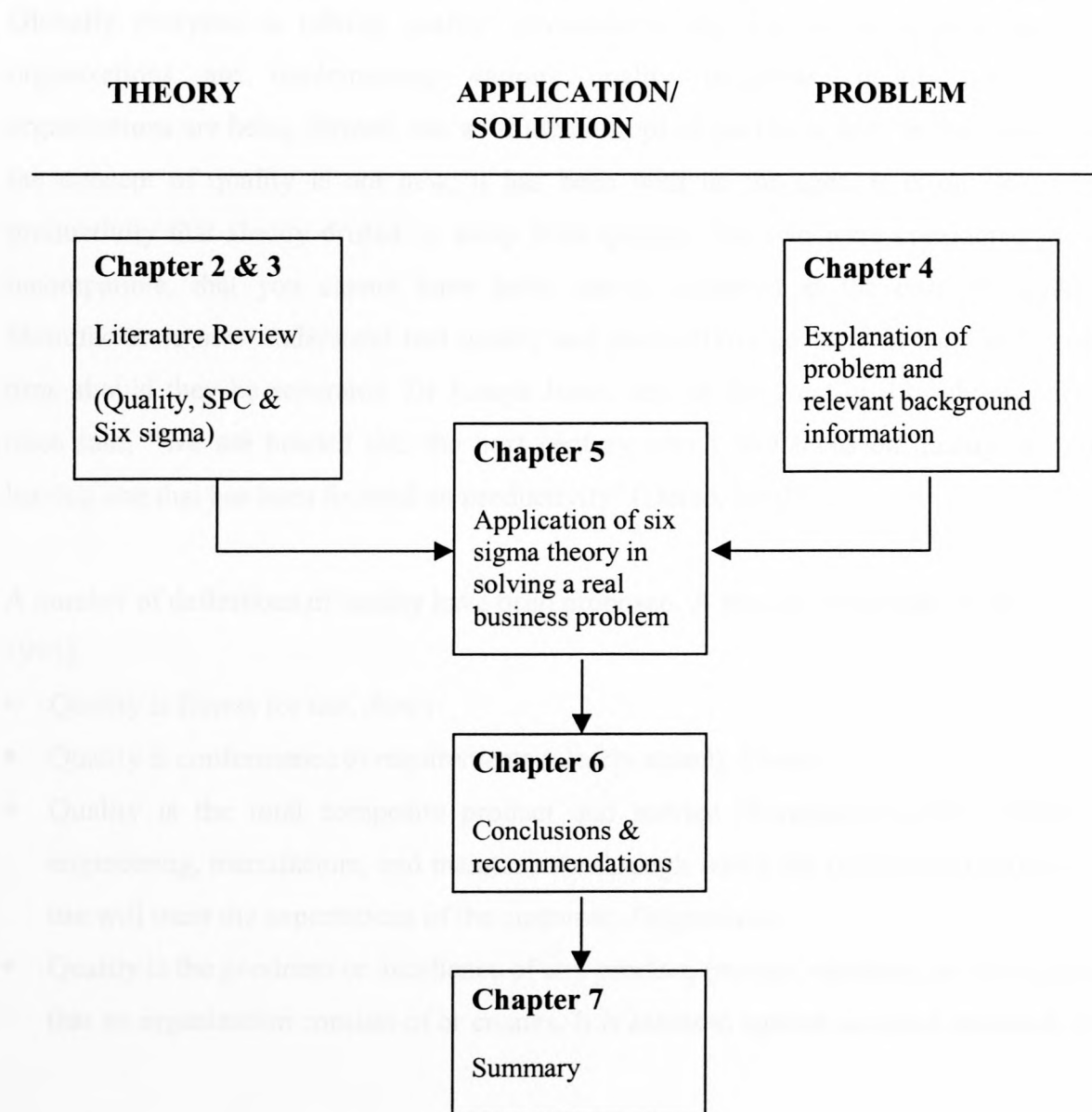


Figure 1.1 Document layout

CHAPTER 2

AN INTRODUCTION TO QUALITY AND SIX SIGMA

This chapter defines the concept of quality and all the terminologies one comes across when talking about quality. An introduction to six sigma is given, from its foundation to its merits and drawbacks. With the roots of six sigma in statistics, a discussion of statistical process control is also included.

2.1 DEFINITION OF QUALITY

Globally everyone is talking quality: governments are formulating quality policies, organizations are implementing various quality programs, quality (standards) organizations are being formed, etc. as if the concept of quality is new. In the true sense the concept of quality is not new, it has been with us for ages. It is our focus on productivity that slowly drifted us away from quality. The two were considered to be incompatible, that you cannot have both; one is achieved at the cost of another. Manufacturers now understand that quality and productivity go hand in hand and at no time should they be separated. Dr Joseph Juran, one of the great quality philosophers, once said, “We are headed into the next century which will focus on quality, we are leaving one that has been focused on productivity” [Defeo, 2002].

A number of definitions of quality have been proposed. A few are listed below [Kolarik, 1995].

- Quality is fitness for use, *Juran*
- Quality is conformance to requirements (clearly stated), *Crosby*
- Quality is the total composite product and service characteristics of marketing, engineering, manufacture, and maintenance through which the product and service in use will meet the expectations of the customer, *Feigenbaum*
- Quality is the goodness or excellence of any product, process, structure, or other thing that an organization consists of or creates. It is assessed against accepted standards of

merit for such things and against the interests/needs of producers, consumers and other stakeholders, *Smith*

- Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs, *ISO 9000*
- Quality should be aimed at the needs of the consumer, present and future, *Deming*

All of the above definitions define quality in terms of meeting the needs of the customer, thus it is only the customer who can define quality and from the customer's definition of quality the manufacturer creates quality.

The customer normally defines quality in ordinary language, for example ease of use, performance, durability, etc. The manufacturer has to translate these needs into technical language, for example: dimensions, breaking strength, etc. so as to develop processes (for example design, development, production, delivery, sales and customer service, use and disposal) which should all create and assure quality. All these processes are equally important, failure in one process will result in total failure of the product and thereby cause customer dissatisfaction.

Below are definitions of terms normally used in the concept of quality [Kolarik, 1995].

- ***Quality Assurance***

Quality assurance means to assure quality in a product so that customers can buy it with confidence and use it for a long period of time with confidence and satisfaction, *Ishikawa*.

- ***Quality Control***

Quality control is a system of means whereby the qualities of products or services are produced economically to meet the requirements of the purchaser, *Japan Industrial Standards*.

- **Quality System**

Organizational structure, procedures, processes and resources needed to implement quality management, *ISO 9000*.

- **Quality Management**

All activities of the overall management function that determine the quality policy, objectives and responsibilities, and implement them by means such as quality planning, quality control, quality assurance and quality improvement within the quality system, *ISO 9000*.

2.2 THE SHAPING OF QUALITY THINKING - QUALITY PHILOSOPHERS

The shaping of quality thinking is widely attributed to the works of a number of people who today have been awarded the status of being the great quality philosophers, and to Japan, the first country which applied the teachings of these great quality leaders. The list of 'the great quality philosophers' includes Dr Joseph Juran (father of quality), Walter Shewart, Edwards Deming, Philip Crosby, Ishikawa, Taguchi, Feigenbaum, etc. They all emphasized a customer-focused philosophy since quality can only be defined by the customer. They also extended the concept of quality control from statistics to include the human dimension as well, since both processes and people are responsible for creating quality [Butman, 2003]. From this new quality concept the Japanese founded total quality management (TQM), which transformed Japan to a quality leader. TQM has become the basis of many quality management systems, for they are all rooted in its principles.

2.3 QUALITY DEVELOPMENT

The concept of quality has evolved through six distinct paradigms over the years due to changing customer needs, technological development and increasing competition [Kolarik, 1995]. These different paradigms are listed below.

i) Custom-craft paradigm

The custom craft quality control was inherent in manufacturing up to the end of the nineteenth century. Skilled craftsman designed and built products exactly the way customers wanted them, by directly involving the customer. The resultant products were of high quality and satisfied customer's needs and expectations. This type of system is still common today, especially in the construction industry where for instance, a house is designed and built exactly the way the customer wants it.

ii) Mass production and sorting paradigm

This paradigm emerged with mass production technology. Huge volumes of products are manufactured for the mass market. The product is designed and manufactured with the customer needs in mind but without directly involving the customer. Once the product is built customers are sourced normally through advertising. Quality is controlled by sorting inspection of non-conforming product from the good product and therefore results in large volumes of scrap. Historically inspection was done manually by full time inspectors, today most of the inspection is automated. When compared to craftsman quality control this system yields lower product performance, lower costs and short delivery time.

iii) Statistical quality control

This paradigm is an improvement on the mass production and sorting paradigm. It came about due to the birth of statistical charts by Walter A. Shewart the pioneer of statistical quality control. Statistical tools such as sampling and control charts are used in an effort to control the process such that any deviations which may result in poor quality, are detected and corrected so that the process yields only quality product. The number of defective products produced was reduced which in turn resulted in lower production costs.

iv) Total quality management (TQM) paradigm

This paradigm evolved in the early 1960s. During this time customers became more cautious of quality and started demanding high quality products. As a result manufacturers did extreme inspections to ensure that only high quality products reach the customer. This in turn resulted in very high production costs. It became clear that statistical quality control on its own was failing to meet the challenge. As a result TQM was born, a totally new concept which focused on prevention rather than inspection in order to achieve high quality. TQM called for the involvement of all stakeholders (customers, suppliers and employees) and for continuous improvement of product quality. This concept proved to be effective, quality improved, yielding high levels of customer satisfaction and manufacturing costs were reduced. Today TQM principles have gained widespread global acceptance.

v) Techno-craft paradigm

The techno-craft paradigm is an enhancement to the custom-craft paradigm. It maintains the same performance as the custom-craft paradigm but reduces the cost and delivery time through integration of people, machines and automation. Modern technologies like computer aided design (CAD) and computer aided manufacturing (CAM) have enhanced this paradigm.

vi) Six sigma paradigm

Six sigma was developed about twenty years ago, and it is gaining momentum in quality management. It is an enhancement of TQM in that not only is it a quality management system but also a business philosophy. It shifts the focus to increasing both productivity and profits.

The evolution of quality through these paradigms may be grouped into two categories

- i) Quality by product inspection.
- ii) Quality by process improvement.

Both these categories ensure that high quality product reaches the customer, which is every manufacturer's objective. The major difference is that the one targets the products while the other targets the process. By targeting the products, any defective products produced are reprocessed while by targeting the process, defective products are prevented from being produced in the first place. This means all the products produced by the process should meet specifications. The process-focused strategy is thus proactive in nature since it prevents problems from occurring as opposed to the product-focused strategy, which is reactive since it waits for a problem to occur, then corrects it. Focusing on the process and preventing the production of defective products results in lower manufacturing cost since rework is eliminated. This ensures a high quality product. Producing high quality product at minimum cost is a necessity in today's tough industry competition and customers' high demands.

2.4 HISTORY OF SIX SIGMA

Six sigma is a quality improvement and business strategy/tool/methodology introduced by Motorola in the mid 1980s. At that time Motorola had serious quality problems and was losing its customers to its competitors who produced quality products at a lower cost. In order to survive, Motorola's CEO at that time started the company on the six sigma quality path. The primary goal was to develop manufacturing processes that were so good that virtually no defective products were produced. So "good" was defined as having six sigma's of process variation fit within the product tolerance specifications [Westgard, 2001]. This led to Motorola winning the Malcolm Baldrige National Quality Award in 1988, and today it is known worldwide as a quality and profit leader [Pyzdek, 2001]. Motorola's achievement with six sigma made many companies interested in the concept and adopting it. Today the six sigma concept has become the new world standard for improving quality, reducing defects and cutting costs [Defeo, 2002].

A number of definitions of six sigma have been developed:

- Six sigma is a strategic initiative to boost profitability, increase market share, and improve customer satisfaction, providing companies with a series of interventions and statistical tools that can lead to breakthrough profitability and quantum gains in quality [Harry, 1998].
- Six sigma is a methodology driven by understanding customer needs and disciplined use of facts, data, and statistical analysis to improve and reinvent organisational processes [Huag, 2003].
- Six sigma is a business method for improving quality by removing defects and their causes in business process activities [Nimkar, 2003].

From these three chosen definitions of six sigma it is seen that six sigma is many things. It can be defined as a vision; a philosophy; a symbol; a metric; a methodology or goal to drive out waste and improve quality, cost and the time performance of any business.

Six sigma is not a totally new concept in quality management. It can be considered an extension of TQM in that it shifts the focus to both productivity and profits [Arthur, 2003]. In fact six sigma is considered to be more about helping organizations make more money [Pyzdek, 2001]. Six sigma differs from other quality management systems in that it targets high standards of performance and aims for virtually error free business performance, measuring defects in parts per million instead of parts per hundred (percent) as was commonly measured [Pyzdek, 1999].

The six sigma concept is data-driven; without accurate data six sigma cannot exist. Six sigma organizations collect data from all their processes and use the data to drive process improvement [Porter, 2002]. When talking of six sigma it is important to know how to collect data and how to translate this data into information. Statistics is the tool of converting data into information and thus knowledge of statistics and statistical process

control is a basic requirement when implementing six sigma. It is therefore proper to first briefly discuss statistical process control before giving a full definition of six sigma in statistical language.

2.5 STATISTICAL PROCESS CONTROL (SPC)

Statistical process control (SPC) is the use of statistical methods and tools e.g. control charts to chart process variables so as to view the progress of the process performance. Not all the characteristics of the process are charted, only the most critical quality characteristics, as these are most important to the final product quality.

Control charts provide a visual presentation of how the process varies over time and hence they give information as to whether the process is in control or out of control. When the process is in control it is considered stable and it can be predicted how it is expected to behave/performance in the future, and when the process is out of control it is considered unstable and its future performance may not be predicted. Thus an unstable process indicates that there is a condition that exists at that moment that is affecting the process and if not corrected the process will produce inferior quality. In statistical language this condition, which causes the process to become unstable, is termed the "special cause of variation". SPC is only capable of detecting the presence of special causes and not identifying the cause. It becomes the responsibility of the process owner to identify the special cause and therefore remove its influence. Nevertheless it helps the process owner understand the variation of her process. Understanding process variation is very important since you can only reduce or eliminate variation if you understand what is causing it. The ability of SPC to detect process upsets immediately when they happen helps the process owner to correct them before they affect the final product quality. This ensures that the process always produces products within specification.

▪ *Attributes and variable measures*

The selection of control charts depends on the type of data to be charted. Data can either be attribute or variable. Attribute data is data that can be counted, for example number of defects, while variable data is data that can be measured e.g. Temperature. In each case the control charts serve as a statistical based warning device for process upsets. In practice the particular situation dictates which type of charts are to be used, attribute or variables charts. Once this is determined the most appropriate chart is chosen based on the sample size (subgroup size and number of subgroups). The various control charts in each category are listed below.

Table 2.1 Variable/Attribute control charts

Variable control charts	Attribute control charts
X-bar chart – sample size is $n > 1$	NP charts – constant sample size
R charts & S charts	P charts – sample size varies
X charts & R_M Charts – sample size $n=1$	C charts – sample size is constant
EWMA and EWMD charts	U charts – sample size varies
CuSum charts & R_m Charts	

[Kolarik, 1995]

The variable control charts are based on the Normal or Gaussian distribution function. They monitor the central tendency/location and the amount of variation of the production process in order to assess the stability of the process. The attribute control charts are based on the Binomial (P and NP charts) and Poisson (C and U charts) model. The P and NP charts are used to monitor defective non-conforming individual products and the C and U charts monitor number of defects per production unit.

The variable control charts are used to monitor only one critical quality characteristic while attributes control charts can be used to monitor multiple quality characteristics. A product is normally defined by more than one critical quality characteristic. For example a pen will have the following quality characteristics: size (length, width), ink quality and

colour, etc. If variable control charts were chosen to be used for process monitoring of the pen, each of the pen's quality characteristics would require a control chart of its own. This would mean many control charts and it would be very costly to manage all these charts. Hence attribute control charts are normally used to cover the entire product unit, and any identified quality bottlenecks are then studied using variable control charts.

2.5.1 Normal distribution

In simple terms the normal distribution can be explained by assuming an average class of pupils given a class test. It is expected that a majority of the students will get the mid marks and a few will get the very lowest or highest mark. The distribution of the marks is actually expected to follow a bell shape, forming a peak at the center and flattening out as you move away from the center. In statistical language the center is referred to as the mean and the scatter of the pupils marks about the mid mark (center) is referred to as the dispersion, of which the standard deviation is a common measure. Both the mean and standard deviation are very important measures for defining normally distributed data.

The normal distribution plot is illustrated below. The information displayed by the plot is also explained.

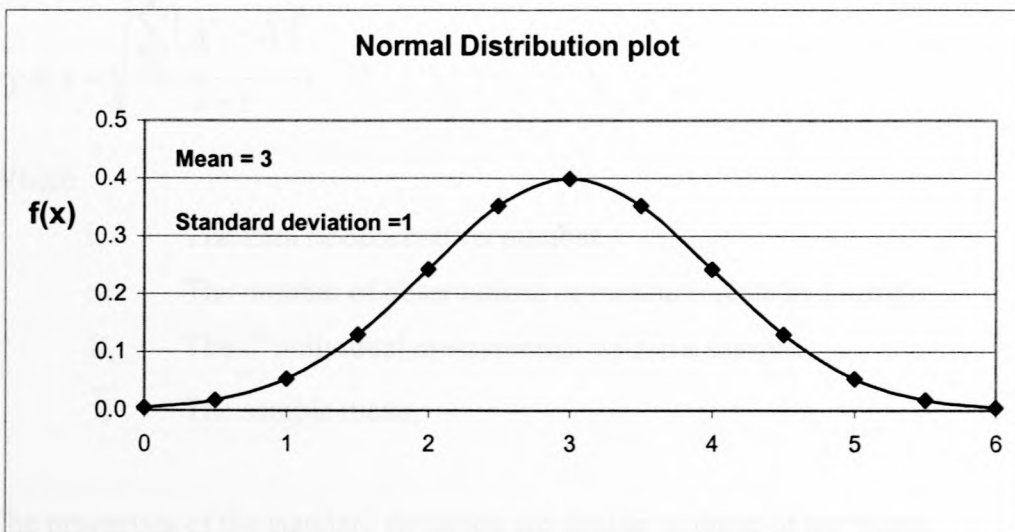


Figure 2.1 Normal distribution plot

▪ *Process mean*

The process mean is a measure of central tendency and often called the balance point. The mean of a sample is defined as follows:

Sample mean

$$\hat{\mu} = \bar{X} = \frac{\sum_{i=1}^n X_i}{n} \quad (2.1)$$

The mean has the following properties:

- i) It is sensitive to all the data that has been used to compute it.
- ii) It is sensitive to extreme values.
- iii) It is insensitive to sampling fluctuations.

▪ *Standard deviation*

The standard deviation is a measure of variation about the mean and thus it is used as a measure of variability. It is defined as follows

Sample standard deviation

$$\hat{\sigma} = s = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} \quad (2.2)$$

Where

- i: The item or observation number.
- n: The number of observations or measurements in a sample.
- X_i : The i^{th} individual measurement within a sample.
- \bar{X} : The sample mean.

The properties of the standard deviation are similar to those of the mean.

- ***Specification limits***

Specification limits are determined based on the customer's requirements of the product. The manufacturer or customer can either specify them. In most cases the manufacturer specifies them since the customer normally defines quality requirements in ordinary language. The manufacturer then translates these requirements into technical specifications. Three specifications are normally specified. The target specification (TS), which is the true specification, desired by the customer and the lower specification limit (LSL) and upper specification limit (USL), which gives the deviation from the TS considered acceptable. The manufacturer considers a product that is within specification to be good product and to be acceptable to the customer, and one that is out of specification to be bad product and not acceptable to the customer. A product, however may be within specifications and not acceptable to the customer if it fails to meet customer requirements.

- ***Control limits***

Control limits give the number of standard deviations away from the center point or mean. In statistical process control the number of standard deviations away from the mean is normally set at ± 3 standard deviations [Kolarik, 1995]. These mean the upper and lower control limits (UCL & LCL) will have an offset of ± 3 sigma from the mean. Control limits are statistically determined from the actual process data. In practical terms they define the boundaries of the normal behavior of the process. Process data that falls outside the control limits on either side (UCL & LCL) are considered outliers or out-of-control points. A process, which falls within the control limits and display, a random pattern is considered to be in control. It is important to distinguish between control limits and specification limits since the two are not the same and serve different purposes. Control limits represent the "voice of the process" while specification limits represent the "voice of the customer" [Carleton, 1999].

2.5.2 Process capability

Process capability measures are used to measure the ability of the process to meet specifications provided the process can be adjusted to target. A high capability means the process can readily produce a product within the tolerance specifications and a low capability means the process is incapable. Various capability measures are used, the most common being the C_p index (potential measure of capability) and the C_{pk} index (actual measure of capability). Both capability indices measure performance relative to process specification and do not consider process consistency across time. The difference between the two is that C_{pk} takes process centering into account while C_p does not. This makes the C_{pk} measure preferred over C_p since it gives an actual measure of the production process.

The capability indexes are defined as follows:

$$C_p = \frac{USL - LSL}{6\sigma} = \text{Specification width} / \text{Natural process variation} \quad (2.3)$$

- $C_p = 1$: The process is potentially capable (in a marginal sense).
- $C_p < 1$: The process variation exceeds the specification width therefore the process is potentially incapable.
- $C_p > 1$: The process variation is less than the specification width and thus the process is potentially capable.

A high C_p however does not guarantee defect free products since a process with a high C_p may produce defective products if the process is not centered. This is because the C_p index does not take process centering into account.

and

$$C_{pk} = \text{minimum} \left\{ \frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma} \right\} \quad (2.4)$$

Again if

$C_{pk} = 1$: The process is marginally capable.

$C_{pk} < 1$: The process is incapable.

$C_{pk} > 1$: The process is capable.

C_{pk} can also be defined in terms of C_p as

$$C_{pk} = C_p (1-k) \quad (2.5)$$

Where

$$k = (\text{target} - \mu) / ((USL - LSL)/2) \text{ or} \quad (2.6)$$

$$k = (\text{Process offset from target}) \div 1/2 (\text{Specification width})$$

for $k=0$, $C_{pk} = C_p$, meaning the process is centered on the desirable target. In practice this does not happen no matter how well the process is controlled. Thus as the process drift from the target ('k') increases, C_{pk} becomes increasingly smaller than C_p .

Not all product specifications have both a lower and upper limit. Some have only a lower limit (LSL) or only an upper limit (USL). For such processes the process capability indexes are redefined as

For processes with only an LSL

$$C_{pL} = \left\{ \frac{\mu - LSL}{3\sigma} \right\} \quad (2.7)$$

For processes with only an USL

$$C_{pU} = \left\{ \frac{USL - \mu}{3\sigma} \right\} \quad (2.8)$$

C_p and C_{pk} are appropriate for normally distributed processes. For non-normal processes the data and specification limits have to be transformed to a normal distribution.

The P_p index is similar to the C_p index. Both measure the process capability. The only difference being that C_p employs the short-term standard deviation while P_p uses the long-term standard deviation. The difference between the two being that the short term distribution displays only random variations while the long term distribution displays both random and non-random variations which tends to expand the standard deviation.

P_p and P_{pk} is based on the same equation as C_p and C_{pk}

$$P_p = \frac{|USL - LSL|}{\pm 3\sigma_{LT}} \quad (2.9)$$

$$P_{pk} = P_p (1-k) \quad (2.10)$$

2.5.3 The Standard normal distribution (Z)

The standard normal distribution is a normal distribution with a mean of zero ($\mu=0$) and a standard deviation of one ($\sigma^2=1$) [Weisstein, 1999].

The transformation is given by the formula

$$Z = \frac{(X - \mu)}{\sigma} \quad (2.11)$$

Where

- X: is any value from the original normal distribution.
- μ : is the mean of the original distribution.
- σ : is the standard deviation of the normal distribution.
- Z: is the standard transform.

The Z value indicates the number of standard deviations above or below the mean; $Z = +3$ means 3 standard deviations above the mean while $Z = -3$ means 3 standard deviations below the mean.

The standard transform can be used to measure process capability [Harry, 1997].

$$Z = \frac{|SL - \mu|}{\hat{\sigma}} \quad (2.12)$$

SL being either the upper or lower specification

The potential sigma value for a process in terms of the C_p index over the short term is defined as follows

$$Z_{ST} = 3C_p \quad (2.13)$$

The actual sigma value for the process over the short term is defined as follows

$$Z_{st} = 3C_{pk} \quad (2.14)$$

The potential sigma value for the process over the long term is defined as follows

$$Z_{LT} = 3P_p \quad (2.15)$$

2.6 STATISTICAL DEFINITION OF SIX SIGMA

The six sigma quality improvement strategy is best defined in statistical terms since that is where it was born. 'Sigma' is a letter in the Greek alphabet used by statisticians to measure the variability in any process. Even though six sigma is heavily embedded in statistics, in business or manufacturing terms the sigma of the process tells us the capability of the process to perform defect free. Thus the higher the sigma value, the lower the opportunity of the process producing defects. Six sigma as a concept focuses on defect or waste reduction in all processes to extremely low levels.

The six sigma concept is illustrated by the normal distribution as shown below:

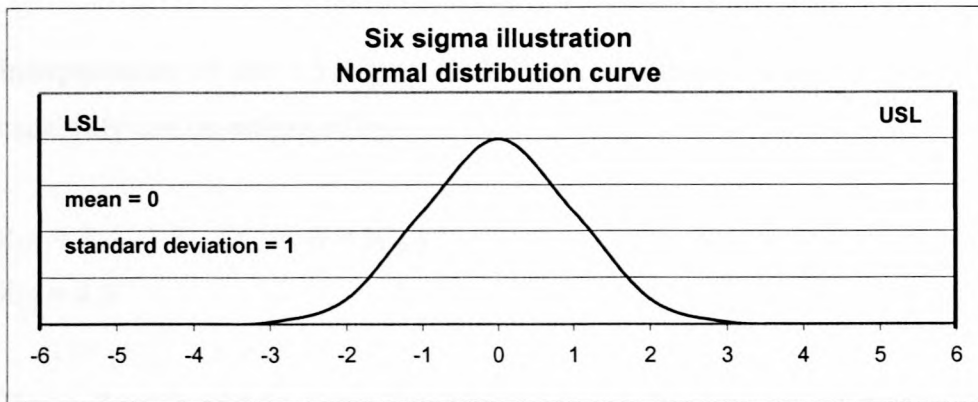


Figure 2.2 Six sigma illustration – normal distribution curve

[Kolarik,1995]

The graph displays the following information: the process mean, process standard deviation and the product specification limits (USL & LSL). As shown by the graph, a six sigma process has ± 6 standard deviations from the process mean to each specification limit. From the definition of C_p (potential capability), a six sigma process is expected to have $C_p = 2$. This means the tolerance specification is twice as wide as the true capability of the process since the process capability is ± 3 standard deviations while the specification limits are ± 6 standard deviations.

By definition a true six sigma process will produce 2 defects per billion opportunities. However a six sigma process as defined by Motorola will produce 3.4 defects per million opportunities. This corresponds to a sigma value of 4.5. Motorola determined through years of process and data collection, that processes vary and drift over time. This is known as the Long Term Dynamic Mean Variation. This variation falls between 1.4 and 1.6 [Harry, 2003]. Based on these findings, a 1.5 sigma shift from the mean has been allowed to compensate for process drifts in the long term. The effect of the 1.5 sigma shift for a six sigma process is insignificant as it would hardly cause any defects. A six sigma process should produce products that are within the desired specifications and with

a low defect rate [Westgard, 2001]. There has been much debate on the statistical basis of the 1.5 sigma shift, this shall not be discussed since it is beyond the scope of this project.

Interpretation of the 1.5 sigma shift in six sigma mathematics means the long term capability can be estimated by

$$Z_{LT} = Z_{ST} - 1.5 \quad (Z_{ST} = 6 = 3C_p) \quad (2.16)$$

$$Z_{LT} = 4.5 \quad (2.17)$$

Thus a Z value of 4.5 is considered Six Sigma quality [Harry, 1997]

The table below shows the level of defects expected for each sigma of a process for both a true six sigma process and a six sigma process allowing for the ± 1.5 sigma shift.

Table 2.2 Six sigma defect rate table

Specification Limit	True 6 sigma process		6 sigma with ± 1.5 sigma shift	
	Percent	Defective PPM	Percent	Defective PPM
± 1 sigma	68.27	317300	30.23	697700
± 2 sigma	95.45	45500	69.13	308700
± 3 sigma	99.73	2700	93.32	66810
± 4 sigma	99.9937	63	99.3790	6210
± 5 sigma	99.999943	0.57	99.97670	233
± 6 sigma	99.999998	0.02	99.99660	3.4

[Kolarik, 1995]

The difference between the level of defects achieved for a six sigma and the traditional 3 sigma quality standard is clearly shown by the above table. Even with zero drift, the level of conformance that can be achieved for a 3 sigma process is only 99.73% meaning a defect rate of 0.27 %. When applying this to practical terms three sigma is equivalent to one misspelled word per 15 pages while 6 sigma is equivalent to one misspelled word per

300 000 pages [Harry, 1997]. This indicates a very big difference between three and six sigma.

In some cases however a high level of quality even beyond six sigma has been achieved e.g. computers, air line industry, etc. This is an indication that such high levels of quality are attainable. To aim for six sigma is thus not to target the impossible as some people think.

2.7 THE FOCUS OF SIX SIGMA

Six sigma is a process focused strategy which aims at the improvement of processes by defining and measuring variation so as to discover its causes and hence develop efficient means to control, or rather eliminate it altogether [Sitinov, 2002]. The ultimate goal is to improve the process by lowering the defect rate and eliminating delay.

Six sigma aims at the ideal case of producing close to target with very minimal variation so that all the products produced by the process are within customer specification limits. This strategy assures consistent and superior product performance, which cannot be achieved by the traditional quality strategies which focused more on product inspection rather than on the process.

The following figures illustrate the difference between a target driven process (six sigma) and an inspection driven process.

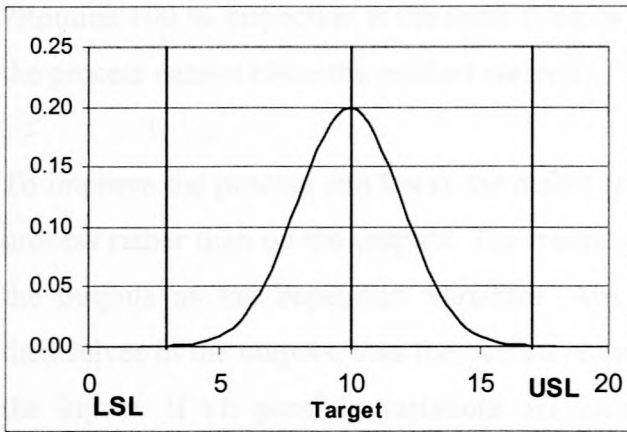


Figure 2.3a: Target driven process

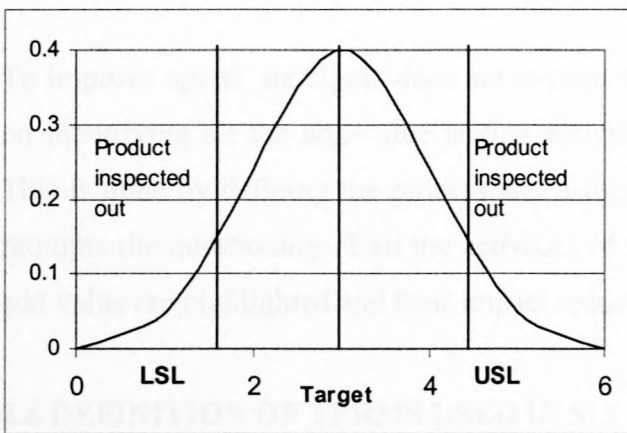


Figure 2.3b: Inspection driven process

[Kolarik, 1995]

The target driven process focuses on hitting the target and reducing variation so as to ensure all products produced by such a process are within customers' specification limits. The inspection focused strategy will produce products not within customers' specification limits and thus qualifying them as defective products. Product inspection will eliminate these defective products and prevent them from reaching the customer. Thus both systems ensures the customer receives only conforming product, however the inspection focused strategy will result in higher production costs due to the reprocessing of rejects which will obviously translate to higher selling prices. Regarding inspection, Deming said, "Quality comes not from inspection, but from the improvement of the process".

“Routine 100 % inspection is the same thing as planning for defects, acknowledging that the process cannot make the product correctly.”

To improve the process and lower the defect rate, six sigma focuses on the inputs to the process rather than on the outputs. The inputs are seen as the independent variables and the outputs as the dependent variables. Any variations in the inputs will manifest themselves in the outputs, thus the outputs shows symptoms of all problems occurring in the inputs. If all possible variations are eliminated in the inputs then the need to constantly test and inspect the outputs falls away since the products will meet specifications.

To improve speed, six sigma does not require the people to work any faster but focuses on identifying all the non-value adding activities e.g. delay, idle time, inspection, etc. This is done by defining the process and using common tools like the flowchart, which prompts the questioning of all the activities of the process. All the activities that do not add value are highlighted and their impact reduced if they cannot be totally eliminated.

2.8 DEFINITION OF TERMS USED IN SIX SIGMA

▪ Defect

A defect is defined as any part of product or service that:

- does not meet customer specifications or requirements.
- causes customer dissatisfaction.
- does not fulfill the required functional or physical requirements.

A defect could be in terms of quality, cost and delivery speed.

- **Unit**

A unit is something that can be quantified by the customer. It is a measurable and observable output of the business process.

- **Opportunity**

An opportunity is the total number of chances per unit to have a defect. .

- **Defect-Per-Unit (DPU)**

The number of observed defects per unit of product

$$DPU = D/U \quad (2.17)$$

D = the number of observed defects.

U = the number of units produced.

- **Defects-Per-Unit Opportunity (DPO)**

The Defects per unit opportunity gives the probability of non-conformance (defect) per given unit area of opportunity.

It is computed as shown

$$DPO = DPU/M \quad (2.18)$$

DPU = Defects per unit.

M = the number of independent opportunities for nonconformance per unit.

▪ Defects Per Million Opportunities (DPMO)

Six sigma measures defects in parts per million and thus the DPO have to be converted to that basis.

DPMO is calculated as shown

$$\text{DPMO} = \text{DPM} \times 1\,000\,000 \quad (2.19)$$

2.9 CALCULATION OF SIGMA OF A PROCESS

2.9.1 Continuous data

For continuous normally distributed data three pieces of information are required for the calculation of the sigma of a process. The process mean which measures process centering indicates how well the process is meeting the target (customer specification), the standard deviation which measures the extent of variation about the mean indicates how well the process is in control and the specification limits gives the customer's requirements of the product. The sigma of the process will indicate the capability of the process in meeting customer specifications. The potential sigma ($Z_{ST} = 3C_p$) will indicate the level that can be achieved by the process and the actual sigma ($Z_{ST} = 3C_{pk}$) indicates the actual capability of the process. The difference between potential and actual capability indicates the process is performing below expectation and can be improved. If a higher sigma value is desired than that which can be achieved by the process, the process itself need to be changed (process re-engineering). Calculation of the potential sigma enables us to know how far can the process be stretched, thus avoiding expecting more than what the process can deliver [Westberg, 2002].

Steps in calculating process sigma

1. Construct a control chart to ensure that the data is statistically stable, with no special causes of variation present.
2. Calculate the process mean.

3. Calculate the estimated standard deviation ($\hat{\sigma}$, sigma hat).
4. Calculate C_p .
5. Calculate Z_{ST} .
6. Calculate C_{pk} .
7. Calculate Z_{st} .

In addition Z_{upper} and Z_{lower} may also be calculated to determine how much of the data falls outside the upper and lower specification limits.

If $C_{pk} < C_p$, it means the process is not centered at the target specification and can be improved by reducing/eliminating variation on the key variables which influence process centering.

If $C_p < \text{desired performance}$, it means the process is potentially incapable and to improve C_p the process may need to be re-engineered.

2.9.2 Discrete data

To calculate the sigma level for discrete data the DPO measure is used. The DPO measure may be correlated to the Z-value since they both measure the probability of a defect. The probability of not finding a defect is given by (1-DPO). The Z-value corresponding to the (1-DPO) value in the Standard Normal Distribution Table [Kolarik, 1995] will give the sigma level of the process. This sigma level will be for long-term data. To determine the sigma level for short-term data 1.5 standard deviations must be added.

Steps in calculating process sigma

1. Define a defect, unit and an opportunity.
2. Calculate DPU.
3. Calculate DPO.
4. Calculate DPMO.

5. Determine Z_{LT} (Z value corresponding to (1-DPO)).
6. Calculate Z_{ST} .

2.10 BENEFITS OF IMPLEMENTING SIX SIGMA

The correct implementation of six sigma brings a number of benefits to the organization. Six sigma implementation has helped a number of organizations increase productivity and profits by mainly focusing on the customer, defects reduction and elimination of delay. The four well known six sigma companies; Motorola, Allied Signal-Honeywell, ABB and General Electric, have openly disclosed the financial benefits obtained from implementing six sigma. General Electric published a net benefit of over \$2 billion in its 1999 annual report and ABB saved \$898 million each year for two years from six sigma [Porter, 2002].

The following are examples of potential benefits of implementing six sigma:

- **Total customer satisfaction and loyalty**– the focus is on understanding and meeting customer's requirements.
- **Employee development and motivation** – employee-training needs are constantly assessed to ensure all employees possess the required skill levels.
- **Quality improvement** – improves the capability of processes and encourages breakthrough improvement.
- **Increase in productivity and profitability** – achieved by reducing total defects, reducing cycle time, eliminating waste, improving the processes and increasing product reliability.

2.11 LIMITATIONS OF SIX SIGMA

The six sigma standard does not automatically yield total customer satisfaction. This is because the standard does not measure the true quality characteristics expressed in the customer's vocabulary but measure substitute quality characteristics as defined by the producer and expressed in the producer's technical vocabulary. The customer true quality

characteristics are normally vague, for instance if a customer wants a food processor she would want it to be robust, easy to use, etc. The manufacturer has to translate these needs into technical specifications, e.g. type of material, volume, etc. so as to come up with a product that will meet all of the customer's expectations. Any differences between the customer's own product specifications and the manufacturer's design specifications will result in customer dissatisfaction. Thus a product may meet all technical specifications, and the six sigma metric satisfied, yet fail to meet customer satisfaction. It is therefore essential to understand the relationship between true and substitute quality characteristic since the degree of match between the two will determine customer satisfaction. Another danger of six sigma would be improvement in the metric while customer satisfaction gets worse by eliminating one type of defect at the numerical expense of a more important one. Despite these limitations the six sigma standard is a very good concept for improving quality, eliminating waste and helping organizations produce products and services better, faster and cheaper.

CHAPTER 3

THE SIX SIGMA PROBLEM SOLVING METHODOLOGY

The previous chapter gave a brief overview of six-sigma, attempting to answer the question ‘What is six sigma?’. The purpose of this chapter is to explain the six sigma methodology in detail.

Six sigma consists of two methodologies, **DMAIC** (define, measure, analyze, improve control) for improving existing processes and **DMADV** (define, measure, analyze, design, verify) for developing new processes or products at six sigma level. This chapter discusses only the DMAIC methodology, giving a step-by-step guide on how to apply the methodology to solve business problems.

A brief discussion is presented of the infrastructure required for successful implementation of six sigma and the different techniques organizations may choose to implement the six sigma system.

3.1 SIX SIGMA DMAIC IMPROVEMENT METHODOLOGY

Six sigma is carried out as projects that follow the DMAIC cycle. The Define step defines the problem and collects all information about the problem and process where the problem occurs. The Measure phase collects all the data that are necessary for determining the current performance of the process. The Analyse phase analyses data of the measure phase and uses the data to isolate the root causes of the problem. The Improve phase develops the optimal solution to eliminate the root causes of the problem. The last step, which is the Control phase, monitors the improvement so as to prevent backsliding to the old state [Nimkar, 2003].

A step-by-step guide of the DMAIC breakthrough strategy is presented below together with the applicable tools normally used for each phase. The tools used are not limited to the ones listed below. In actual fact the list of six sigma tools is endless since six sigma

integrates quality, business, statistics and engineering methods. It is important to be familiar with the range of tools in these areas since this will help in the selection of the appropriate tools for each phase.

3.1.1 The six sigma DMAIC breakthrough strategy

Table 3.1 Six Sigma DMAIC Breakthrough strategy

Breakthrough strategy	Method
1. DEFINE	
Define problem	Simplify the problem using tools like - Tree diagram, Line graph, Pareto chart
Define goal	Goal should meet the SMART criteria (specific, measurable, attainable, relevant and time-bound)
Identify team members	Select champion, project team and team leaders (Green belts/Black Belts/Master Black Belts)
Define performance variables and scope of project	Parameter development
Develop project plan and milestones	Gantt charts, Pert networks, Microsoft Project
Gather the voice of the customer and customer critical to quality (CTQ) requirements	Voice of the customer gathering techniques eg surveys, market research etc. CTQ definition
Develop a high level process map	Create a SIPOC Diagram (Suppliers, Inputs, Process, Outputs and Customers)
2. MEASURE	
Define Defect, Opportunity, Unit and Metrics	Agreed upon Definitions
Develop data collection plan	Data collection plan
Validate measurement system	Measurement system analysis (Gauge Repeatability and Reproducibility study)
Collect data	Interviews, check sheets, concentration diagram, experimental methods

Breakthrough Strategy	Method
Develop $Y=f(X)$ relationship	SIPOC Diagram ($Y=CTQ$, $X=$ inputs)
Establish performance capability	-Calculate capability indices (short-term and long term process capability) -Calculate process sigma
3. ANALYSE	
Identify value/non-value added process steps	Develop a sub process map
Identify variation sources	Root cause analysis tools (Seven Basic Japanese tools eg. Cause and Effect diagram, Histograms etc)
Screen potential causes and determine the vital few X 's of $Y=F(X)$ relationship	Statistical Analysis Design of Experiments (DOE)
4. IMPROVE	
Develop potential solutions	Brainstorming, DOE, Modeling
Select the best solution	Meet the two criteria: effective and feasible
Define operating tolerances of potential system	Mistake proofing
Verify performance improvement	Pilot studies
Establish new process capability	Capability indices calculation
5. CONTROL	
Define and validate control system	Control plan
Develop standards and procedures	Quality management system eg. ISO 9000
Implement statistical process control	Control charts
Verify benefits, cost savings, profit growth	Cost savings calculations, Return on Investment (ROI)
Audit control system	Internal audit system (ISO 9000)
Monitor performance metrics	Capability indices calculation

3.2 DEFINE

The Define phase is the first phase of the six sigma methodology. It consists of three steps: Team charter, Customer focus and Process mapping. The first step defines the improvement project, the project goals, project scope and the importance of embarking on the project. The improvement team is also selected.

The second step involves defining the customer so as to gather the voice of the customer. The voice of the customer is used to determine the critical to quality (CTQ) requirements, which must be satisfied to achieve customer satisfaction. The project focuses on the CTQ requirements, thus these are translated into measurable requirements.

The last step involves the creation of a process map that describes the process in detail. This helps to identify all the response variables within each process step [Waddick, 2003].

3.2.1 Team charter

The team charter includes the following: business case, problem and goal statement, project scope, milestones, roles and responsibilities and the communication plan.

- ***Business case***

The business case states the main business reasons the company is embarking on the project. The project selected should be in line with the strategic objectives of the organization, and there should be financial benefit to the organization in engaging in the project. The financial losses incurred as a result of the substandard process to be improved should be stated.

- ***Problem statement***

The problem statement is a brief description of the problem stating what the problem is, when it occurs and the extent of the problem. The problem statement should be well written and include everything about the problem since it serves as a basis for identifying the root causes.

Most problems are usually too big and complex to be understood. It is recommended to first identify the components of the problem (eg. types of defects, steps or delays in process, etc.) and then break down the problem into small pieces. This will give a clear picture of the problem and help in writing the problem statement.

- ***Goal statement***

Once the problem has been defined a goal or target for improvement, that is in line with the objective of eliminating the problem, is set. The goal statement states the improvement goal and how the project team and the organization will measure complete success of the project. The problem and goal statement should meet the SMART criteria (specific, measurable, attainable, relevant, and time-bound). Since six sigma targets breakthrough improvement, it is good practice to have a goal that aims for breakthrough improvement rather than incremental improvement.

- ***Project scope***

The project scope clearly states the boundaries of the project, stating what will be covered by the project and what will not, the project start date and the completion date. The project scope should be manageable and it should identify any constraints or obstacles that might impact the team. It acts as a guideline for ensuring that the project team keeps up with their project and are not deviated from its objectives.

- ***Milestones***

This gives the actual project start date and the estimated completion date. As the project proceeds, the actual progress is compared to the expected project plan. Any deviations from the plan should be addressed to ensure the project is completed on the expected completion date.

Tools like Gantt Charts and Pert/CPM networks are normally used to facilitate the scheduling of tasks.

- ***Roles and responsibilities***

The roles and responsibilities of each person in the project team should be clearly stated and understood by all. It is good practice to have these documented.

- ***Communication plan***

A communication plan should be developed to ensure accurate information on the project reaches the relevant persons on time. The communication plan should include communication channels, the type of information to be communicated and how the meetings are to be conducted.

3.2.2 Customer focus

The first step towards achieving total customer satisfaction is to focus on the customer. In business it makes sense to focus on the customer since all businesses rely on customers for their survival. The customer focus step is a very important step in the six sigma methodology since six sigma aims for total customer satisfaction. Six sigma seeks to understand the needs of the customer by forming a close relationship with the customer. When the needs of the customer are known, then one can strive to meet those needs. Six sigma recognizes that customers' needs are not static but change with time due to product

improvement by competitors or development of new products. To achieve customer satisfaction all the time, it is essential for organizations to respond to customers' changing needs. Six sigma not only requires forming customer relationships, but also supplier relationships. This is because supplier involvement is in the same way critical to successful quality improvement as is customer involvement. A supplier with poor quality compromises the quality of the final product reaching the customer [Goldstrin, 2003].

The customer focus step has three parts, to identify the customers, to gather their needs and to prioritise these needs so as to determine the critical to quality requirements.

- ***Define the customer***

According to ISO 9000:2000 the definition of a customer is “an organization or person that receives a product”. A product can be physical or a service. There are two categories of customers, internal or external. Internal customers are those within the production process and external customers are those, who receive the final product. The needs of these customers will not be the same. It is important that the customer is identified since only when the customer is known can information on the customer's needs, expectations and demands be obtained.

- ***Customer's requirements***

There are three types of customer requirements as described by Kano [Mazur, 1996]. A product or service must meet all three requirements for customer satisfaction. The absence or presence of these requirements effect customer satisfaction in different ways.

Revealed requirements – these may be obtained by just asking the customers what they want. These requirements satisfy or dissatisfy in proportion to their presence or absence in the product or service.

Expected requirements- these requirements are often so basic that the customer may fail to mention them. Meeting this requirement often goes unnoticed by most customers,

however their absence is very dissatisfying. Expected requirements must always be fulfilled otherwise the product or service may cease to be of value.

Exciting requirements- these classes of requirements are beyond the customer's expectation, they come as a bonus to the customer. The absence of these requirements is not dissatisfying, their presence however is very exciting. They are unspoken and invisible to both the customer and producer. Customers do not demand these requirements and it becomes the responsibility of the organization to uncover these unspoken needs since they are value adding and bring great competitive advantage over competitors.

▪ *Voice of the customer (VOC)*

The voice of the customer is gathered to determine the true needs of the customers. There are a number of customer information gathering techniques. Visiting the customer and observing how he uses the product has proved to be the best way of getting complete and accurate information on both the spoken and unspoken needs of the customer.

Customer information gathering techniques:

-focus groups

-surveys

-market research

-Going to the Gemba – (visit the customer so as to see the customer's problems and opportunities as they happen in order to get an understanding of the customer needs)

▪ *Critical to quality (CTQ) requirements*

The voice of the customer is prioritized according to how important the product characteristic is to customer satisfaction. The characteristics that the customer expects the product to have and are very important to the value of the product are termed the critical to quality (CTQ) characteristics. The absence of these requirements leads to customer

dissatisfaction. Often the customer states her requirement in common language (not scientific or engineering language) and sometimes this is unclear. Once the CTQ requirements have been verified the customer requirements have to be translated into the corresponding technical quality requirements so as to set technical targets and specifications for the product. It is important that the message is not lost when the customer needs are translated into technical language, since the degree of match between the two determines customer satisfaction or dissatisfaction.

3.2.3 Process map

A process map provides a visual presentation of the transformation of input resources to product outputs. Many specialized forms of process mapping have been developed depending on the process type. The most common are flowchart diagrams.

The process map provides all information as to the operation of the process since it shows the happening of all activities up to the final product. Since the process map breaks down the process into small pieces, it helps identify process bottlenecks, non-value adding activities or any other process limitation impacting on the value of the product thereby offering an opportunity for process improvement. Suppliers, Inputs, Process, Outputs, Customers (SIPOC) diagrams are used in the six sigma methodology to identify all elements of a process. The SIPOC diagram considers the process from all perspectives thus they uncover all information about the process as a whole and the customers that it serves. This helps highlight the non-value adding activities (waste, delay, etc) and determine what needs to be measured in the Measure phase (Process Indicators) so as to improve quality, speed and cost.

- **SIPOC Diagram**

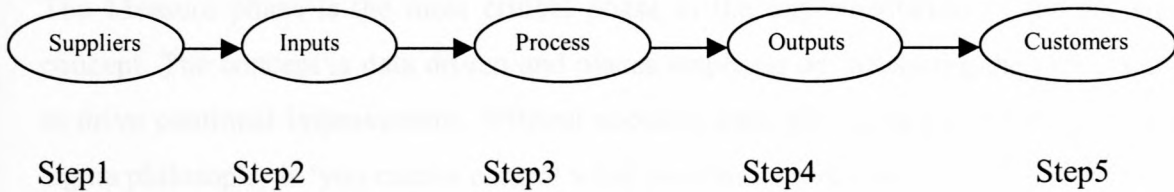


Figure 3.1 SIPOC diagram

The SIPOC diagram is created by following steps 1 to step 5 [Simon, 2000].

Suppliers – the supplier of inputs to the process could be internal or external supplier or service provider for the process.

Inputs – the resources that a process use to produce a desired output, product or service.

Process – transform inputs or resources to the desired output. They are a linkage between outputs (products) and inputs (resources).

Outputs – the result of a process step. It can either be a final product or an input to the next process step.

Customers – the ones who receives the output(s) of the process.

Processes and inputs determine to a large extent the quality of the product. The six sigma concept place emphasis on the measurement and improvement of the inputs and processes since quality inputs and processes will automatically yield a quality output.

3.3 MEASURE

The Measure phase is the most critical phase in the implementation of the six sigma concept. The concept is data driven and places emphasis on measuring the process so as to drive continual improvement. Without accurate data, six sigma cannot work. The six sigma philosophy is ‘you cannot control what you cannot measure’.

The measure phase collects all the necessary data that will give information to the performance of the process, highlighting problem areas that require improvement. Measuring the process gives an indication of the performance of the process; whether it is under control, improving or worsening. For measurement to be effective and give the required information on the process, it is important that what is to be measured is known, how to measure it and how to use and manage the data. Applying the wrong measurement is more destructive than not measuring at all, since it results in misleading information.

The measure must have the following properties:

- i) Specific in that they measure directly what is intended to be measured.
- ii) Measurable in that accurate and complete data may be collected.
- iii) Actionable in that metrics are easy to understand.
- iv) Relevant in that they measure only the things that are important.
- v) Timely in that data can easily be obtained when required.

In order for the measurement to be meaningful and useful, the selected unit of measurement ‘metric’ for the process should measure the right things. Since all processes are about producing products/services that meet customer expectations the measures selected should measure what is critical to the customer (CTQ) to ensure the customer’s needs are met.

It is not an easy task to select the appropriate metrics. The metric will only be useful if it is appropriate for the situation and serve its purpose. The following five questions should be asked when selecting the appropriate metric [Goyal, 2003].

- i) Why is the measurement required?
- ii) What needs to be measured?
- iii) What is the precision of measurement required?
- iv) How will it be measured?
- v) How will the results be used? By whom?

▪ **Key measures**

Input measures – measures of the key quality and delivery requirements placed on suppliers both internal and external.

Process measures – measures of key quality and delivery requirements internal to the process (process indicators) so as to determine the performance of the internal work process. They help find and fix problems before the customer is affected.

Output measures – measure of customer satisfaction (quality indicators)

Any of the three variables may be measured. A process focused strategy will measure the input and process variables while a product focused strategy will measure the output variable. This however does not mean a process-focused strategy will not be concerned with the product and vice versa. In actual fact one hardly finds a strictly process focused strategy or a strictly product focused strategy. The strategies, though different in what they measure, both aim in increasing customer satisfaction by meeting or exceeding the requirements of the customer.

Table 3. 2 Quality strategy versus Key measures

Quality Strategy	Types Of Measures		
	Input	Process	Output
1. Process focused strategy	×	×	
2. Product focused strategy			×

The six sigma concept to improving quality is more process-focused. Six sigma views a process as one having a mathematical relationship between its inputs and outputs denoted by $Y = f(X)$ [Harry, 2003]. Where Y is the output(s), X the input(s) and f the process(es) by which X is transformed into Y . In practice there will be more than one inputs, processes or outputs, thus the mathematical relationship may be viewed as:

$$Y = f(X) \quad (3.1)$$

Where

$$Y = [Y_1, Y_2, Y_3, \dots, Y_n]$$

$$X = [X_1, X_2, X_3, \dots, X_n]$$

$$f = [f_1, f_2, f_3, \dots, f_n]$$

In practical language this mathematical relationship means Y is a function of X , Y is dependent on X . Hence the Y 's are referred to as the "response variables" since they respond to anything that happens to the X 's. On the other hand the X 's are independent of the Y 's and are referred to as the "underlying cause system or underlying system of causation". Any state change in X will alter Y , thus Y shows the symptoms of all problems that occurs in X . To minimize variation we therefore need to control X , the independent variables and monitor Y the dependent variables. If the control of X is good, automatically Y will be good. In improving product quality the focus should be on controlling the inputs of the process. This does not mean neglecting the outputs since the process and its product are correlated; to measure process quality is to measure product quality.

The SIPOC diagram developed in the Define phase will help in identifying the X 's and the Y 's so as to develop the $Y=f(X)$ relationship for the process. The Y 's will be the CTQs and the X 's the inputs of the process. The Analyse phase will determine the vital few X 's from the trivial many independent variables which influence the dependent variables (Y 's).

3.3.1 Data collection

The main objective of measuring processes is to collect data on the key measures (inputs, process or output) so as to determine the current performance and identify those areas in the process that require improvement. The data collection process should be kept as easy as possible and the required data must be easy to collect and use. Too cumbersome or complex data should be avoided since it may be difficult to understand or even use. It is therefore essential that the data collection process be adequately planned so as to ensure that the data is collected in the most efficient way.

The following steps give a guideline in developing a data collection plan [Waddick, 2003]

Step 1: Define goals and objectives

This gives the objective of the data collection process as to why data is collected, what information is the data expected to provide and how will it be of help in the attempt to improve the process.

The goals and objectives should include:

- The specific data that is needed.
- The rationale for collecting the data.
- How the data will be used.

Step 2: Define operational definitions and methodology

The purpose of this step is to ensure the data collecting team reach agreement and the same understanding on all applicable definitions, procedures and guidelines that will be used in the collection of data. It's important that the team members have the same understanding on what is been done, otherwise the data collected would be unreliable.

This step should provide answers to the following questions:

- What data is collected? (type of data: discrete/continuous)
- How is the data collected? (e.g. interviews, check sheets, concentration diagrams, sampling, etc.)
- The scope of the data collection.
 - i) How many observations are needed?
 - ii) What time interval should be part of the study?
 - iii) Whether past, present, and future data will be collected?
 - iv) Which methodologies will be employed to record all the data?
- How a numerical value will be assigned so as to facilitate measurement?
- Is the customer collecting the same (or similar) data? If so can comparisons be made and best practices shared?

Step 3: Ensure data consistency and stability

The purpose of this step is to ensure the measurement system is repeatable, reproducible, accurate and stable.

It involves

- Identifying all the possible factors that could cause the data being collected to vary and find ways to mitigate or to eliminate these factors altogether. It may be necessary to perform Gauge Repeatability & Reproducibility studies so as to evaluate how the measuring system varies with respect to accuracy, repeatability and reproducibility (equipment and operator variation).
- Testing on a small scale how the data collection and measurements will proceed.

Step 4: Data collection process

This step allows for the project team to review all the applicable definitions, procedures, and guidelines to check for universal agreement and also ensure they are error-proof. The

project team members have to be trained on the data collection process as defined in the plan to ensure a common understanding. It is normally recommended that the project leader is present at the beginning of data collection to provide some supervision. This helps detect any shortcomings, which may bias the data collected.

Step 5: Review measures to ensure data consistency and stability

As the data collection proceeds, it is necessary to check and improve the data collection. This step involves checking that the data collection and measurement system are reproducible, repeatable, accurate, and stable. If not, the project leader should determine where any breakdowns exist and what to do with data/measurements that are suspect. It is also worth reviewing the definitions and procedures to help clarify any misunderstandings that might have lead to the breakdowns and to ensure the procedures remain consistent.

3.3.2 Data presentation and calculation of process sigma

Once the data collection process is complete, the data collected has to be converted into information, because in its raw form, it is meaningless. To convert the data into information requires knowledge of statistics. It is therefore necessary that the project team members have knowledge of statistical tools.

The data collected is used to determine the current process performance in terms of its capability indices or sigma level. The current process performance is compared to the desired performance, and the magnitude of the gap between the two is determined. Any obvious problems that can be picked up through common sense (“Ground fruit”) which their elimination would narrow the performance gap are identified and documented. The ‘Low hanging fruit and the Bulk fruit’ are determined in the Analyse phase using the seven basic tools and process characterization and optimization.

3.4 ANALYSE

The purpose of the Analyse phase is to identify the sources of variation so as to find ways to reduce or eliminate variation. This step can be considered as the heart of the six sigma methodology since the main goal of six sigma is to reduce variability.

The Analyse phase seeks to identify the key X's that affect the process outputs, the Y's. Finding these key X's will enable better control and optimization of the process. It involves performing a detailed data and process analysis so as to create a better understanding of the data and process, a root cause analysis to identify all the possible causes (sources of variation) and identifying the gap/opportunity between current performance and the goal performance. The key product performance metrics are benchmarked against best-in-class performance.

Variation is a key limiting factor of processes. It is the variation in processes that leads to an increase in defects, cost and cycle time. By reducing or eliminating variation, the capability of the process improves thereby reducing the probability of producing defective products. Thus when one eliminates variation one eliminates defects and the delays which translates to reducing costs.

When one talks of improving quality it is important to first understand variation. It is therefore appropriate to present a brief discussion of variation.

3.4.1 Variation

All manufacturing and measurement processes are subject to variation and these variations limit the efficiency and effectiveness of these processes. There are two types of variations: (1) common cause variation, sometimes called natural variation or random variation, and (2) special cause variation or non-random variation [Stephens, 2003]. Common cause variation occurs from within the process. Its impact may be reduced by changing the process (creating robustness against variation) or by improving the process.

On the other hand, special cause variation occurs from outside the process and can be eliminated by identifying its source and removing it so as to prevent its reoccurrence. A process, which only displays common cause variation, is considered a stable process and can therefore be predicted within limits how it may vary in the future [Carleton, 1999].

There are five main causes of variation and these are normally called the 3Ms and 2Ps. These are machines, materials, measurements, people and processes.

The variation in any process measurement is due to variations in the process or product itself plus variations associated with the measurement system. This is expressed as follows:

Total variation = Process variation + Measurement variation

Process variation covers all the long-term and short-term process variation, and also any variations due to all 'processes' required to obtain a result eg. samples/data collection etc. (Process variation = common cause variation + special cause variation)

Measurement variation covers variation due to instruments (Gauge), variation due to operators (Reproducibility) plus variations due to all 'processes' required to obtain a result e.g. samples/data collection etc.

The measurement variation should be very small when compared to the process variation so as not to obscure the process. Measurement variation can be minimized by using good instrumentation and having a well-trained workforce. Process variation can be minimized by identifying and eliminating the effects of special causes.

3.4.2 Data and process analysis

Data analysis involves the use of statistical tools like stratification analysis, scatter diagrams, histograms, pareto charts, etc. so as to breakdown the data and view it as small

subsets. These tools are useful since they give a visual presentation of the data making it very easy to identify the key problem areas (variation sources). Sometimes the data collected in the measure phase may not be sufficient and it may be necessary to collect additional data or perform specialized experiments to create a better understanding of the data.

The process analysis step involves determining the independent variables (X's) that are the cause of variation. This is done by developing a detailed process map (sub process map) which shows all the inputs (both controlled and uncontrolled), process and output variables. It gives an in depth analysis of the process highlighting all the critical steps of the process and also prompts the questioning of every activity thereby highlighting any non-value adding activities which need to be eliminated.

3.4.3 Root cause analysis

Root cause analysis involves using information obtained from the data and process analysis to zoom in on all the highlighted problem areas so as to generate a list of all the possible causes of variation (trivial many variables). The trivial many variables are prioritized based on the influence they have on the dependent variable so as to determine the 'vital few' variables which are the key sources of variation. Statistical analysis is normally used to quantify and verify the root causes of variation. Knowing the root causes of variation is the first step towards reducing or eliminating variation. The Improve phase focuses on doing just that.

Common tools used in performing the root cause analysis are Cause and Effect diagrams, 5 Why's, Pareto charts, Failure Mode Effect Analysis, Systems thinking, Design of Experiments (DOE), etc. [Kolarik, 1995].

3.4.4 Quantify gap/opportunity for improvement

Determine the performance gap between the current and the goal performance so as to develop a roadmap to reach the desired goal. If the current process is severely broken it may be necessary to re-design the process (design for six sigma). Since six sigma focuses on both productivity and profits it is essential to determine the cost of poor quality and the financial benefits to be achieved from narrowing or closing the performance gap.

3.5 IMPROVE

The Improve phase focuses on finding the best methods of eliminating the problems identified in the Analyse phase. The focus is on problem prevention rather than on correction since six sigma is a proactive strategy.

The improve phase therefore involves the generation of possible solutions, selection and testing of the best solutions and developing an implementation plan. The main objective being to find a breakthrough improvement in quality, speed and cost.

3.5.1 Generating possible solutions

Once the root causes of variation are identified the next step is to generate possible solutions so as to eliminate all the causes of variation. For each of the problems identified, the project team has to generate improvement theories, which states what needs to be done to improve the process. This exercise requires the project team to be knowledgeable about the process and also to be creative in their thinking so as to come up with new ideas. Brainstorming is favored since it is a very good tool to encourage creative thinking among a group of people. According to the normal practice of conducting a brainstorming session, all solutions pointed out by the group have to be documented even if they appear stupid and irrelevant.

3.5.2 Selecting the best solution

The best solution is selected based on the satisfaction of two criteria, effective and feasible. Effective in the sense that the solution will result in quality improvement, customer satisfaction, cost savings and increased business opportunity. Feasible in terms of cost, time and ease of implementation. The effectiveness and feasibility of each possible solution is ranked on a scale (Low-L, Medium-M, High-H). These analyses allow the selection of the optimal solution. A graphical presentation is shown on how the evaluation of each solution is done.

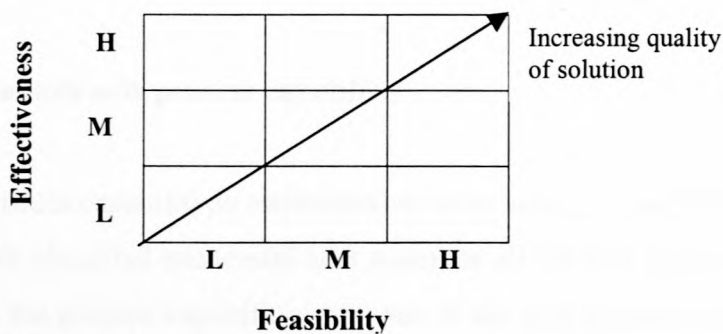


Figure 3.2 Evaluation matrix (optimal solution)

Mistake-proofing and testing of the solution is required so as to detect any mistakes in real-time and to ensure the solution does in fact remove the key sources of variation. This allows for corrections to be made so as to prevent any failures and to ensure that the solution is successful.

3.5.3 Cost/Benefit analysis of optimal solution

Six sigma focuses on financially measurable results. It is important to do a cost/benefit analysis of the optimal solution. This is to ensure that by implementing the solution there will be financial benefit for the organization. The cost analysis should include all the costs to be incurred by implementing the solution and the benefit analysis should include costs of poor quality to be eliminated and any financial gain to be realized as a result of an improvement in quality and speed.

3.5.4 Implementation plan

The implementation plan is developed to show how the proposed improvement will be implemented. The implementation plan should contain guidelines for implementing the solution, the resources required, monitoring plan and a contingency plan for potential problems occurring during implementation.

Sometimes it may be necessary to pilot the solution. This is especially true for big projects, in order to gather information on the effects of the solution and on how to make the full-scale implementation more effective.

3.5.5 Establish new process capability

A new process capability is established so as to verify the performance improvement. The solution is classified successful if it removes all the key sources of variation identified such that the process capability improves to the goal performance. If not, the solution is classified unsuccessful and it is necessary to go back to the Analyse phase. In some cases it may be necessary to redesign the process (Design for Six Sigma) in order to improve the process capability to the required performance level.

3.6 CONTROL

The main objective of the control phase is to sustain and monitor the improvement so as to ensure continuous improvement and to avoid backsliding to the pre-improved state.

It involves the development and documentation of a process control plan to ensure the process is operated at the new level of performance. The process has to be audited on a frequent basis to ensure it progresses as planned and the process capability evaluated so as to ensure continuous improvement of the process.

The process control plan should contain the following:

Process standardization – to ensure consistency.

Documented operating procedures – to ensure consistency.

Monitoring plan – gives the control/monitoring plan of the key measures (inputs/process/outputs) and the tools to be used. E.g. statistical process control etc.

Response plan – gives the critical parameters to be observed, and a corrective action guide that needs to be followed if the process gets out of control.

The requirements of the control phase (documented procedures, internal audit system, etc.) are the same as those required by the ISO standard (International Standards Organization). Like six sigma, the ISO standard requires a strong focus on the customer, and the measurement, analysis and improvement of processes, so as to ensure high levels of quality. The strong emphasis of the ISO standard in documentation of procedures and regular auditing of the processes will ensure sustainability of six sigma project(s) improvements. Hence the control phase of six sigma can be well integrated into the ISO standard assuring that there is no regression of the improved processes.

3.7 SIX SIGMA INFRASTRUCTURE

A six sigma organization uses the DMAIC methodology to improve customer satisfaction through the elimination of defects within business processes. The execution of projects to improve the business processes becomes a way of life. The improvement projects are led by fully trained and dedicated practitioners normally referred to as six sigma change agents.

The six sigma change agents are the key people in driving the six sigma culture throughout the organization and thus it is important that they understand and practice six sigma. Training and development of employees is a key success factor. Having good problem solvers is a prerequisite for the six sigma teams, since breakthrough improvement can only be achieved through identification and solving of the key business

problems. It is therefore important to have the best people participating in six sigma. According to Jack Welch, General Electric’s success with six sigma was attributed to the selection of the brightest and best employees into six sigma and by promoting a learning organization [Welch, 2000].

For six sigma improvement projects to be successful and bring financial benefit to the organization, six sigma requires the creation of the following infrastructure [Pyzdek, 2000].

3.7.1 Six sigma organization structure

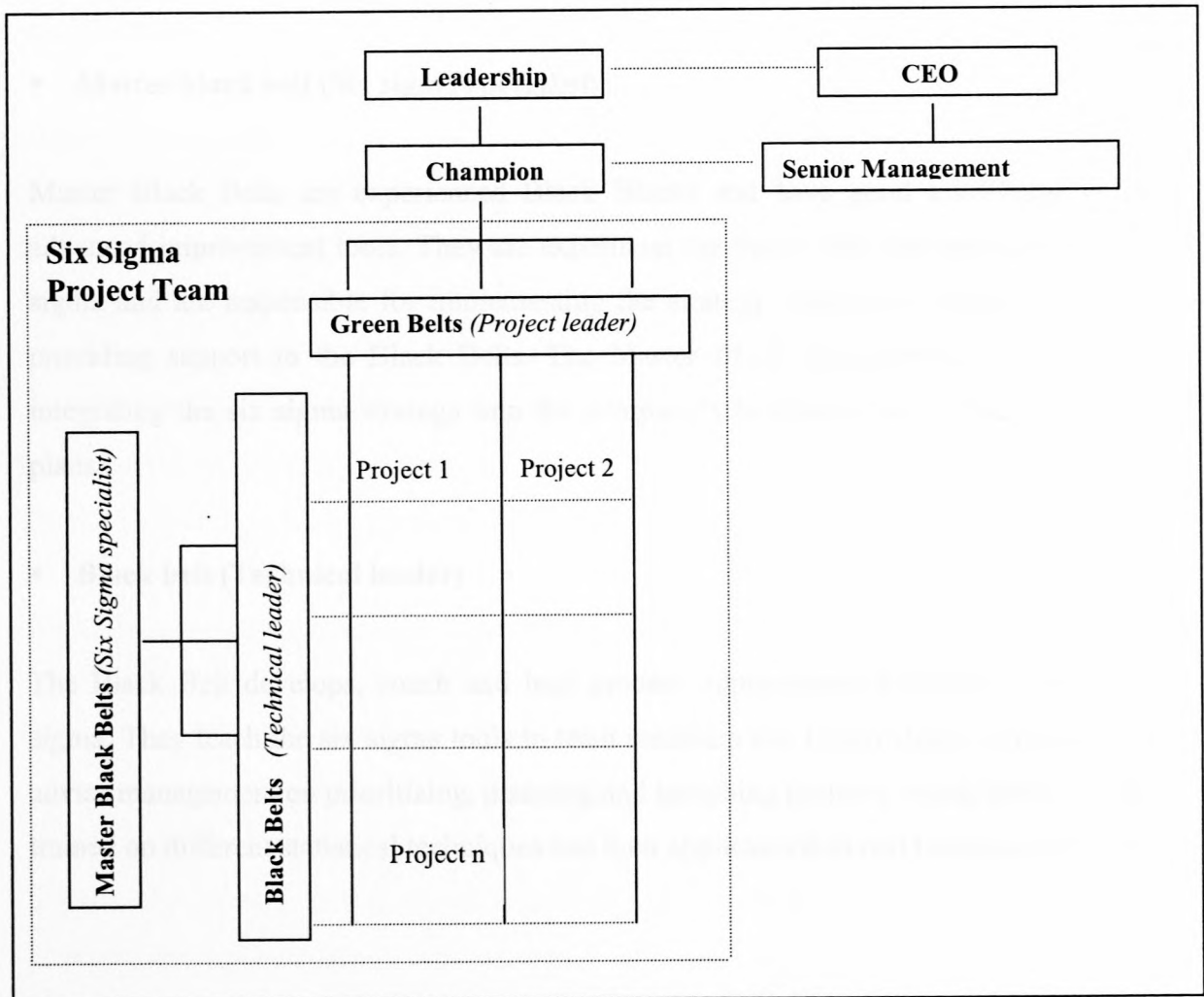


Figure 3. 3 Six sigma organization structure / change agents

- **Leadership**

To adopt the six sigma way of doing business, it is a basic requirement that the top leader of the organization e.g. CEO embraces the concept, since like any quality system there is no way it can succeed without top management support. Six sigma must be implemented from the top downwards.

- **Champion**

The Champion is a member of senior management who is totally responsible for the deployment of six sigma in the company and committed to its success.

- **Master black belt (Six sigma specialist)**

Master Black Belts are experienced Black Belts and have good knowledge of the advanced improvement tools. They are experts on the theory and implementation of six sigma and are responsible for implementing the strategy, teaching the philosophy, and providing support to the Black Belts. The Master Black Belt provides leadership in integrating the six sigma strategy into the company's business strategy and operational plans.

- **Black belt (Technical leader)**

The Black Belt develops, coach and lead process improvement teams that deploy six sigma. They teach the six sigma tools to team members and Green Belts, and also act as advise management on prioritizing, planning and launching projects. Black Belts are fully trained on different statistical techniques and their applications to real business situations.

- **Green belt (Project leader)**

Green belts are six sigma project leaders whose function is to select the improvement project and also assist in the selection of the improvement team. The Green belt takes full ownership of the project and leads it from concept to completion. Green belts are trained on quality management tools, quality control tools, project management, problem solving, and descriptive data analysis.

3.8 SIX SIGMA IMPLEMENTATION

All the six sigma companies agree that implementation of six sigma is a long-term process and requires total commitment from the organization's senior leadership. For it to succeed, the organization must see the need to implement six sigma as a tool for achieving business excellence and not implement it because "everyone else does".

The implementation of six sigma is more than following the DMAIC problem solving method. It requires a complete culture-change whereby everyone in the organization focuses on the needs of the customer, defects reduction, problem prevention, waste reduction, continuous improvement and excellence. All employees are actively involved and understand the role they play in achieving total customer satisfaction and business goals. To attain the six sigma quality culture a paradigm shift in the organization's ways of working and thinking is required. The organization leadership is responsible for driving this culture shift as well as providing the infrastructure required to support it.

The approach in implementing six sigma is the same as in TQM and requires the organization to concentrate on eight key elements: Leadership, Ethics, Integrity, Trust, Training, Teamwork, Recognition, Communication [Padhi, 2001]. Like any other quality system, the success of six sigma implementation depends on the willingness of the organization to accept change [Miller, 2002].

3.8.1 Six sigma implementation strategies

There are three general strategies of implementing Six Sigma.

- Six sigma organization
- Six sigma engineering organization
- Strategically selected projects and individuals

The main aspects of each of these strategies are outlined below.

Table 3:3 Main aspects of six sigma implementation strategies

Aspect	Six Sigma Implementing Strategies		
	Six Sigma Organisation	Six Sigma Engineering Organisation	Strategically selected projects and individuals
Personnel trained	-All employees, senior and area managers from all areas of the organisation	-A large percentage of the engineering staff: design/product, manufacturing/process	-Strategically selected individuals: project driven, informal leaders
Typical course content	-Overview -Philosophy and basic concepts -Fundamental tools and methods -Project work	-Overview -Philosophy and basic concepts -Fundamental tools and methods -Advanced fundamental tools -Project work	-Overview -Philosophy and basic concepts -Fundamental and advanced tools and methods -Specific tools and methods as needed for individual projects -Project work

Aspect	Six Sigma Organisation	Six Sigma Engineering Organisation	Strategically selected projects and individuals
Strengths	<ul style="list-style-type: none"> -High level awareness -Common language -Common tool set and problem solving approach 	<ul style="list-style-type: none"> -Focused resources -Larger set of tools for engineers -Similar backgrounds among individuals in training -More attention given to project application 	<ul style="list-style-type: none"> -Projects aligned with organizational objectives -Less initial amount of money required for training -High amount of flexibility in training content -Strongest project focus
Common weakness	<ul style="list-style-type: none"> -Tendency for cynism to develop -A focus on slogans -Large amounts of resources required for mass training -An inflexible road map for process improvement or problem solving 	<ul style="list-style-type: none"> -Lack of common language across all areas of the organisation -Difficult in deployment outside of operations and engineering -Managers not provided training to effectively integrate skills learned into everyday engineering responsibilities 	<ul style="list-style-type: none"> -Isolation of those trained -Lack of common language -Difficulty in integrating beyond "Six Sigma Projects" -Tendency for attitude of elitism to develop

[Sanders, 2000]

Each of the above strategies implement six sigma by targeting a certain group within the organisation and teaching that group the six sigma methodology and the problem solving tools involved. The first strategy targets everyone in the organisation. Everyone in the organisation from top managers to the bottom is trained on six sigma. The level of training depends on the employee's function in the organisation. This method is the best method since everyone in the organisation shares the same vision and work towards

achieving it. Its main disadvantage is that it requires a very large investment in training especially for large organizations.

The second strategy focuses only on the engineering and manufacturing staff, since they are the ones directly responsible for the design and manufacture of product. This however creates a gap between the manufacturing section and the other functions of the organisation since their cultures become different.

The third strategy focuses on training a selected few individuals, normally those who demonstrate a very high talent and potential. These individuals are assigned complex projects identified by the needs and objectives of the organisation and work full time on six sigma projects. Having dedicated staff to work on six sigma projects full time reduces the risk of not completing projects since there will be no situations whereby six sigma projects are abandoned because team members have to concentrate on their day-to-day jobs. However situations can occur where the six sigma specialist are isolated and not welcomed into operations by the process owners. Also sometimes a feeling of anxiety develops from the selected individuals of being left behind by their peers who had remained in operations on issues such as promotion and career development.

Overall, the strategy selected for six sigma deployment will vary between organisations depending on the organization's needs and objectives. Before an organisation starts on its journey of implementing six sigma, it is advisable that the organisation first conducts a self assessment which will help the organisation understand its 'current state' and help identify the opportunities for improvement. The organisation should then determine its 'to be state'. Knowing the magnitude of the gap between these two states will help the organisation in developing an effective six sigma plan on how it will narrow the gap [Phandis, 2003].

In implementing six sigma the author favours the third strategy with a goal of moving towards the first strategy. The six sigma team need not be separated from the organisation. The third strategy is favoured since less money is required for training since

few individuals are trained. Secondly having few of the right people will be more effective in driving culture change than initially engaging everyone in the organisation. “Research shows that transformational change begins with less than five percent of the work force. It also suggests that to accelerate the change you will want to reduce the number of people involved” [Arthur, 2003]. Thus the selected individuals act as change agents slowly transforming the organisation into a full six sigma organisation with top management as the driver. Having the whole organisation speak one language is a requirement since the functions of the units are dependent on each other, thus any weak link weakens the whole organisation.

All in all it should be appreciated that six sigma is not only a technical program but also a management program. Therefore a culture-change should be part of the six sigma implementation program [Yuejin, 2001]. Like all quality improvement systems, the success of six sigma will be based on the people’s attitude toward it and their willingness to accept change. With so many quality management programs (TQM) failing, most organisations are reluctant to take on the six sigma challenge as they think it will die in the same way. However the reasons most quality systems failed is not that the systems were bad and failed to improved quality, but it is because of the approach taken. Surveys of failed TQM programs cite management attitudes, lack of commitment and threat of change as some of the reasons for their failure [Watt, 2002]. Another reason for failure was having the wrong goals. For instance from learning the benefits that can be achieved with TQM or ISO certification, many organisations rushed in implementing these systems so as to achieve the promised benefits without actually building the required infrastructure. Their goals became implementing the system as quickly as possible rather than to improve quality, eliminate waste, cut costs and increase productivity. Certainly, with the wrong goals the quality systems are bound to fail.

Secondly by implementing a quality system quickly brings in the danger of installing the system rather than implementing it. Installing a system is very easy and anyone can do it without much effort since it is all about generating manuals, running training programs, etc. On the other hand, implementing is more difficult since it requires putting into

practice a quality system and building a sustainable long-term behavioural change. These cannot be achieved with the wrong goals and without the required structure. So for six sigma to succeed, the organization should have the correct goals, the required support structure and understand what six sigma can do and cannot do.

The previous chapters gave a theoretical background of six sigma and the DMAIC problem solving methodology. This chapter focuses on the application of six sigma in a real-world process, namely the colour removal from sugar cane.

4.1 RESEARCH PROBLEM

The six sigma problem solving methodology was implemented to improve the colour removal process of the refining operation at Milburg Sugar Estate. Colour is an important parameter in sugar refining and is used as a measure of the amount of non-sugars in a sugar solution due to the fact that most non-sugars are coloured (Meyer, 2007). The performance of a sugar refinery is therefore measured on the amount of colour it is capable of removing from the raw sugar. The degree of colour removal is dependent on the technology/method being used and the efficiency of the operation. The decolourisation and sulphitation process, with the addition of a humic acid, can be used to improve the colour removal. These processes make use of calcium chloride and calcium dioxide which forms a calcium precipitate in water. This removes the colour and many other impurities. Both these processes are a part of removing the colour from raw sugar.

The colour removal process of Milburg Sugar Estate was chosen for the reasons:

- 1) pH control of this process is very poor and as a result of that the colour removal achieved is below expectation
- 2) Colour removal is a key process in sugar refining and has the biggest influence on final sugar quality. Thus, the starting point when improving sugar quality should be in better control and optimization of the colour removing process.

CHAPTER 4

EXPLANATION OF PROBLEM AND RELEVANT BACKGROUND INFORMATION ON THE COMPANY AND THE PROCESS TO BE IMPROVED

The previous chapters gave a theoretical overview on the subject of six sigma and the DMAIC problem solving methodology. The next chapter will demonstrate a practical application of six sigma in a continuous processing plant manufacturing raw and refined sugar from sugar cane.

4.1 RESEARCH PROBLEM

The six sigma problem solving methodology is demonstrated by application to the colour removal process of the refining operation of Mhlume Sugar Estate. Colour is a very important parameter in sugar refining and is used as a measure of the level of non-sugars of a sugar solution due to the fact that most non-sugars are coloured [Moodley, 2002]. The performance of a sugar refinery is therefore measured on the amount of colour it is capable of removing from the raw sugar. The degree of colour removal depends on the technology/method being used and the efficiency of the operation. Mhlume uses the carbonation and sulphitation process, with the addition of a cationic flocculant to further improve the colour removal. These processes make use of carbon dioxide and sulphur dioxide which forms a calcium precipitate in each case. This removes the colour bodies, and many other impurities. Both these processes are capable of removing 80-85% of the colour in raw sugar.

The colour removal process of Mhlume Sugar Estate was chosen for two reasons:

- 1) pH control of this process is very poor and as a result of this the colour removal achieved is below expectation.
- 2) Colour removal is a key process in sugar refining and has the biggest effect on the final sugar quality. Thus, the starting point when improving sugar quality should be in better control and optimization of the colour removal process.

The project is aimed at improving the pH control of the colour removal process by applying the six sigma problem solving methodology known as DMAIC.

4.2 BACKGROUND OF MHLUME SUGAR ESTATE

Mhlume Sugar Company is one of the three sugar mills in Swaziland. The mill was constructed in 1958 producing raw sugar from company and private owned sugar cane. Over the years the company has been increasing its production, as sugar cane has become a popular commercial crop in Swaziland accounting for 59% of agricultural output. In 1996 Mhlume further expanded building a refinery extending its production to refined (white) sugar. Today the company processes 1.3 million tonnes of sugar cane per year which amounts to the production of 110 000 tonnes of refined sugar. In year 2003 Mhlume formed a joint merge with one of the sugar mills in Swaziland, Simunye Sugar Estate forming the largest sugar company and the biggest employer in Swaziland. The sugar produced is sold through the Swaziland Sugar Association, which sources out the markets. The main markets being the European Union (EU), United States (US), Southern African Customs Union (SACU), the world market as well as the domestic market. Sugar sold in the domestic market is consumed by manufacturing companies producing sugar based edible concentrates and blends, canned fruits, sweets and other edible commodities.

Today the swazi sugar industry faces a lot of challenges because of the falling sugar prices and the termination of preferential agreements which offered protection from the world giant sugar producers e.g. Brazil, India, etc. In-order for the swazi sugar industry to survive and compete with these sugar giants, it is critical that they become efficient in their operations so as to cut down on production costs and produce high quality sugar. To achieve this it will be necessary to adopt new technologies and to embrace quality systems which aims for the improvement of business processes e.g. six sigma. This will not be an option considering that the country's economy is highly dependent on agriculture.

4.3 REFINED SUGAR MANUFACTURING FLOW DIAGRAM

For familiarization with refined sugar manufacturing, a process flow diagram is presented which shows all the unit operations from melting very high pol sugar (VHP) to refined sugar packaging.

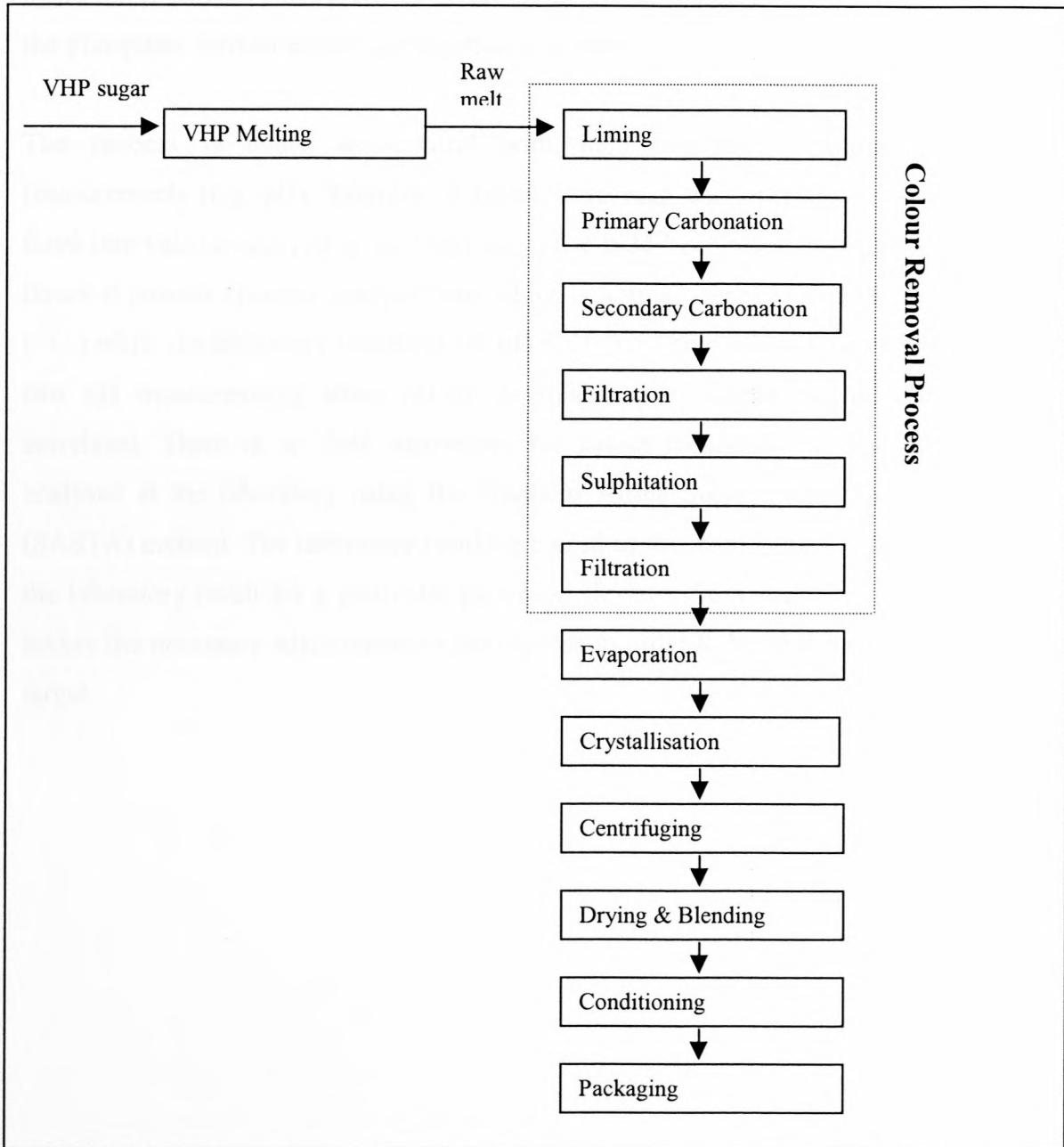


Figure 4.1 Refined sugar manufacturing process flow diagram

Explanation Of Problem

The bounded region represents the colour removal processes, and consists of three unit operations; liming, carbonation and sulphitation. Each unit operation has inputs and outputs, and a specification target for the output. The output from one unit becomes an input to the next unit operation. The pH and colour of the liquor are the main variables that are being monitored throughout the colour removal processes. The filtration operation is omitted since it has no effect on the pH and colour. It involves the removal of the precipitate formed in both carbonation and sulphitation.

The process is under auto-control with field instruments taking the required measurements (e.g. pH). Samples of liquor from each unit operation are also taken at fixed intervals for analysis at the laboratory. The field instruments measure the pH of the liquor at process operating temperature, which is normally between 80-85 degrees celsius (°C) while the laboratory measures the pH at 20 °C. There is a difference between these two pH measurements since pH is dependent on temperature, however they are correlated. There is no field instrument for colour measurement. The latter is only analysed at the laboratory using the Southern Africa Sugar Technologist Association (SASTA) method. The laboratory results are used as the main control. This means that if the laboratory result for a particular parameter deviates from specification, the operator makes the necessary adjustments to the process in order to bring it back to the required target.

CHAPTER 5

APPLICATION OF THE SIX SIGMA PROBLEM SOLVING METHODOLOGY AT MHLUME SUGAR COMPANY REFINERY COLOUR REMOVAL PROCESS

5.1 DEFINE PHASE

5.1.1 Team charter

- **Business case**

This project aims to improve the operation of the colour removal process of the sugar refining operation of Mhlume. The colour removal process is a very important process in sugar refining because that is where the colour in the raw (brown) sugar is removed so as to produce refined sugar. Colour not removed in the colour removal process ends up in the refined sugar. Since colour is one of the parameters that affect the sale of sugar this will compromise the sugar quality. The colour removal process also remove floc-forming impurities, which if not removed can cause the sugar to form floc. Again floc formation is undesirable especially for refined sugar that will be used in the beverage industry. The efficiency of the colour removal process impacts in the final refined sugar quality. It therefore makes sense to improve and optimize this important process.

- **Problem statement**

The pH control of the two unit operations of the colour removal process, carbonation and sulphitation is poor. The poor pH control results in poor colour removal, since pH is one of the variables that determines the amount of colour removal. The first carbonation stage fails to lower the pH to the required specifications and the second carbonation stage is highly variable with the pH fluctuating between too high and too low. The sulphitation process adds more sulphur dioxide than required. As a result the pH is lowered below the lower specification limit. Low pH's are undesirable since they favour sucrose degradation into glucose and fructose, and acid corrosion of plant equipment and piping. Addition of

more sulphur dioxide than required translates to higher chemical costs and also increases the sulphur content in the sugar produced.

- **Goal statement**

The goal of the project is to determine the causes of poor pH control so as to improve the capability of the process to operate within the required pH specifications. This will ensure maximum and consistent colour removal and thus improve the final sugar quality produced.

- **Project scope**

This project is limited to the demonstration of a six sigma improvement methodology for the colour removal process of Mhlume refining operation and not actual implementation of the methodology. Past data on the process will be used in the investigation.

- **Roles and responsibilities**

The project is done as an academic assignment. The student therefore takes full responsibility for all the requirements of the project. The student supervisor and mentor give guidance where necessary.

- **Communication plan**

All information on the project will be communicated to the project supervisor electronically or through mail for assessment in terms of meeting project objectives and university requirements.

5.1.2 Customer focus

- **Define the customer**

There are two types of customers; internal and external customers. The external customer receives the final product, refined sugar and the internal customers are within the production process and they receive the output of each unit operation. Since this is a process improvement project the focus will be on the internal customers. This does not mean the external customers' needs are neglected, since the needs of the internal customers are derived from that of the external customers. Thus, to meet the needs of the internal customer is to meet the needs of the external customer. The customers of the colour removal process are the unit operations that receive the output of the process and that are affected in one way or another by the quality of the product. Referring back to Figure 4.1 on page 63, the customers are the next two unit operations, the crystallization and centrifuging processes. The filtration and evaporation processes are omitted since they do not really depend on the key outputs of the colour removal process which are pH and colour. The filtration process removes the precipitate formed in the carbonation and sulphitation process. The evaporation process evaporates the water in the liquor (juice) to the desired concentration. Thus both these processes are not really influenced by the pH and colour like the crystallization and centrifuging processes.

The crystallization process is the first internal customer of the colour removal process since it receives the liquor produced from this process and crystallizes it using steam so as to produce sugar. Impurities not removed in the colour removal process will affect the sugar crystallization process. The centrifuging process is the second internal customer despite the fact that it receives output from the crystallization process. This is because the amount of water and steam used in the centrifuging process for washing the massecuite depends on the massecuite colour, which in turn depends on the liquor colour from the colour removal processes. The washing of the centrifuging process however cannot make up for poor colour removal.

▪ **Customer requirements - voice of the customer**

The voice of the two identified customers, crystallization and centrifuging processes were gathered so as to determine the true needs of the customer. The voice of the customer (VOC) was then prioritized according to product characteristic importance to the customer so as to determine the customer critical to quality (CTQ) characteristics. The VOC/CTQ requirements are recorded in tabular form showing the customer requirements and the consequence of a deviation in the requirements.

Table 5.1 Customer requirements (VOC/ CTQ)

	Customer requirements	Consequence of deviation in requirement
1. Crystallisation process		
i	pH=7.0	Low pH/High pH -poor/very slow crystallization -increased boiling times -low throughput
ii	Thick liquor colour < 570 ICUMSA units	High colour - Low throughputs (reject resultant runoffs)
iii	70 Brix	Low Brix -increased energy consumption -increased (long) boiling times -low throughput
iv	Temperature 80°C	Low Temperature -increased energy consumption
2. Centrifuging process		
i	Thick liquor colour < 570 ICUMSA units	High colour - Low throughputs (reject non-conforming sugar) - Low yields (increase wash water settings) - Sugar colour out of specifications

5.1.3 Process mapping

▪ Process map

A process map has been developed to show the actual production sequence of the colour removal process and the specification targets for each unit operation.

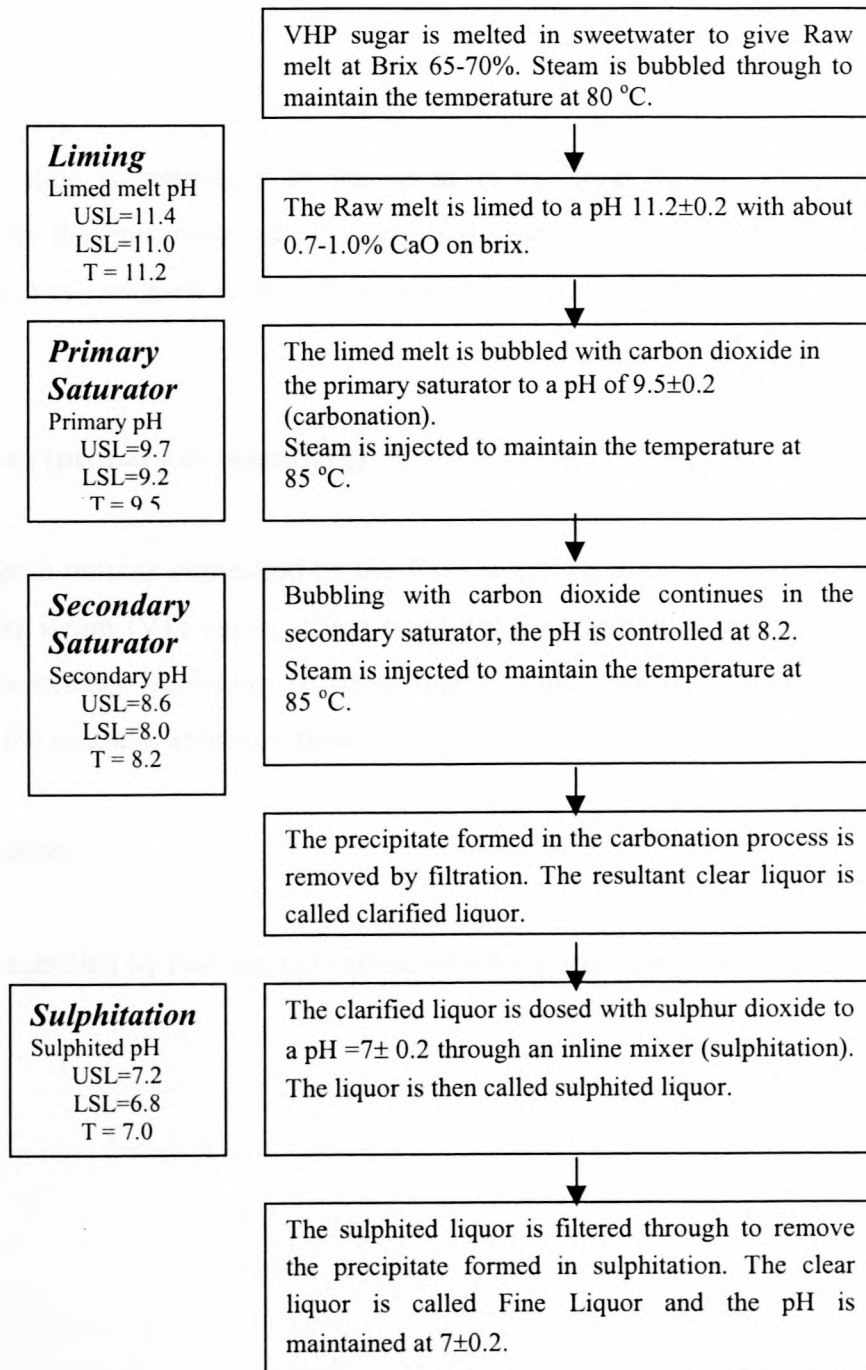


Figure 5.1 Colour removal process map

▪ **Process operating philosophy**

The process operating philosophy is briefly explained. The process is under auto control with the exception of the primary saturator pH control, which is manually operated. This is because the CO₂ gas valve stays at 100% fully open.

i) Liming

Addition of lime is controlled by the speed of the lime pumps. The pump speed is determined by the lime ratio, which is manually entered by the operator. The lime ratio gives the ratio of raw melt flow to lime, and is determined using the raw melt flow as a basis.

ii) Saturators (primary & secondary)

The pH in both units is controlled by the flow of carbon dioxide, and the temperature is controlled by steam (V1) valve, which regulates the addition of steam. The outlet flow from the secondary saturator is controlled by the saturator's level control. This determines the saturator retention time.

iii) Sulphitation

The pH is controlled by two control valves, which regulate the flow of sulphur dioxide.

- **SIPOC diagram**

A SIPOC diagram was developed to identify all the elements of the process as shown by the process map in Figure 5.1 (page 69). The outputs/customers of one unit operation becomes the inputs/suppliers of the next unit operation.

Table 5.2 SIPOC diagram

	Suppliers	Inputs	Process	Outputs	Customers
1	Rawhouse	VHP sugar (<1100 Icumsa colour) V1 steam (150 kPa pressure) Sweet water	Melting	Raw melt (pH, colour, brix, temperature)	Liming process
2	Lime plant Melting process	Calcium hydroxide Raw melt (pH, colour, brix, temperature)	Liming	Limed melt (pH, %CaO, brix)	Carbonation process
3	Boilers Rawhouse Liming process	Carbon dioxide (>15%) V1 steam (150kPa pressure) Limed melt (pH, %CaO, brix)	Carbonation	Clarified liquor (pH, colour, brix, temperature)	Sulphitation process
4	Sulphur dioxide plant Rawhouse Carbonation process	Sulphur dioxide V1 steam (150kPa pressure) Clarified liquor (pH, colour, brix, temperature)	Sulphitation	Fine liquor (pH, colour, brix, temperature)	Crystallisation and centrifuging processes

5.2 MEASURE PHASE

The Measure phase was done by collecting past data on each unit operation from the laboratory (Lab) and field instruments (FI). This data was used to determine the current performance of the process as it revealed the ‘voice of the process’.

5.2.1 Identification of key measures

The key measures of the colour removal process were identified so as to determine the variables to be measured.

Table 5.3 Colour removal process key measures

Key Measures	
Input Measures	VHP sugar colour
	% Calcium oxide
	% Carbon dioxide
	% Sulphur dioxide
Process Measures	% Colour removal
Output Measures	pH
	Colour

The % colour removal achieved, a “bigger-is-better yardstick” indicates the performance of the colour removal process. The % colour removal is therefore the key process indicator, as it will indicate whether or not the process will deliver what the customers wants.

The colour removal process can be denoted mathematically as $Y = f(X_1, X_2, \dots, X_n)$. Y is the process output and denotes the liquor pH and colour. This is represented as shown:

pH: $Y_1 = f_1(X_1, X_2, \dots, X_n)$

Colour: $Y_2 = f_2(X_1, X_2, \dots, X_n)$

The X's are all the input/process variables which have a major effect on the output of the process. In other words the X's will control the output of the process. The X's represents both controlled and uncontrolled inputs variables. The focus will be in identifying these X's, in particular to finding the critical X's since these will enable better control and optimization of the process.

5.2.2 Data collection

▪ Data collection goal:

The goal is to collect data on the colour removal process so as to gain knowledge on the performance of this process. The data should give information as to whether the process is under control or not, able to meet product specifications or not and highlight any problem areas within the process so that these problems can be corrected so as to improve and allow better control of the process.

▪ Data collection strategy

The project collected past laboratory results data on the process and where applicable the corresponding field instruments data available from the workstation unit. The process is continuous and samples for laboratory analysis are taken every 2 hours for pH and every 4 hours for colour analysis. The type of data can therefore be considered to be continuous. The required sample size was determined by performing the following statistical test.

- For each unit operation a mini sample of 20 readings were taken ($n = 20$).
- The sample mean (\bar{X}) and standard deviation (s) were calculated using equations 2.1 and 2.2 (page 15).
- The sample size (N) was calculated using the following formula:

$$\text{Sample size} = N = \left(\frac{Z_{\frac{\alpha}{2}} s}{K \bar{X}} \right)^2 \quad (5.1)$$

Where

K = Margin of error (Maximum error allowed between the estimated mean and the true mean).

$Z_{\frac{\alpha}{2}}$ = Critical value (the positive z value that is at the vertical boundary for

the area of $\frac{\alpha}{2}$ in the right tail of the standard normal distribution

The table below presents the calculated sample sizes for each of the three unit operations product output(s). The sample size was determined with a 95% degree of confidence ($\alpha=0.05$) and the margin of error was selected based on the calculated sample standard deviation. Most of the processes have a very small standard deviation and thus a very small margin of error was allowed.

Table 5.4: Sample size requirements for the colour removal processes

Unit Operation	Sample Mean (\bar{X})	Standard Deviation(s)	Margin of Error (K)	Sample Size (N)
1. Liming process				
Limed melt pH	11.30	0.22	0.5%	60
2. Carbonation process				
Primary pH	9.98	0.24	0.5%	92
Secondary pH	8.49	0.74	1.0%	288
3. Sulphitation process				
Sulphited Liquor pH	6.85	0.54	1.0%	173
Fine Liquor pH	6.79	0.35	1.0%	102

The laboratory data was considered to be accurate and stable since the laboratory participates in inter-laboratory comparison where for specific samples the results obtained are compared with those from other laboratories. The purpose of this exercise is to ensure gauge repeatability and operator reproducibility.

▪ Data presentation

The data collected from the laboratory and field instruments is presented in the Appendices. The pH data was used to construct normal probability plots so as to assess the normality of the population. An example of the normal probability plot is shown below.

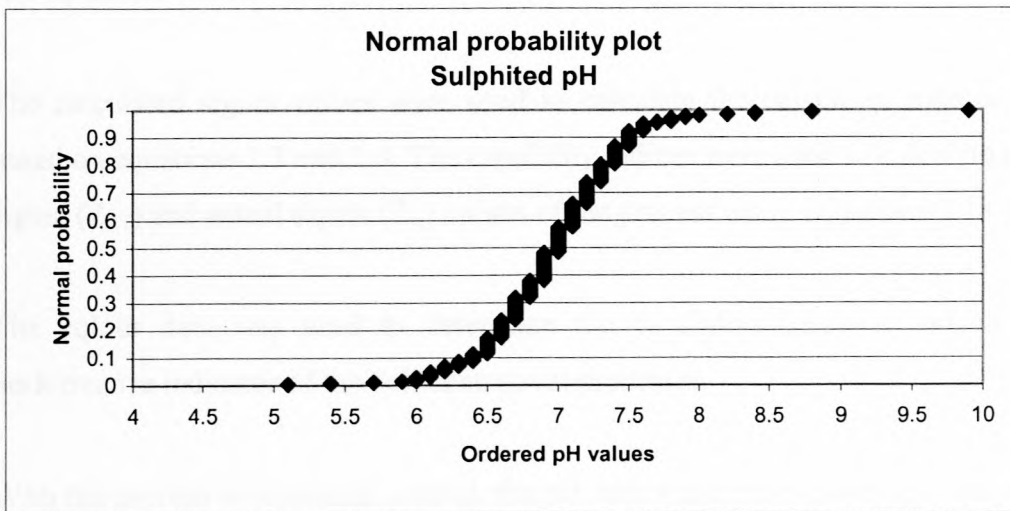


Figure 5.2: Normal probability plot

The x-axis of the graph presents the ordered pH values (ranked from smallest to largest) and the y-axis presents the cumulative frequency. The cumulative frequency is given by:

$$\text{cumulative frequency} = \frac{\text{Rank order}}{(\text{Total number of data points } (n) + 1)}$$

The X-Y values of the normality plot lie along a straight line and therefore it can be assumed that the pH data is from a normal distribution. There are however a few points that lie off the line and these points can be considered as outliers. The S-shaped nature of the curve indicates that the data is from a light-tailed distribution.

The laboratory pH data was used to determine if the colour removal processes are statistically able to meet the required specifications. In order to compare the process performance to the specification limits, the process has to be stable, in statistical control. Control charts (X-MR charts) were prepared so as to remove the effects of special causes such that only common causes of variation exist in the process. The information from the control charts (\overline{R}_M) was used to calculate the estimated standard deviation $\hat{\sigma}$ (sigma hat) using the following equation

$$\hat{\sigma} = \frac{\overline{R}_M}{d_2} \quad (5.2)$$

where the denominator d_2 is a weighting factor whose value is based on the subgroup size, n , for the control chart [Kolarik, 1995].

The calculated sigma values were used to calculate the capability indices C_p and C_{pk} based on equations 2.3 and 2.4. The capability indices were used to calculate the potential sigma (Z_{ST}) and actual sigma (Z_{st}) values of the process using equations 2.13 and 2.14.

The colour data was used to determine the % Colour removal, which is the key performance indicator of the colour removal processes.

With the process in statistical control, the pH data was used to develop histograms for the outputs of each of the three unit operations; liming, carbonation and sulphitation. The histograms provide a visual presentation of the actual process performance with respect to its location and dispersion.

The percentage frequency distribution plots for each process parameter are presented. The x-axis represents the Actual pH - Target pH (deviation from target) for that particular parameter and the y-axis represent the percent frequency (% frequency). The x-axis pH data was grouped into class intervals of constant width. For instance the following class interval [$11.0 \leq \text{pH} < 11.2$] would consist all the pH data falling within this range. This is then converted to represent the deviation from target (Actual pH - Target pH) which

will be the x-axis value [$0.0 \leq \text{pH} < 0.2$]. If there are 30 data points (frequency =30) in this class interval [$0.0 \leq \text{pH} < 0.2$], the frequency is converted to a percentage frequency which will be the y-axis value. The percentage frequency gives the percentage of the total number of data points

Percentage frequency = (Frequency of class interval / Total frequencies of all the class intervals) \times 100 %

% frequency = relative frequency \times 100 %

The plots show the process spread, specification limits (USL, LSL, T), capability indices and the percentage data points falling outside the specification limits. The data falling outside the specification limits represents the pH measurements, which do not comply with specifications.

i) Liming process

- **Limed Melt pH**

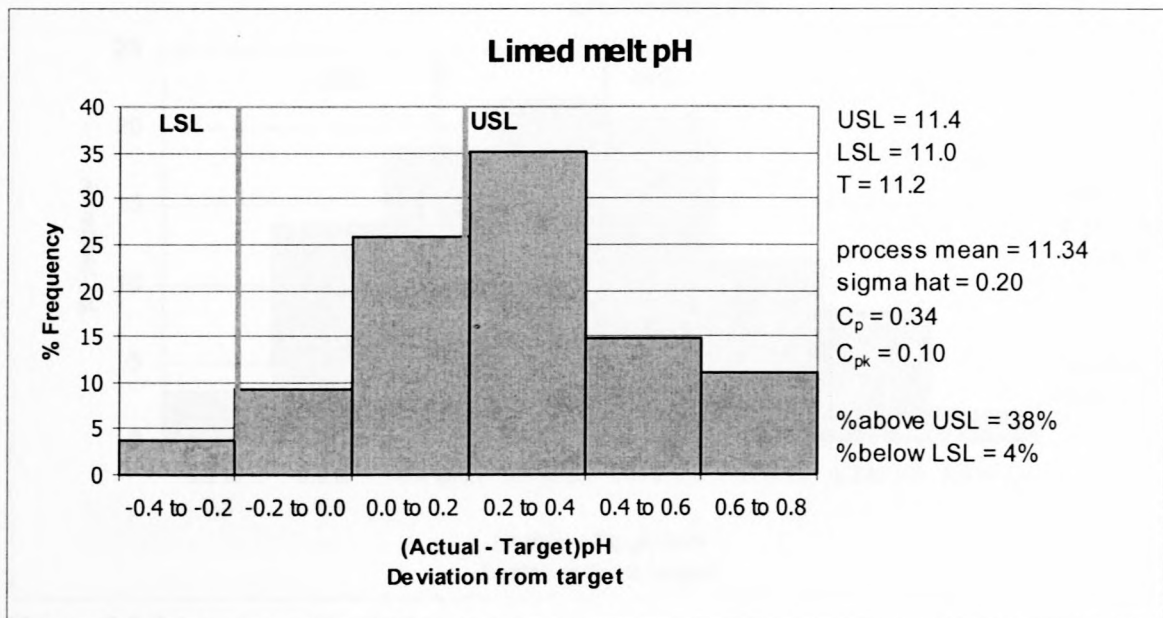


Figure 5.3 Limed melt pH

ii) Carbonation process

▪ Primary pH

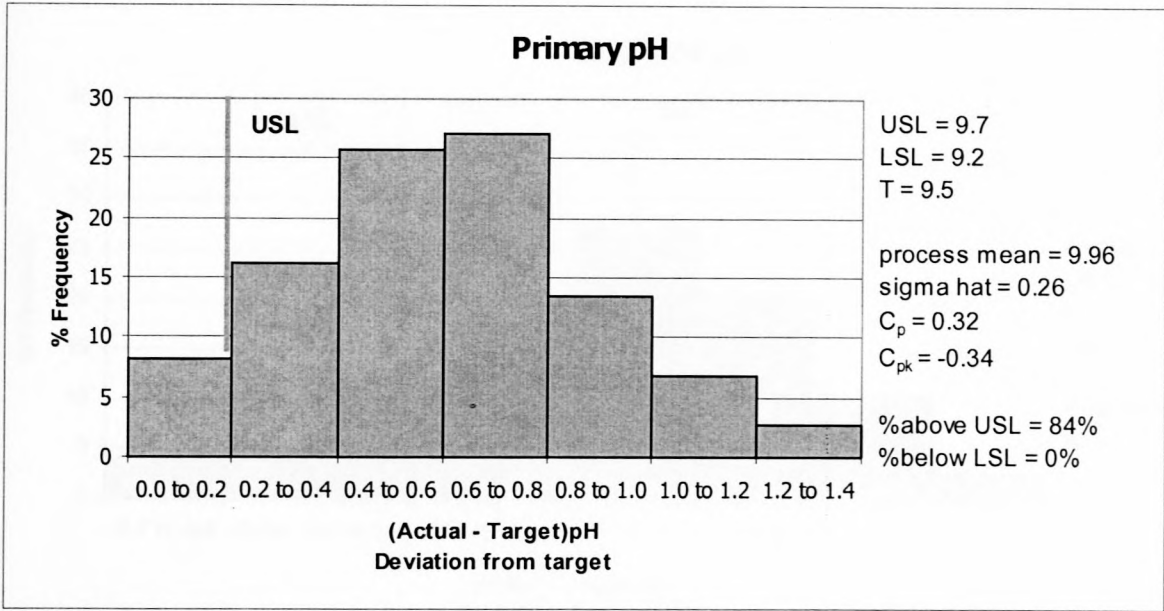


Figure 5.4 Primary pH

▪ Secondary pH

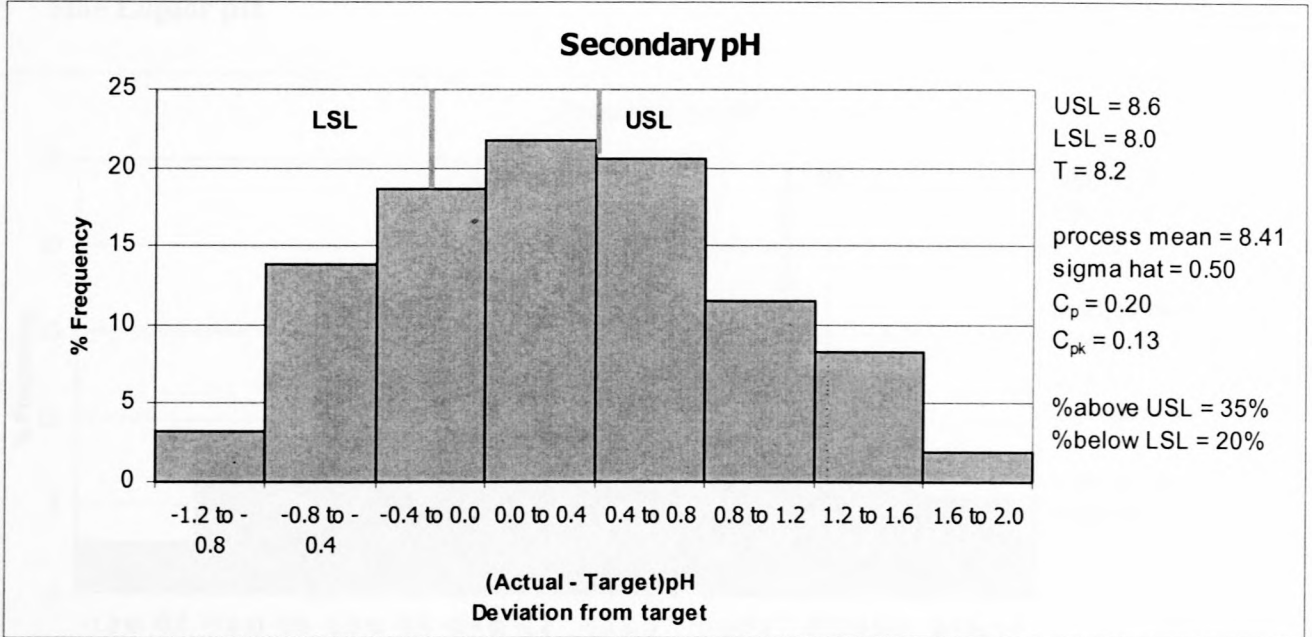


Figure 5.5 Secondary pH

iii) Sulphitation process

▪ Sulphited Liquor pH

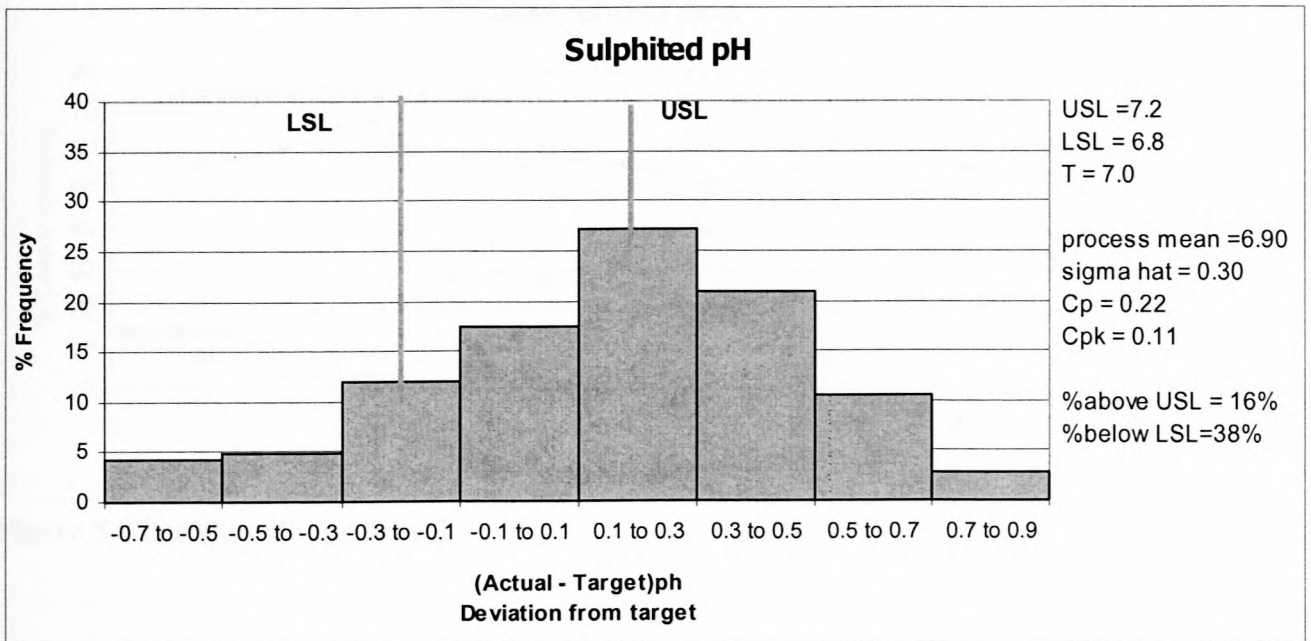


Figure 5.6 Sulphited Liquor pH

▪ Fine Liquor pH

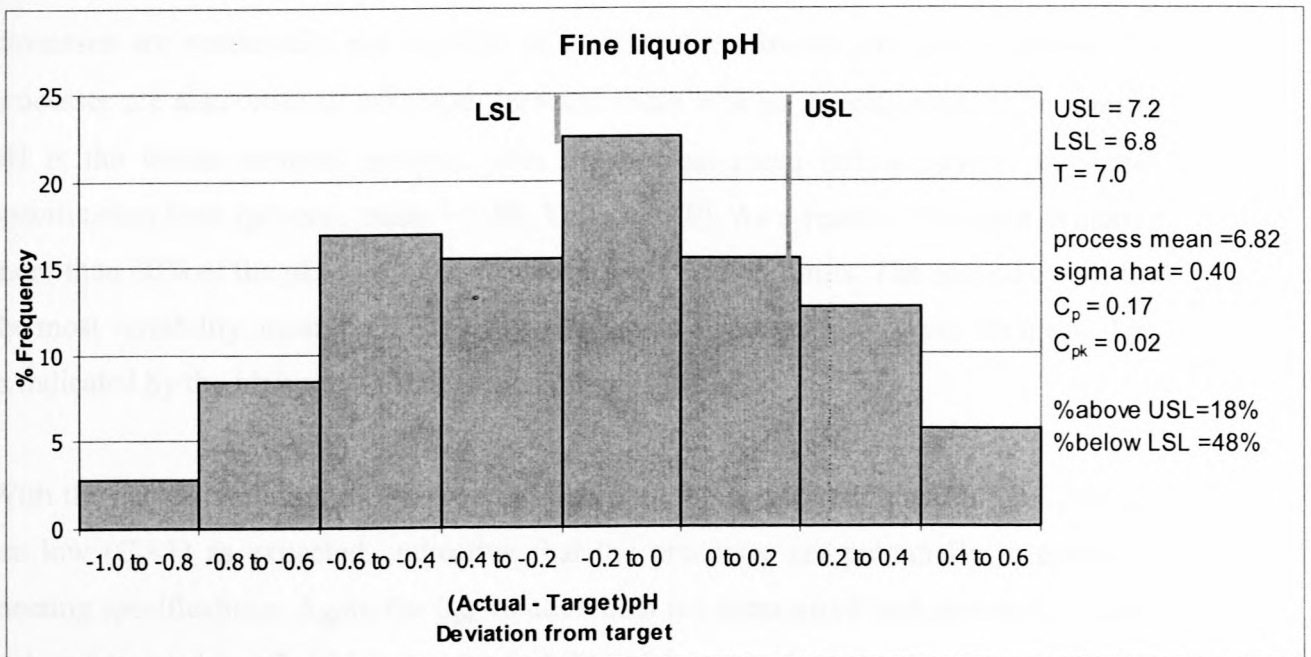


Figure 5.7 Fine Liquor pH

iv) Percent colour removal

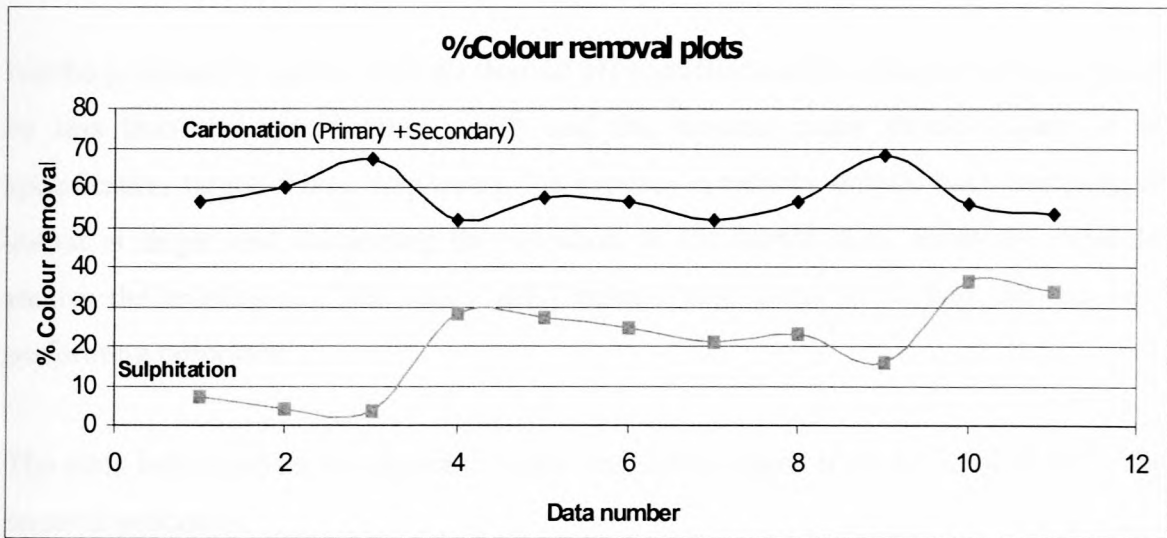


Figure 5.8 Percent colour removal

From the displayed charts it is clear that the three unit operations; liming, carbonation and sulphitation, of the colour removal process do not meet specifications. All the processes display a process variation greater than the specification width. The data points that fall outside the specification limits indicate non-conformance. This means that the processes are statistically not capable of meeting the required pH specifications. The processes are also centered off target (process mean \neq target specification). The primary pH is the worse centered process, with the process mean falling beyond the upper specification limit (process mean = 9.96, USL = 9.70). As a result of the poor centering more than 80% of the pH data fall outside the specification limits. The secondary pH has the most variability, meaning it has more data points dispersed away from the mean. This is indicated by the high standard deviation ($\hat{\sigma}$).

With the natural variation of the process exceeding the specification width the C_p values are low ($C_p < 1$) as expected, indicating that the processes are potentially incapable of meeting specifications. Again the C_{pk} values which is a measure of both process centering and variation is low ($C_{pk} < 1$) due to the inability of the processes to maintain centering on the target. For the primary pH the C_{pk} is negative ($C_{pk} < 0$) since the process average falls

outside the specification limits. The poor pH control of these processes results in an inconsistent colour removal as displayed by Figure 5.8.

For the processes to better meet the desired pH specifications the process variation should be less than the specification width and the process mean should equate to the specification target. Thus, improving the process capability entails both centering the output at target and decreasing the variation of the output data. From the capability studies the primary and secondary pH requires more focus since they are the worse performing processes.

The table below shows the potential sigma and actual sigma level for each of the colour removal processes.

Table 5.5 Process Sigma levels

Unit operation output	Potential Sigma (Z_{ST})	Actual Sigma (Z_{st})
Limed melt pH	1.02	0.30
Primary pH	0.96	-1.02
Secondary pH	0.60	0.39
Sulphited pH	0.66	0.33

The actual sigma values over the short term are smaller than the potential sigma values ($Z_{st} < Z_{ST}$) indicating that the processes can be improved by improving process centering. The potential sigma values are however very low, below one sigma level. For a process to better meet product specifications C_{pk} should be at least equal to 1.25. To approach this level for the colour removal processes may not only require the reduction of common cause variation but also process engineering.

To improve the colour removal processes the focus should be in improving process centering and reducing process spread. All the various sources of variation that influence the process mean and spread have to be identified so that they are reduced or better still

eliminated. The next phase, which is the Analyze phase, focuses on identifying and quantifying these various sources of variation.

5.3 ANALYSE PHASE

This phase analyses the data presented in the previous phase with the aim of reducing the displayed variation since reducing variation is the key to quality improvement. In-order to reduce or eliminate variation, knowledge of the variation and its sources is essential.

To determine the sources of variation, it is important to first define the Y's (outputs), the X's (controlled and uncontrolled inputs) and the processes by which the X's are transformed into Y's. This relationship is mathematically denoted as $Y_1 = f_1(X_1, X_2, \dots, X_n)$. The Y's are the dependent variables and the X's the independent variables. Controlling the critical X's will enable better control of the process and lead to a reduction of variation. For this project in order to identify the key critical X's that control the outputs (Y's), the Testing Theories method was used.

The Testing Theories Method is described below.

- Determine all the variables (X's) that might have an effect on the process outputs (Y's)
- Collect data on these variables and perform cause and effect studies so as to identify those variables that cause the variation in the process outputs (key/critical process variables).

The $Y = f(X)$ relationship for the colour removal processes was developed based on work done by sugar researchers on the carbonation and sulphitation process. Scatter plots were developed to confirm the relationship of these variables (X's) to the outputs (Y's). Stratification was then used to determine the key critical X's.

5.3.1 Process analysis

The purpose of this step was to develop a sub-process map so as to define the dependent variable Y, the independent variable(s) X, and the process by which X is transformed into Y.

▪ Sub process map- Colour removal process

i) Liming

The liming process involves the addition of lime to raw melt at a pH of 6 to achieve a limed melt at a pH of 11.2 and about 1.0% CaO on brix. The limed melt pH and % CaO are the key outputs of the liming process and they depend on the amount of lime added to the process and on the initial concentration of the lime (lime density). The addition of lime to the process is determined by the lime ratio, which gives the ratio of raw melt flow to lime flow. The lime ratio is manually inputted by the operator and it controls the speed of the lime pumps. As the raw melt flow increases the lime flow also increases so as to maintain the lime ratio. This in turn means the speed of the lime pumps also increases. The same logic applies when the raw melt flow decreases.

Inputs		Process	Outputs
Controlled	Uncontrolled		
Raw melt colour	Variation in raw melt colour	Liming	
Lime ratio & density Ca(OH) ₂	Variation in lime density	Addition of lime to raw melt	Limed melt % CaO
Raw melt brix			Limed melt brix
Raw melt pH			Limed melt pH
Raw melt temperature			Limed melt temperature

$$Y_1 = f_1(X_1, X_2)$$

$$\text{Limed melt \% CaO} = f(\text{lime ratio, lime density})$$

$$Y_2 = f_1(X_1, X_2)$$

$$\text{Limed melt pH} = f(\text{lime ratio, lime density})$$

ii) Primary saturators (First carbonation stage)

The first carbonation process involves the addition of Carbon dioxide gas to the limed melt so as to achieve an outlet primary pH of 9.5. The added carbon dioxide chemically reacts with the lime in the melt to form a calcium carbonate precipitate according to the following reaction; $\text{Ca(OH)}_2 + \text{CO}_2 = \text{CaCO}_3$. The pH drops as the precipitate is formed.

The primary pH is the key output of interest, and is dependent on the available % CaO for reaction with the carbon dioxide and the complete precipitation of calcium carbonate. The complete precipitation of calcium carbonate is dependent on the V1 steam pressure and the reaction time allowed (retention time).

Inputs		Process	Outputs
Controlled	Uncontrolled		
Limed melt pH	Variation in pH	Chemical reaction of lime in melt with carbon dioxide to form a calcium carbonate precipitate which traps impurities and colour bodies $\text{Ca(OH)}_2 + \text{CO}_2 = \text{CaCO}_3$	Primary pH
Limed melt %CaO	Variation in % CaO		
% CO ₂	Variation in % CO ₂		
Limed melt Brix			Primary brix
V1 steam pressure	Variation in V1 steam pressure		Primary temperature

$$Y_1 = f(X_1, X_2, X_3, X_4)$$

Primary pH = f (Limed melt % CaO, % CO₂, V1 steam pressure, Retention time)

iii) Secondary saturators

The second carbonation process involves the addition of more carbon dioxide so as to achieve an outlet secondary pH of 8.2. The same chemical reaction occurs as in the first carbonation stage. The outlet pH is dependent on the available % CaO for reaction with carbon dioxide, V1 steam pressure and the retention time. The pH is an indicator of the amount of CaO (% CaO) available for reaction.

Inputs		Process	Outputs
Controlled	Uncontrolled		
Primary pH	Variation in pH	Chemical reaction of lime in melt with carbon dioxide to form a calcium carbonate precipitate which traps impurities and colour bodies.	Secondary pH
% CO ₂	Variation in % CO ₂		Secondary brix
Primary Brix		Ca(OH) ₂ + CO ₂ = CaCO ₃	Secondary temperature
V1 steam pressure	Variation in V1 steam pressure		Secondary colour
Melt colour	Variation in melt colour		

$$Y_1 = f(X_1, X_2, X_3, X_4)$$

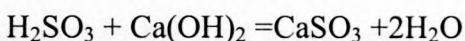
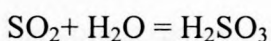
Secondary pH = f (Primary pH, % CO₂, V1 steam pressure, Retention time,)

$$Y_2 = f(X_1, X_2, X_3, X_4)$$

% Colour removal = f (Raw melt colour, % CaO, % CO₂, Secondary pH)

iv) Sulphitation

The sulphitation process involves the addition of sulphur dioxide gas via a static mixer to the filtered liquor of the secondary saturators normally referred to as the clarified liquor. The sulphur dioxide chemically reacts with the lime in the clarified liquor to form a calcium sulphite precipitate, which also traps the colour bodies in the liquor. The outlet liquor pH (sulphited liquor) is maintained at 7.0. The chemical reaction is denoted as follows;



The sulphited liquor pH is the key output of interest and it depends on the availability of CaO in the liquor (indicated by secondary pH) to react with the sulphur dioxide, the amount of sulphur dioxide added and the V1 steam pressure.

The amount of colour removed, % colour removal depends on the initial secondary colour and on the final sulphited liquor pH.

Inputs		Process	Outputs
Controlled	Uncontrolled		
Secondary pH	Variation in pH	Chemical reaction of lime in liquor with sulphur dioxide to form a calcium sulphite precipitate which remove colour bodies.	Sulphited pH
Sulphur dioxide, SO ₂			
Secondary Brix			Secondary brix
Secondary colour	Variation in liquor colour	SO ₂ + H ₂ O = H ₂ SO ₃ H ₂ SO ₃ + Ca(OH) ₂ = CaSO ₃ + 2H ₂ O	Sulphited colour
V1 Steam pressure	Variation in V1 steam pressure		Sulphited temperature

$$Y_1 = f(X_1, X_2, X_3, X_4)$$

Sulphited pH = f (Secondary pH, % SO₂, V1 steam temperature)

$$Y_2 = f(X_1, X_2, X_3, X_4)$$

% Colour removal = f (Secondary colour, Secondary pH, % SO₂, Sulphited pH)

The total colour removal for the two colour removal processes (carbonation and sulphitation) will depend on the initial raw melt colour, limed melt % CaO, V1 steam pressure and the final sulphited liquor pH.

$$Y_1 = f(X_1, X_2, X_3, X_4)$$

% Total colour removal = f (Raw melt colour, limed melt % CaO, V1 steam pressure, sulphited liquor pH)

The colour removal processes discussed above are on auto-control with the pH measured on line by pH field instruments. The processes are operated based on the settings of the field instruments. The laboratory pH is thus dependent on the field instruments pH.

$$\text{Laboratory pH} = f(\text{Field instrument pH})$$

As discussed earlier the field instruments pH is not expected to be equal to the laboratory pH due to the dependence of pH on temperature. However they should be a correlation between the two. The integrity of the pH results requires the maintenance of a stable and

consistent correlation between the two. Fluctuations in either or both of the pH readings (laboratory and field instruments) will result in inaccurate pH readings.

5.3.2 Data analysis

Stratification analysis was used to determine the critical X's, the 'vital few variables' from the 'trivial many variables' identified in the process analysis step that are the key sources of variation. The data was manipulated such that it revealed the key variables, which control the process mean and those, which control the process standard deviation. This analysis was done for all the colour removal processes.

i) Liming

Stratification of the data to study the effects of % CaO and the effect of the variation between laboratory pH and field instruments pH revealed that the % CaO is the key variable that controls the process centering and the latter controls the process spread.

With the % CaO within specifications the process mean shifts from 11.34 to 11.22, which is closer to the target specification and the process spread remains unchanged. With a consistent difference between laboratory and field instruments pH [(Lab – FI) pH], the process mean shifts to 11.40 which is the USL and the C_p value improves from 0.34 to 0.44. These results indicate that % CaO has a much stronger effect in process centering since the shift in mean is more significant. The improvement in C_p indicates that the difference between pH readings controls the process spread.

Limed melt pH

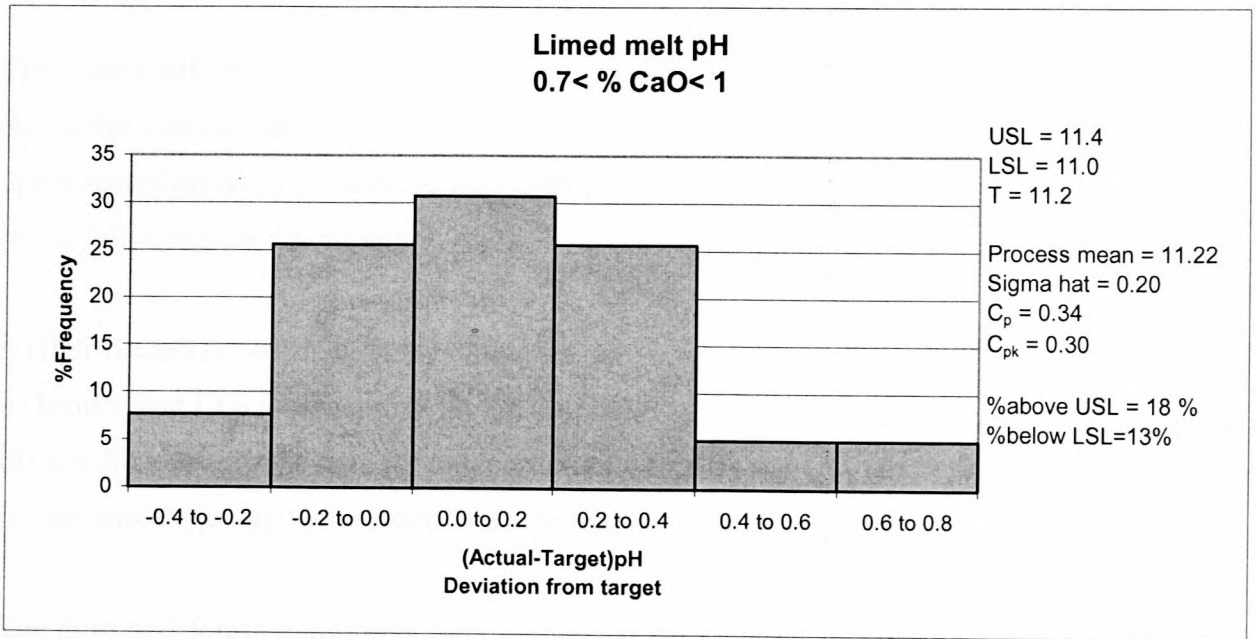


Figure 5.9 Limed melt pH, % CaO < 1

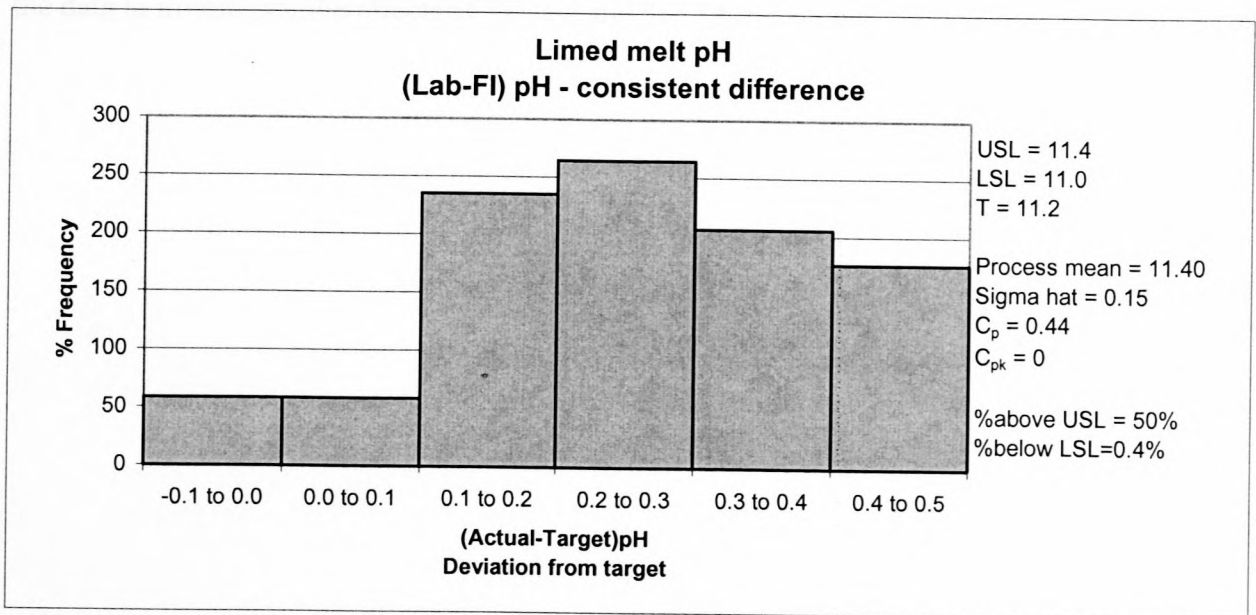


Figure 5.10 Limed melt pH, (Lab - FI) pH consistent difference

ii) Carbonation

The output pH for the two carbonation stages, primary and secondary is centered way above the nominal target. The primary pH is centered at 9.96, which is way above the upper specification of 9.7 and the secondary pH is centered at 8.41. A high pH means any of the following conditions apply:

- i) High % CaO (overliming in the liming stage)
- ii) Insufficient CO₂ for reaction with the Ca(OH)₂
- iii) Insufficient reaction time for the reaction of Ca(OH)₂ and CO₂ (short reaction time)
- iv) Incomplete precipitation reaction due to low temperatures

The third and fourth conditions were eliminated from the list because the saturators are controlled at maximum level meaning maximum retention and temperatures in the saturators were always maintained at the desired temperature of 80 degrees for the period corresponding to when the pH data was taken. The results obtained from stratification of the data to investigate the effects of % CaO and % CO₂ are shown.

Primary pH

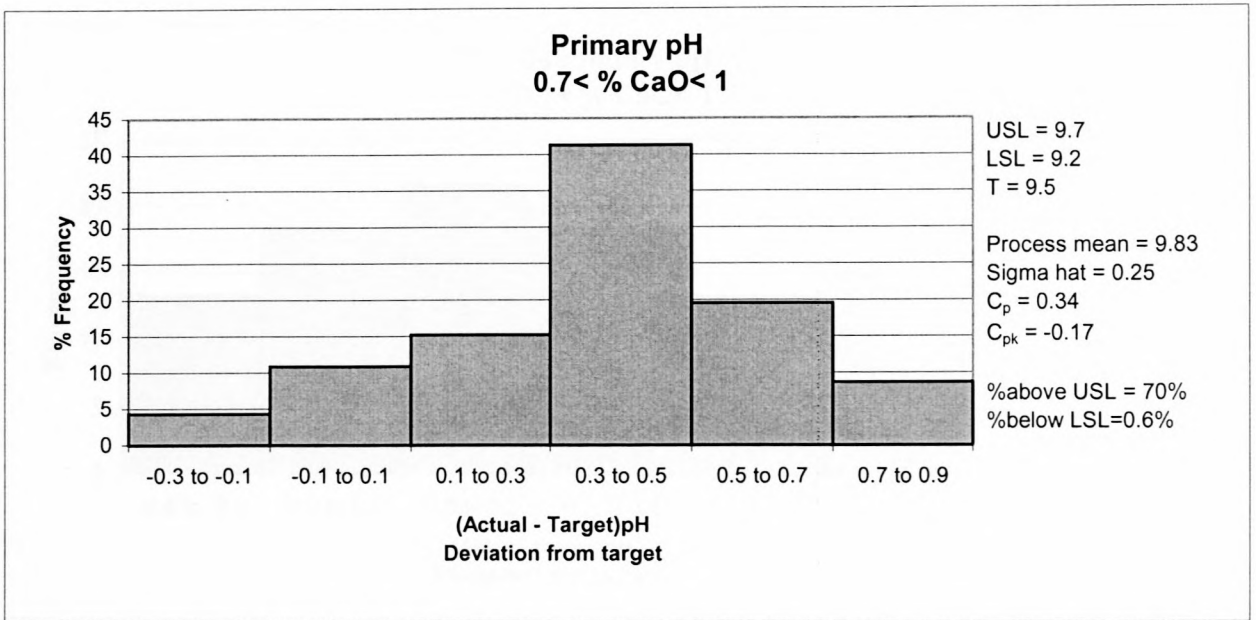


Figure 5.11 Primary pH, 0.7 < % CaO < 1

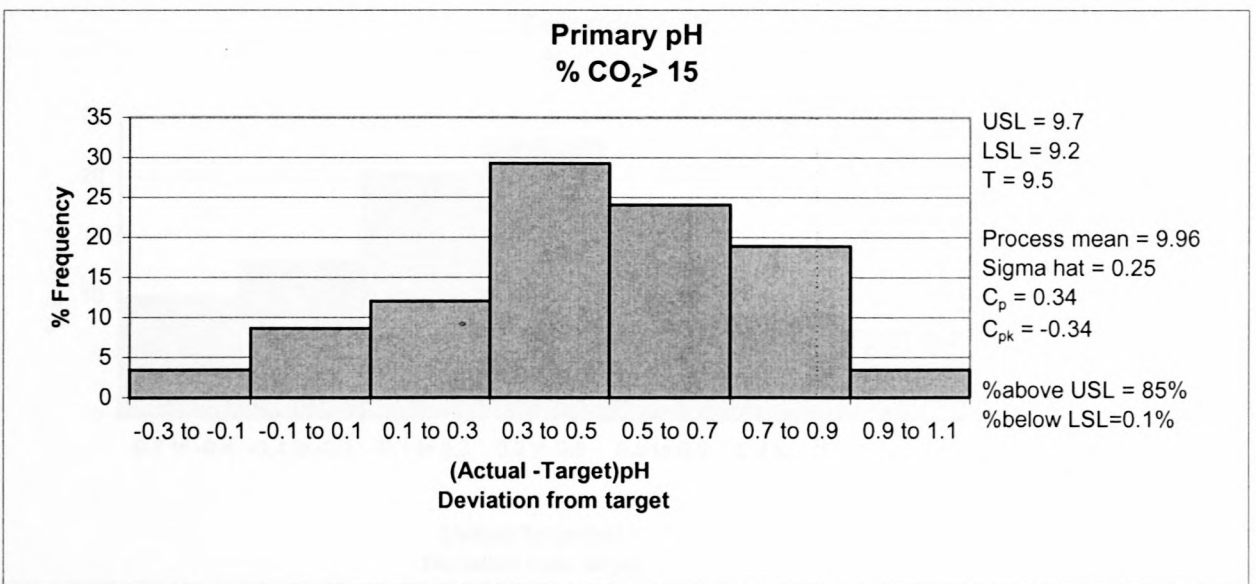


Figure 5.12 Primary pH, % CO₂ > 15

Secondary pH

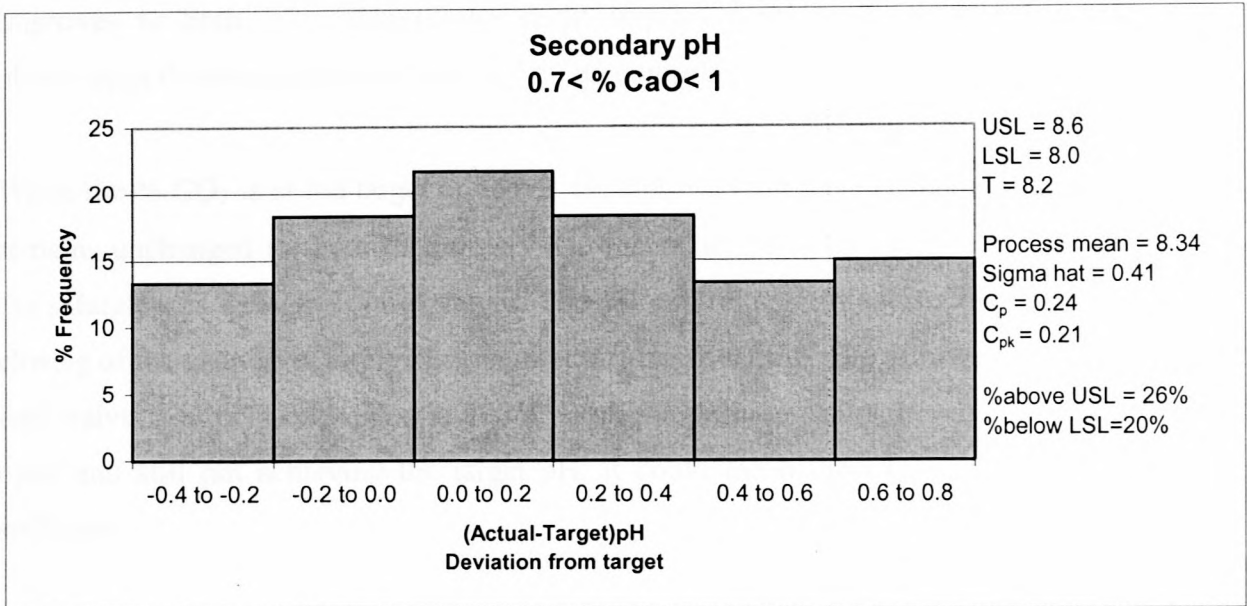


Figure 5.13 Secondary pH, % CaO < 1

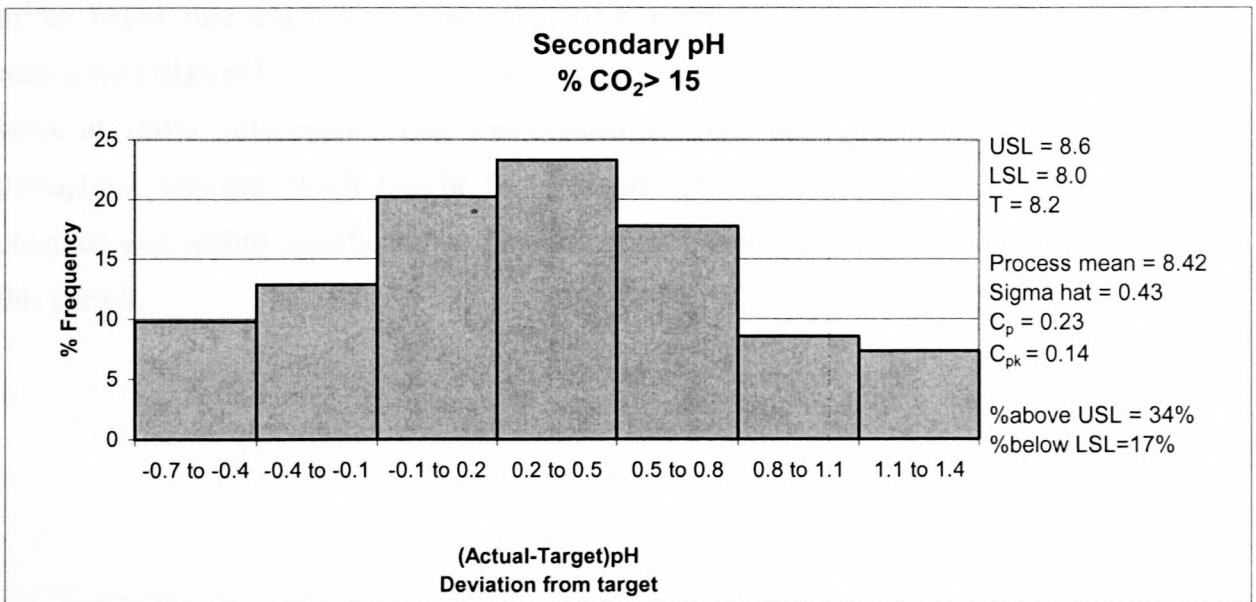


Figure 5.14 Secondary pH, % CO₂ > 15

When the % CaO is within specification, between 0.7 and 1, the primary pH is centered at 9.83 and the secondary pH at 8.34. The C_p remains more or less the same but the C_{pk} improves in both cases due to the slight improvement in process centering. This observation therefore indicates that the % CaO controls process centering.

When the % CO₂ is at the target or above, (% CO₂ ≥ 15) the process centering and sigma remains unchanged for both the primary and secondary pH. The addition of CO₂ gas to the saturators is through control valves. The pH control system adjusts the opening and closing of the gas valves to give the required pH target setting. The primary saturator CO₂ feed valve is always fully open at 100%. With the primary saturator valve always fully open and still not achieving the target pH, it could mean the CO₂ gas supply is not sufficient.

The volume of flue gas required for carbonation is around 140 m³/ton of solids in melt [Sugar Milling Research Institute Refinery Notes]. The colour removal process handles 35 tonnes solids/hr (50 tonnes/hr raw melt at 70 brix), and this would require approximately 4900 m³ of gas/hr. The gas flow on average ranges between 4200-4550 m³/hr, below that which is recommended. The insufficient gas supply seems to be the reason why high pHs' are obtained at the primary saturator even with the CO₂ gas supply valve at 100% fully open. This was confirmed when the refinery ran at a reduced throughput between 30-40 tons/hr for a month. During this period the primary pH obtained was within specifications. The histogram below shows the primary pH during this period.

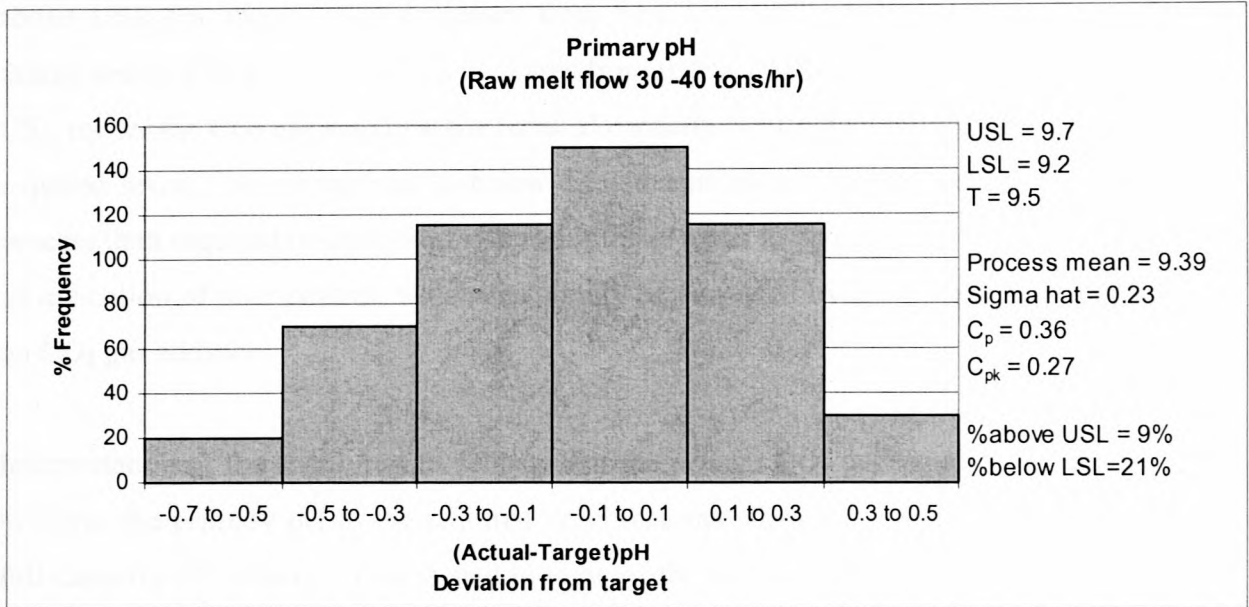


Figure 5.15 Primary pH, Raw melt flow 30-40 tonnes/hr

To enable easy comparison of the primary saturator performance at full capacity (Figure 5.4) and at reduced capacity (Figure 5.15), the primary pH results obtained in either case are presented in tabular form.

Table 5.6 Primary pH comparison at full capacity (Raw melt 50 tons/hr) vs reduced capacity (Raw melt 30-40 tons/hr)

Parameter	Primary pH	
	Full capacity	Reduced capacity
Process mean	9.96	9.39
Sigma hat	0.26	0.23
C _p	0.32	0.36
C _{pk}	-0.34	0.27
% above USL	84.0	9.0
% below LSL	0	20.9

The improvement in performance is visible; the process mean improves from 9.96 which was way above the USL of 9.7 to 9.39, which is well within specifications and closer to the nominal target (9.5). This improvement in process centering resulted in an increase in C_{pk} from -0.34 to 0.27. A slight increase in C_p is also seen from 0.32 to 0.36. This indicates a slight reduction in the process dispersion. The percentage data points falling

above USL (% above USL) decreases from 84.0% to 9.0%, however the data points falling below LSL (% below LSL) increases from 0% to 20.9%. The decrease in % above USL means the CO₂ gas supply at the reduced capacity is sufficient to lower the pH to the required level. The increase in % below LSL means more CO₂ gas was added to the process than required (overdosing) as a result the pH was lowered below the LSL. This is an indication of poor control, which can simply be corrected by ensuring vigilant control on CO₂ gas addition.

Interpretation of the above results tells us that the present CO₂ gas supply is insufficient to lower the primary pH to the required specifications when the refinery is operating at full capacity (50 tons/hr). This is said in view of the fact that the primary saturator CO₂ feed valve is always 100% fully open, yet the primary pHs' are always high, way above the USL. The achievement of primary pHs' within the specification limits at reduced capacity (30-40 tons/hr raw melt) under the same process conditions means the high primary pHs' at full capacity are due to insufficient CO₂ gas supply. The results also means that CO₂ gas supply controls process centering. The shift in process mean for CO₂ gas supply is more significant than that of % CaO. This means for carbonation, CO₂ gas supply is the key variable that controls process centering and the % CaO has a much weaker effect.

The CO₂ gas is supplied to the saturators by two gas pumps at a rating of 4000 m³/hr and 2 500 m³/hr. This means the insufficient gas supply is not a delivery problem since the pumps are capable of delivering gas up to 65000 m³/hr. It therefore means there is insufficient gas from the main supply source.

To gain an understanding of the reaction rate of the carbonation reaction, a sample of limed melt at a particular % CaO was reacted with 1Molar Hydrochloric acid (HCL) under laboratory conditions. The results obtained were then used to plot the graph shown below.

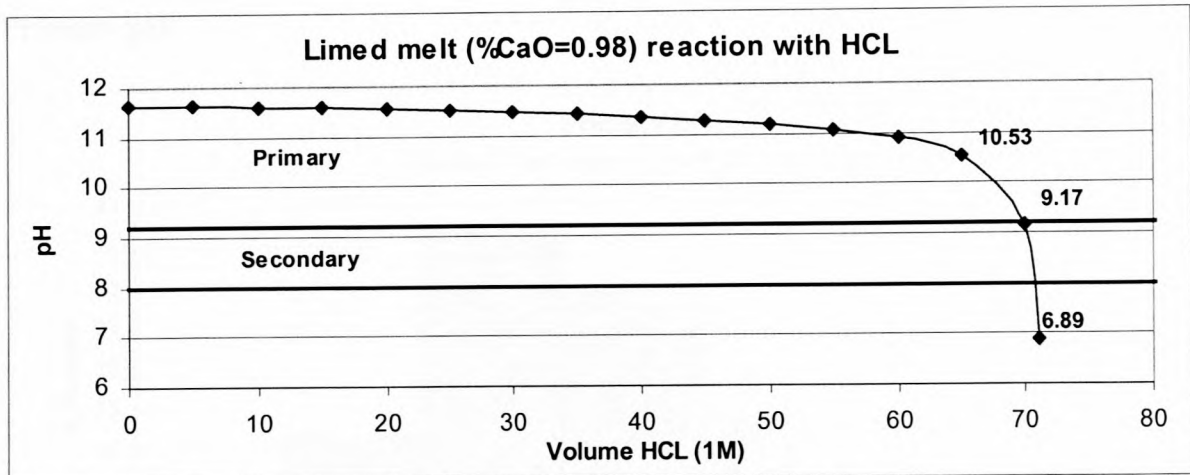


Figure 5.16 Limed melt reaction with 1Molar Hydrochloric Acid

The x-axis shows the volume of HCL added to the limed melt sample, and the y-axis show the corresponding pH. The graph has been divided to show the pH region corresponding to the conditions of the primary and secondary saturators.

As the volume of HCL is added the pH drops showing a very slow response. At pH = 10.53 the response gets faster and the graph shows a sharp downward pattern. With the addition of 1ml HCL the pH drops from 9.17 to 6.89.

The shape of the graph (Figure 5.16) means the reaction in the primary saturator is slow and requires a large volume of gas to lower the pH to the required level. At the secondary saturator the reactions occurs very fast and a small amount of gas brings down the pH to very low levels. The graph therefore further shows that the primary saturator requires a large volume of gas and why very good control is required at the secondary pH since over gassing very slightly will reduce the pH significantly. The fast reaction rate in the secondary saturator explains why the current secondary pH values are erratic.

To determine the key variable controlling the process spread (sigma) stratification of the data was done for the data points corresponding to a consistent difference between the Laboratory pH results (Lab pH) and the Field instruments pH results (FI pH). The plots are shown below.

Primary pH

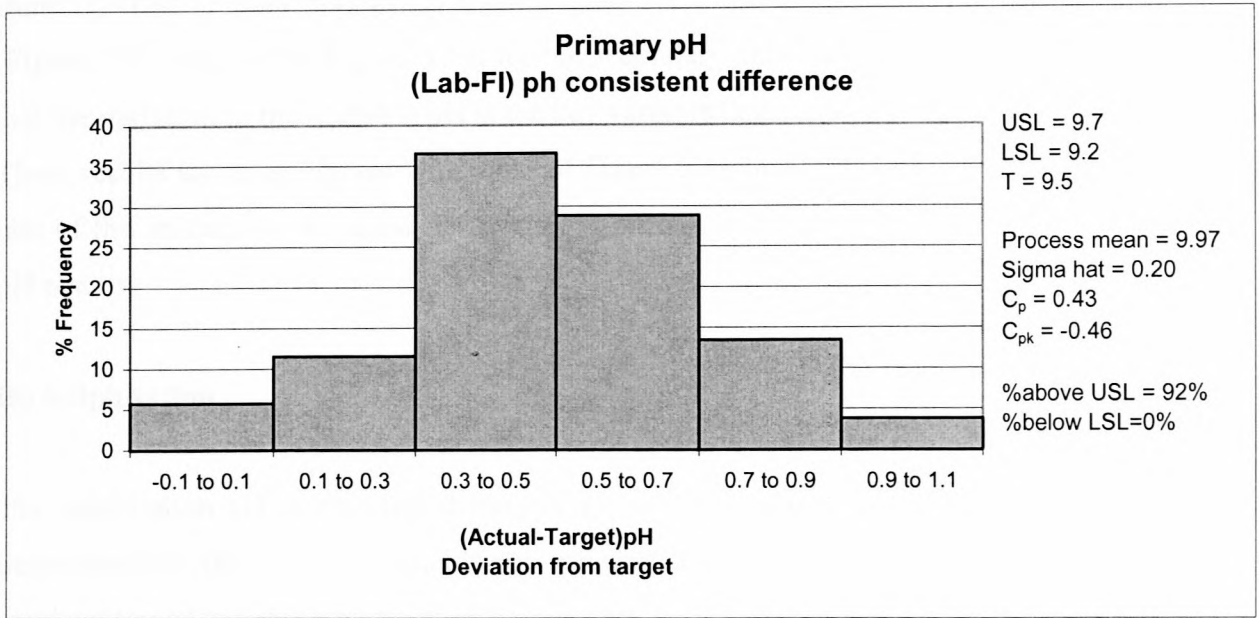


Figure 5.17 Primary pH, (Lab-FI) pH consistent difference

Secondary pH

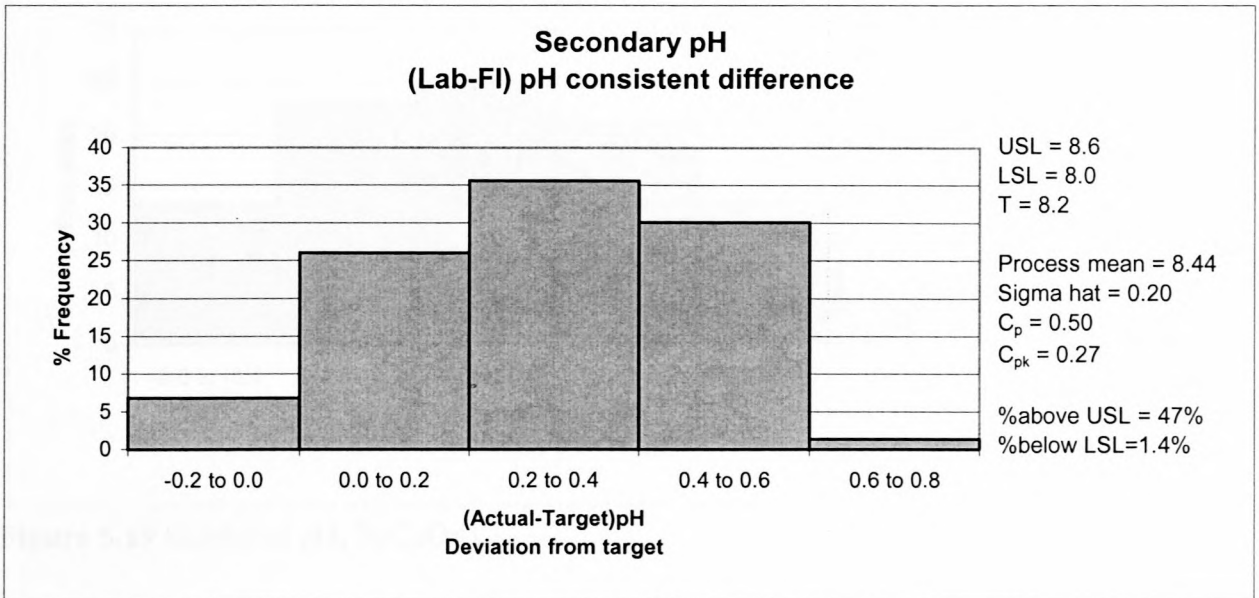


Figure 5.18 Secondary pH, (Lab-FI) pH consistent difference

The plots show an improvement in the process spread as a result the C_p index improves from $C_p=0.32$ (Figure 5.4) to $C_p=0.43$ (Figure 5.17) for the primary pH and $C_p=0.20$ (Figure 5.5) to $C_p=0.50$ (Figure 5.18) for the secondary pH. These results therefore show that the variation in the (Lab-FI) pH is the key variable that controls the process spread. These results are in agreement with those of Figure 5.16 that due to the very fast reaction rate of the secondary pH, good pH control is critical in ensuring minimal variability of pH results.

iii) Sulphitation

The sulphitation pH is centered at the lower specification limit. The sulphitation pH is determined by the % CaO available for reaction and the amount of SO_2 addition. The result obtained on the stratification of the data to investigate the effect of % CaO is shown.

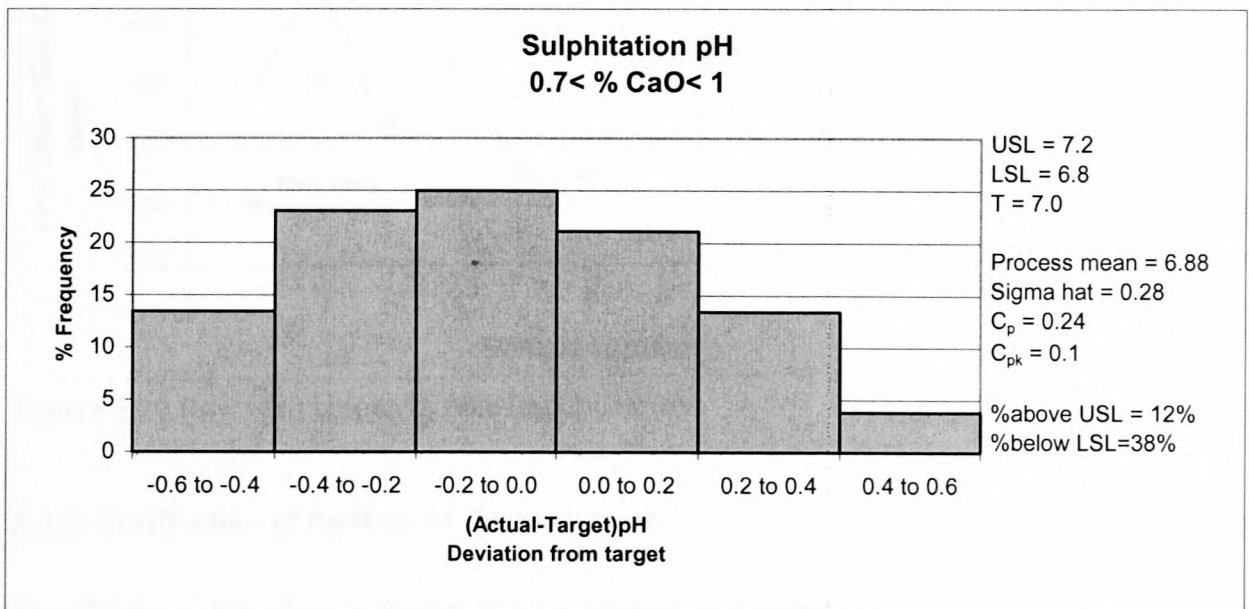


Figure 5.19 Sulphited pH, % CaO < 1

The process mean and sigma remains unchanged at 6.88 and 0.28. This means the low sulphitation pH is not due to % CaO and must be a result of overdosing SO_2 . Since the addition of SO_2 is automatically controlled, overdosing would occur if the field

instrument pH setpoint is set low and if there is inconsistency between the field instrument pH's and laboratory pH's.

iv) Colour removal

The resultant fine liquor colour follows the same pattern as the raw melt colour, increasing and decreasing with the raw melt colour. High raw melt colours results in high fine liquor colours and vice versa. This shows that the amount of colour removed is a function of raw melt colour, thus to achieve maximum decolourisation it is crucial to monitor the input raw melt colour. This is also according to findings of Moodley that colour removal is a function of the raw melt colour, amount of lime added and the final pH [Moodley, 2002].

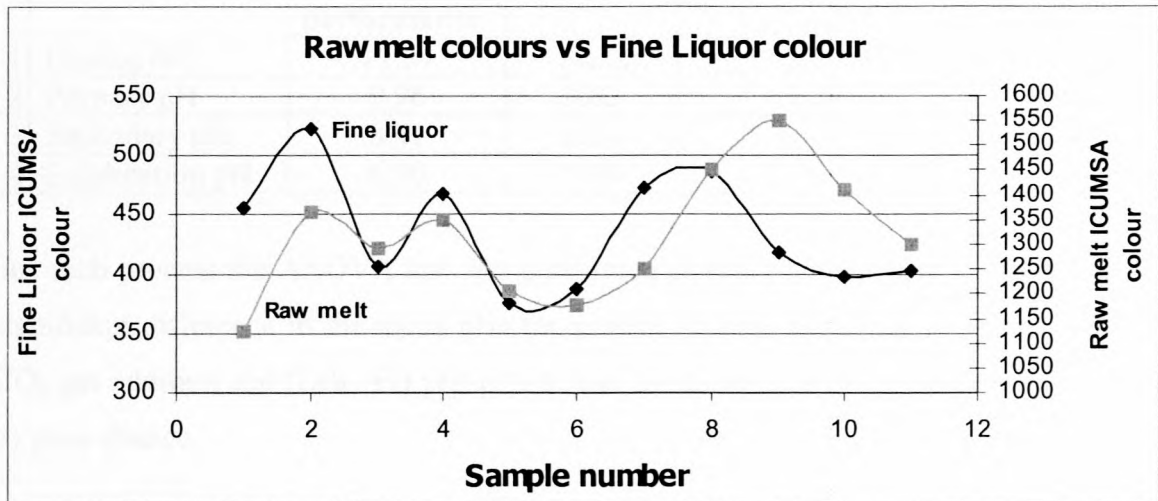


Figure 5.20 Raw melt colour vs Fine liquor colour

5.3.3. Verification of findings of the analyse phase

Stratification of the data in the ANALYSE PHASE revealed that the % CaO and CO₂ gas addition are the key variables that controls process centering. The % CaO having the strongest effect in the liming process and a weaker effect for the subsequent processes, while CO₂ gas addition has the strongest effect for the carbonation process. The variation between laboratory and field instruments pH was found to be the key variable that controls the process spread. In order to ensure that the stratification analysis has surely

identified the right variables, which controls the process centering a statistical study was done to verify and confirm the results.

▪ **Analysis of variance test (ANOVA)**

The stratification results of each of the unit processes are presented below. The table shows the mean pH at the present process performance and on studying the effects of % CaO, CO₂ gas addition and the variation between (Lab- FI) pH.

Table 5.7 Colour removal processes mean pH values

	Process	Mean process pH			
		Present process performance	% CaO	CO ₂ gas addition	(Lab-FI)pH consistent difference
1	Liming pH	11.34	11.22		11.40
2	Primary pH	9.96	9.83	9.39	9.97
3	Secondary pH	8.41	8.34		8.44
4	Sulphitation pH	6.90	6.88		

For each process the ANOVA test was performed to test whether there is any statistical significant difference in the mean pHs (at present process performance versus % CaO, CO₂ gas addition and (Lab –FI) pH) or whether the difference in means occurred merely by pure chance.

The following hypotheses was developed:

H₀: There is no statistical significant difference in the means, the difference in means occurred merely by pure chance

H₁: There is a statistical significant difference in the means

Microsoft excel software was used to calculate the ANOVA and the results are presented. For simplicity a sample of 20 pH readings were used in the calculation and not the whole data set.

I) Liming pH**SUMMARY**

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Process performance	20.00	226.50	11.33	0.03
%CaO	20.00	224.40	11.22	0.02
(Lab-FI) pH	20.00	228.00	11.40	0.03

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.33	2.00	0.16	5.58	0.01	3.16
Within Groups	1.67	57.00	0.03			
Total	2.00	59.00				

The F ratio 5.58 is larger than the F critical value 3.16 thus H_0 is rejected in favour of H_1 . This conclusion supports the results of the stratification analyses that the % CaO is the key variable that controls process centering for the liming process.

ii) Primary pH**SUMMARY**

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Present Performance	20.00	199.60	9.98	0.06
% CaO	20.00	196.20	9.81	0.07
CO ₂ gas addition	20.00	186.60	9.33	0.10
(Lab - FI)pH	20.00	198.70	9.94	0.05

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	5.33	3.00	1.78	25.97	0.00	2.72
Within Groups	5.20	76.00	0.07			
Total	10.52	79.00				

The F ratio 25.97 is larger than the F critical value 2.72, meaning there is a statistically significant difference in the means and thus we reject H_0 . The very small P-value (2.6e-11) supports the rejection of H_0 . Again this conclusion confirms the results of the stratification analyses that CO₂ gas addition is the key variable that controls process centering for the primary pH.

iii) Secondary pH**SUMMARY**

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Process performance	20.00	168.40	8.42	0.03
% CaO	20.00	166.60	8.33	0.13
(Lab- FI) pH	20.00	168.40	8.42	0.04

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.11	2.00	0.05	0.82	0.44	3.16
Within Groups	3.75	57.00	0.07			
Total	3.85	59.00				

The F ratio 0.82 is smaller than F critical value 3.16. This means there is no statistical significant difference in means and hence H_0 is accepted.

iv) Sulphitation pH**SUMMARY**

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Process performance	20.00	137.70	6.89	0.08
% CaO	20.00	136.60	6.83	0.06

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.03	1.00	0.03	0.42	0.52	4.10
Within Groups	2.71	38.00	0.07			
Total	2.74	39.00				

Again the F ratio 0.42 is smaller than F critical value 4.10. This means there is no statistical significant difference in means and hence we accept H_0 . Again this confirms that the low sulphitation pH is not due to % CaO and must be a control problem since the dosing of SO_2 is automatic.

5.4 IMPROVE PHASE

Quality improvement for the purpose of better meeting the required pH and colour specifications of the colour removal processes should focus on the **control** of the identified 'vital few variables', process variables in each unit and the **monitoring** of the output variables. Reducing variation in the vital few variables will improve the process centering and the process spread. As the process mean approaches the nominal target and the process spread the specification width, the capability of the process to meet specification will increase. Improving process capability translates to increasing product quality. The higher the process capability the better, as this means less pH data falling outside the specification limits.

The colour removal processes capability indices are low, less than 1.0 and $C_{pk} < C_p$. The starting point in improving the processes, should be in centering the processes within the nominal target so as to minimise the total losses outside the specification limits. This will improve C_{pk} , making it more comparable to C_p . To improve C_p the process variation has to be studied further in an effort to minimise it. This will reduce the process spread resulting in some marginal improvement in C_p since it is evident from the capability studies that the colour removal processes are not capable of meeting specifications. To aim for a higher capability would require process re-engineering.

The following points are suggested for improvement of the colour removal processes based on the findings of the Analyse phase.

5.4.1 Limed melt % CaO content

The % CaO is the key variable that controls the process centering of the liming process. As was illustrated, reducing the variation in % CaO improves the process centering towards the target specification. The graph shows the current liming process performance.

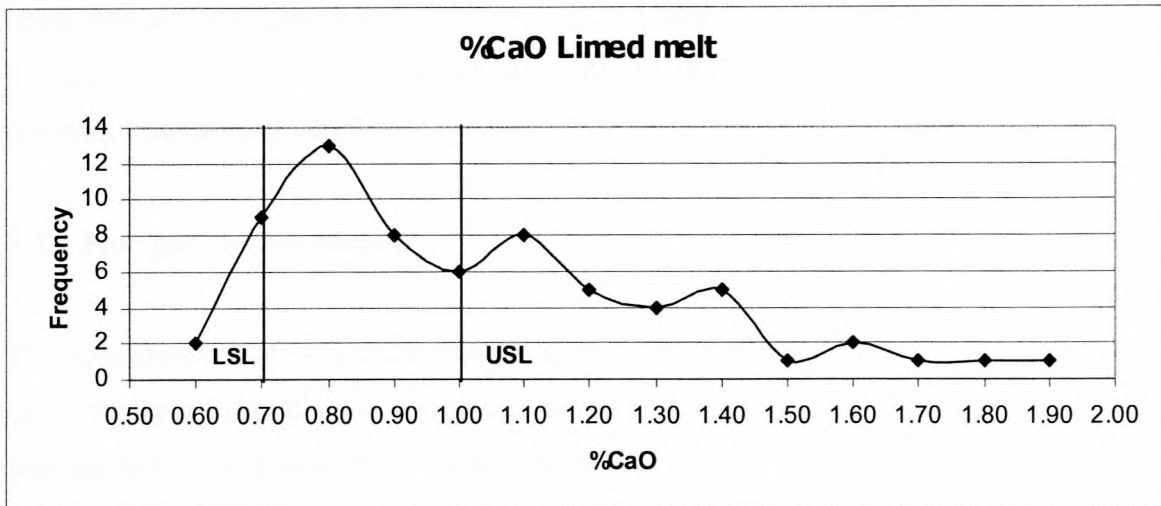


Figure 5.21 Limed melt % CaO content

The long tail beyond the specification limits results in the high limed melt pH's obtained, which in turn impacts in the downstream processes by shifting the process center away from the nominal target towards or beyond USL. The high % CaO, ($\text{CaO} > 1$) is undesirable since it will result in an increase in ash content which reduces the efficiency of the colour removal processes. It is therefore important that the % CaO is maintained within specification. The focus therefore should be on reducing this long tail such that the process spread is within the specification width.

The % CaO is determined by the amount of lime added (lime ratio) and the lime concentration (density). The addition of lime is controlled by the operator inputted lime ratio (ratio of raw melt flow to lime flow) that is calculated based on the raw melt flow. The lime ratio will determine the speed of the lime dosing pumps, increasing or decreasing the pump speed as the raw melt flow changes. The lime density however will influence the lime ratio. In order to maintain a consistent % CaO on limed melt regardless of the raw melt flow it is important to ensure a fairly constant lime density. The quality checks done by the laboratory for every lime consignment is a very good system for controlling lime quality as this also has an effect on the lime density. Lime solution preparation is manually controlled with the operator measuring the lime density for every batch prepared. This arrangement does not allow for a constant lime density since measurement is only done after the lime solution has been prepared. There is therefore a

need for continuous monitoring of lime density. Many sugar refineries use on line nuclear density meters/DP cells to measure lime density and this has the benefit of ensuring a constant lime density supply.

5.4.2 Flue gas % CO₂ content

The concentration of CO₂ in the flue gas is on average above 15%, which is very good and actually the best that can be achieved from boiler combustion. The benefit of drawing flue gas from a baggasse-fired boiler is therefore seen by the high CO₂ content. A plot of the flue gas % CO₂ is shown below.

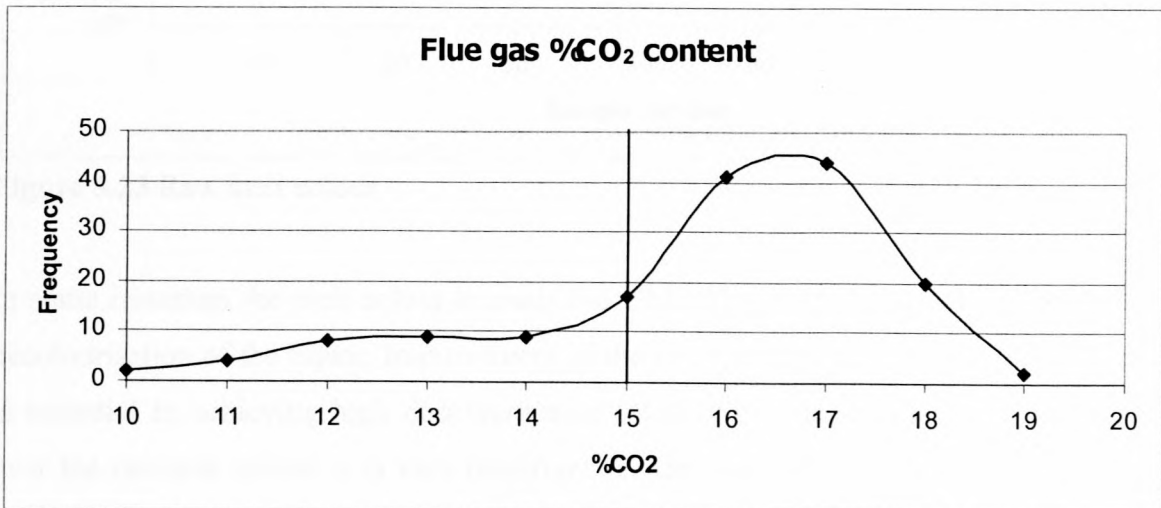


Figure 5.22 Flue gas % CO₂ content

The focus therefore should be on improving the flue gas supply to at least 4900 m³/hr in order to achieve the primary pH within specifications as was shown in Section 5.3.2 ii and by Table 5.6 (Page 93). Once this is achieved the next step would be to run the primary saturator pH in automatic mode. In doing so the benefit of the automation will be fully realized.

5.4.3 Raw melt colour

The amount of colour removed in the colour removal process depends on the input melt colour. The graph shows the input raw melt colour.

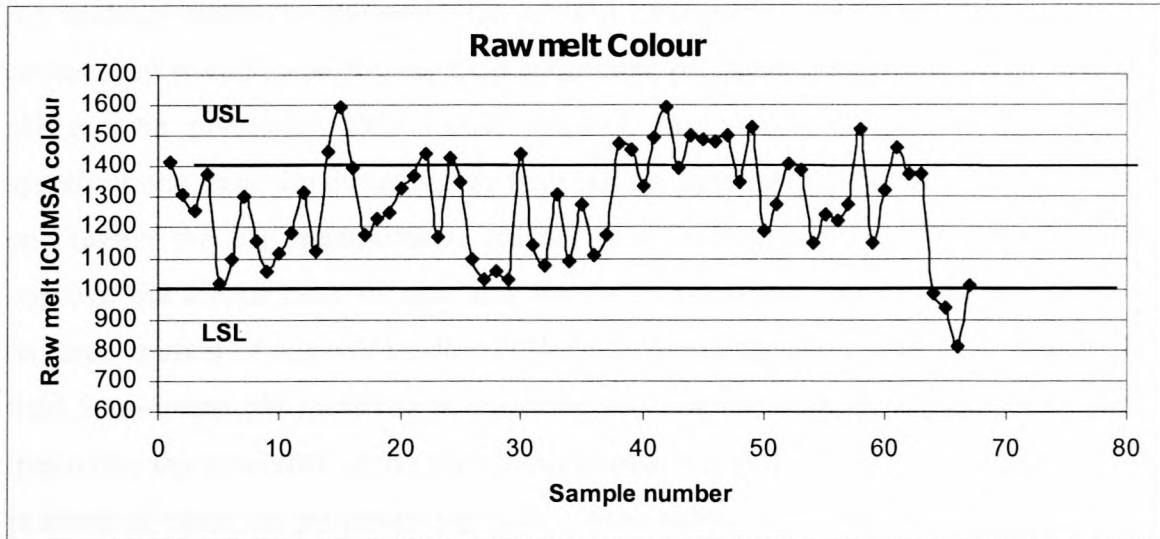


Figure 5.23 Raw melt colour

In some instances the melt colour exceeds the USL. This high colour will comprise the decolourisation of the liquor. Improvement of the raw melt colour to within specification is essential in achieving high decolourisation levels. Since the refinery has no control over the rawmelt colour, it is very important for the rawmelt supplier (rawhouse) to be fully aware of the implications of high raw melt colours and for the refinery to be vigilant on the quality they receive. The current decision made by the refinery not to accept a raw melt colour exceeding 1400 ICUMSA units is a positive step in striving to maintain high decolourisation levels.

5.4.4 Field instruments pH and the Laboratory pH

The variation in the field instruments pH and laboratory pH is the key variable that controls the process spread. The large scatter between the two yields a process spread greater than the specification width resulting in a large percentage of the data falling

outside the specification limits. The large scatter is due to the uncontrolled variation that exists between the two. The focus should be on improving the process stability so that only controlled variation exists between the two. This would mean the process mean is constant and the difference between the field instruments and laboratory pH readings is consistent. Consistency and repeatability between the two is what is required because the pH readings cannot be the same due to the temperature dependence of pH. Achieving consistency would mean for any field instrument pH value the corresponding laboratory pH can be predicted. This would improve the process ability to meet the pH specifications since the inconsistency between the field instruments and laboratory pH is one reason the pH specifications are not met. Improvement in the pH control will improve the colour removal and also translates to savings in SO₂ gas since only the required amount of gas will be dosed. The daily cleaning and frequent calibration of the field instruments pH meters is an effective way for minimizing measurement bias and improving the reliability of the pH measurements. Reliability of the field pH instruments is essential since the processes (eg. CO₂ / SO₂ addition) are operated based on the pH readings.

5.4.5 Process control/monitoring

For process monitoring, the operator records the laboratory result for each parameter with the corresponding field instrument result in a log sheet. The laboratory results are used for control. If for instance the laboratory result is not within the required specifications, the operator makes the necessary changes to the process (e.g. adjust field instrument pH setpoint) so as to bring back the process to within specifications. All changes made to the process are documented. This is a good system since the process is continually tracked and it helps the operator to pick problems as they occur. This method of process monitoring however does not give the operator any information on the type of variation, special cause or common cause. Knowledge on the type of variation experienced by the process is the first step towards solving the problem since it helps to determine the type of change that needs to be taken. For instance if the process displays common cause variation, the operator immediately knows that the variation is within the process and can

be corrected by adjusting the process. If however the process display special cause variation, the operator will know that the variation intervenes from outside the process and can only be eliminated by finding it, removing it, and preventing it from happening again and not by process adjustment. Any effort to improve the process without knowledge of the type of variation that exists will only result in making it worse by mistakenly treating a special cause as a common cause and vice versa. Statistical process control charts (SPC) are normally used for separating variation into common cause and special cause.

Since the maintenance of pH specification is very critical to the achievement of maximum colour removal the method of process control can be improved with the use of statistical control charts. Control charts will provide a visual presentation of the process performance and give a more manageable and meaningful data as opposed to recording tables of raw data as it is presently done. Control charts are effective for monitoring process stability as they detect instabilities and out of control situations timely allowing the operator to correct the process before it produces results that are out of specifications. It was seen that the colour removal processes are highly unstable and thus difficult to control since they cannot be predicted. Having a tool to monitor process stability will improve the ability of the process to be controlled. Process stability is the first requirement for a process in order to be able to produce outputs that meet specifications.

5.5 CONTROL

The objective of the control phase is to ensure the gains of the improvement phase are sustained so that the process is continually improved and not allowed to return to the old state.

The available documentation prepared as part of the ISO 9001:2000 Quality Management System is efficient and serve their purpose. The use of statistical process control however should be included as part of the process control system. The colour removal processes are highly unstable, the starting point therefore would be to determine the reason why

they are unstable and to remove these assignable causes so that process stability is achieved. The use of control charts will help track the process stability since any process change will be detected immediately after it occurs. Since the control chart separates the variation due to special cause or common cause, the operator will have a hint on what process change to make or where to look for the problem to bring the process back under control. Since the operators are not familiar with statistical process control, it would be necessary to provide such training.

As part of the control plan, the process capability indices have to be evaluated on a frequent basis so as to ensure continuous improvement of the processes. It is good practice to set an achievable target for C_p . It is recommended that the assessment of these indices be incorporated as part of the ISO 9000 internal audits.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSION

This study has demonstrated the application of the six sigma DMAIC problem solving methodology to a real business problem in an attempt to close the gap between theory and practice. Six sigma is a data driven concept and requires the collection of process data to determine actual process performance and to drive process improvement. This six sigma project was successful in using the process data to lead to the key problems resulting in the poor pH control of the colour removal processes.

Failure of the first carbonation stage to lower the pH to the required level is due to an inadequate supply of CO₂ gas. The current CO₂ gas supply ranges between 4200-4550 m³/hr. At a capacity of 50 tons/hr raw melt flow, the CO₂ gas flow should be at least 4900 m³/hr in order to achieve the required primary pH. Improvement of the colour removal processes should focus on increasing the CO₂ gas supply, and the control of the following variables which are the key causes of variation; Limed melt % CaO, variation between the field instruments pH and laboratory pH and raw melt colour.

The % CaO and CO₂ gas addition were found to be the key variables that control process centering. The % CaO having a stronger effect on the liming process and a weaker effect on the down stream processes and CO₂ gas addition having a stronger effect in the carbonation processes. The variation between field instruments pH and laboratory pH was found to be the key variable that controls the process spread. The instability of the two pH readings is the main reason for the high variability in the pH values of the processes more especially the secondary pH which has a very fast reaction rate. The focus should be on minimizing the variation on these identified critical variables that controls the process mean and process spread. This will allow better control of the processes and hence improve the degree of colour removal. It is also necessary to ensure

vigilant control on the raw melt colour by not accepting high colours (above USL) from the rawhouse since the final liquor colour is dependent on it.

From the process capability calculations it is clear that all the colour removal processes have a very low C_p , ($C_p < 1$). This means the processes are statistically not capable of meeting specifications at the given operating conditions. The starting point should be in improving the centering of the processes so as to improve C_{pk} making it more comparable to C_p . To improve the C_p to at least $C_p=1$ which corresponds to marginal capability, the variation that exists within the processes (common cause variation) needs to be reduced by making the processes more robust against variation. This may require process re-engineering.

6.2 RECOMMENDATIONS

The following recommendations are suggested to improve the current colour removal processes.

- **Statistical process control (SPC) - control charts**

Since the maintenance of pH to within specifications is critical in achieving maximum colour removal the use of control charts for process control should be considered. Control charts truly represent the 'voice of the process' detecting any process anomalies.

- **Determine causes of the high instability of the process (special causes)**

The processes are highly unstable and therefore cannot be predicted. Process stability is the first requirement before a process can meet specifications. It is therefore important to determine the causes of process instability so that they can be eliminated. The use of control charts will help in detecting the effects of special causes of variation.

- **Lime control**

The high % CaO on limed melt indicates that lime control is poor. Since lime addition is automatically controlled by the lime ratio the main problem appears to be in maintaining a constant lime density. There is a need for a better measurement instrument to continually monitor the lime density as opposed to measuring the density after preparation of each batch as it is presently been done. The use of nuclear density meters or DP cells as used by other sugar refineries is recommended.

- **CO₂ gas supply flow rate**

Consider improving the flue gas supply source so as to achieve at least 4900 m³/hr of gas. The insufficient CO₂ gas supply appears to be due to a source deficit and not a delivery problem since the total rating of the two gas pumps is 6 500 m³/hr.

- **Appraisal of Capability indices -ISO 9000:2000 internal audits**

The appraisal of capability indices should be incorporated as part of the ISO 9000:2000 internal audits so as to ensure continuous improvement of the processes, since these indices are a good tool for demonstrating improvement.

CHAPTER 7

7.1 SUMMARY

In the last 20-30 years, the concept of quality became a very important subject in industrial engineering. All along little attention was paid to it because of the manufacturer's believe that quality and productivity cannot exist together. The six sigma quality concept has proven to be the best strategy in helping organisations achieve high levels of quality. It is therefore important for all manufacturers to learn and embrace the six sigma quality techniques if they want to become more profitable and competitive.

The main objective of this project was to demonstrate a practical application of the six sigma quality concept to a manufacturing problem. This study was done because few of us really know how to apply the six sigma method to improve our organization's performance. This is partly because there is not much information available for newcomers on six sigma on how to exactly implement it. Secondly, six sigma is heavily based on measurement, which most of us do not understand. The study therefore attempted to address these needs by giving a full theoretical and practical presentation on six sigma.

The six sigma method was demonstrated by application to a section of a process (colour removal process) in a continuous plant manufacturing refined sugar. The colour removal process was chosen because the pH control of this process is very poor as a result the degree of colour removal achieved is below expectation. Colour removal is a very important operation in sugar refining because that is where the refining occurs by removing the colour (impurities) in the raw sugar. This project was considered successful in terms of meeting its objectives since it was able to use the process data to identify the causes of poor pH control and in identifying parameters that could be adjusted to improve the process. This is in line with the six sigma concept since it requires the use of process data to lead to the problem and solution.

At an academic level this project has enhanced the student's knowledge on six sigma and statistical process control (SPC). Since this project was the student's first experience in applying SPC to a real manufacturing situation, it was quite interesting to see the amount of information SPC reveals about the behavior of the process, which one could never see by simply reading through process data.

A last word for all manufacturers is to learn the language of statistics to allow better understanding and control of variation in their processes. Even if they choose other quality management systems instead of six sigma, by using statistics they will simply be doing what six sigma requires and will surely be opening up for big improvements in process control which will translate to increased product quality. To speak the language of statistics will not require us to be statisticians but at least we need to be able to think statistically.

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APPENDIX

Appendix A

- Raw data- Laboratory and Field instruments data

Appendix B

- Sample size, Process mean and $R_m(\text{bar})$ calculation – Primary pH
- Scatter plots

Appendix C

- Process capability calculations spreadsheet

Appendix A

- Raw data – Laboratory and Field Instruments Data

Appendix A

1. Laboratory ph/Colour Data

Date	Sample No.	Raw melt Colour	Limed melt pH	%Cao	Primary pH	Secondary pH	Clarified Liquor pH	Clarified Liquor Colour	Sulphited Liquor pH	Fine Liquor pH	Fine Liquor Colour	%CO ₂
2-May	1	1415	11.50	0.62	9.70	9.70	7.70		7.50			7.63
	2				10.10	8.10			7.50			16.23
	3	1311	11.10	0.73	9.90	8.20	6.90	544	6.50	6.20	535	17.70
	4	1258	10.90	0.72	9.90	8.10	7.40		7.40			16.84
	5				10.10	8.90	7.20					17.86
	6	1374	11.60	0.77	10.00	8.10	8.60	665	6.70	6.60	623	14.12
	7	1016	11.40	0.74	10.30	9.20	8.90		7.10			15.69
	8				10.60	8.30	7.40					15.69
3-May	9	1100	11.40	1.05	10.10	8.20	8.90		8.40	7.60	411	15.42
	10				10.10	10.10			9.90			16.65
	11	1300	11.40	0.88	10.20	8.90	8.20	470	6.50			15.24
	12				9.80	7.40			6.60			15.82
	13	1158	11.50	0.90	9.90	7.80	7.90	510	6.80	6.60	505	16.93
	14				9.50	7.40			6.70			15.96
	15	1058	11.40	0.95	9.90	8.80	8.50		7.70			14.02
	16				9.90	8.30			6.60			13.39
	17	1120	11.10	0.77	9.80	7.00	5.60		6.10	6.40	465	14.46
	18				9.90	8.10			6.10			16.74
4-May	19	1186	11.20	0.73	10.20	7.60	7.40	584	6.90			16.76
	20				9.70	7.30			6.70			15.35
	21	1313	11.20	0.78	9.90	7.60	7.60		7.50	6.20	425	16.14
	22				9.70	7.70			6.20			16.04
	23	1126	11.40	0.86	10.00	8.30	8.00	553	6.70			15.94
	24	1445	11.20	0.70	9.70	8.20	7.90		7.00	6.80	472	16.50
	25	1591	11.40	1.55	10.40	9.20	9.10		6.70	6.40	565	16.25
	26				10.50	9.50			5.70			16.56
5-May	27	1398	11.40	1.23	10.30	9.10	9.10	402	6.50			16.13
	28				10.20	9.00			6.00			15.91
	29	1175	11.40	1.15	10.20	9.30	8.80		6.80	6.90	455	9.49
	30				10.40	9.50			6.50			14.46
	31				10.30	9.70	9.60		6.10			15.19
	32	1230	11.60	1.34	10.90	9.90	9.70		6.60	6.50	358	16.28
6-May	33	1250	10.80	0.70	9.80	8.30	8.50	364	6.30			16.58
	34				10.00	8.30			6.20			16.71
	35		11.00	0.70	9.90	8.30	8.10		6.80	6.30	387	13.23
	36				9.70	7.80			6.50			12.62
	37				9.40	7.80			7.70			13.51
	38	1329	11.00	0.64	9.70	7.80	8.10		7.10	7.00		12.28
	39				9.90	8.50			6.70			12.86
	40	1371	11.20	0.92	10.30	9.40	8.60	558	7.20	6.70	547	12.50
	41	1444	11.40	1.37	10.50	9.70	8.60		6.90			11.13
	42				9.90	8.40			7.00			12.31
7-May	43	1167	11.30	1.23	10.30	9.90	8.60	504	6.70	6.80	387	13.84
	44				10.10	8.70			6.30			10.41
	45	1429	11.20	0.91	10.00	8.80	8.50	520	6.30			9.90
	46				10.00	8.80			6.70			14.02
	47	1350	11.30	0.64	10.30	8.40	8.50	630	7.20	7.20	288	13.28
	48				9.60	7.80			7.20			12.97
	49	1094	11.40	0.76	9.90	8.20	8.10		7.40			14.89
	50				10.10	8.30			7.30			12.97
	51	1030	11.30	1.26	10.50	9.70	8.90					14.89
	52				10.10	8.40			6.00			16.16
8-May	53	1058	10.90	0.98	10.00	7.70	7.50	501	6.00			15.79
	54				9.30	7.20			5.90			15.24
	55	1030	10.30	0.85	9.10	7.40	6.90	459	6.70	6.70	299	14.58
	56				9.30	7.70			6.80			14.95
	57	1442	11.40	1.10	10.30	9.10	8.60	555	7.20			15.04
	58				10.10	9.10			6.90			15.51
	59	1143	11.30	0.79	10.40	9.20	8.70		6.80	6.50	432	16.13
	60				9.70	8.70			6.60			16.18
	61	1076	11.10	0.77	9.90	9.10	8.20	484	6.90	6.60		16.24

Date	Sample No.	Raw melt Colour	Limed melt pH	%Cao	Primary pH	Secondary pH	Clarified Liquor pH	Clarified Liquor Colour	Sulphited Liquor pH	Fine Liquor pH	Fine Liquor Colour	%CO ₂
8-May	62				9.50	6.50			5.10			15.74
	63	1312	11.10	0.71	9.80	8.30	7.90		7.50			13.76
9-May	64				9.50	7.40			6.20			13.00
	65	1090	10.80	0.70	9.40	8.60	6.90	602	6.30	6.20	405	11.67
	66				9.70	7.60			6.20			13.79
	67	1275	11.20	0.53	11.00	8.30	7.10	618	6.70			13.24
	68				10.70	9.60			6.90			15.81
	69	1112	11.60	1.02	10.50	9.00	8.90	665	7.20	6.80	509	17.09
	70				9.10	7.40			7.10			16.42
	71	1179	11.30	0.88	9.90	7.90	7.90		6.90			16.84
	72				9.70	8.00			7.00			11.14
	73		11.20	1.05	10.30	9.30	8.70	514	8.20	7.50	505	13.10
	74	1475	11.60		10.60	9.40	9.30		5.40			10.85
10-May	75				10.50	8.90			6.70			17.77
	76	1456	11.50	1.04	10.30	9.00	8.90	684	6.30	6.10	4	16.33
	77				9.70	8.20			6.40			17.12
	78	1333	11.10	0.89	10.00	9.50	8.40	755	6.90			16.70
	79				9.80	8.80			6.50			16.52
	80	1496	11.60	1.20	10.20	8.70	8.20	538	7.00	6.90	515	17.32
	81				10.00	9.20			7.10			17.46
	82	1592	11.20	1.16	10.30	9.00	8.80	554	7.10	7.20	576	16.81
	83				9.80	8.20			6.20			18.12
	84	1394	11.20		9.90	8.20	7.70		6.60			17.63
11-May	85				9.50	7.80			6.90			16.17
	86	1502	11.50	0.63	10.00	8.30	8.50	424	7.40	7.10	397	16.92
	87				10.00	8.10			7.00			18.33
	88	1489	11.40	0.81	10.10	8.50	8.10		7.30			17.72
	89				10.10	8.90			7.00			17.23
	90		11.80	0.76	9.90	8.30	8.40		7.00	6.90	340	16.60
	91				9.70	7.70			7.10			17.93
	92				9.10	7.80	7.80		7.20			18.24
	93				9.90	7.70			6.50			17.17
	94	1480	11.50	0.98	10.30	8.70	8.10	517	7.20	7.50	518	17.39
	95				9.90	8.10			6.90			16.92
	96	1504	11.70	1.89	9.90	7.90	8.00		7.00			18.13
12-May	97				9.80	8.20			7.10			16.13
	98				9.30	7.20	8.10		7.00	6.90	367	16.74
	99	1350	11.50	0.95	10.10	8.50	8.20	700	6.90			16.75
	100				9.90	8.80			6.60			16.97
	101	1525	11.60	0.88	10.30	8.80	8.50	675	7.20	7.00	406	17.96
	102				10.00	8.60			7.00			16.77
	103	1192	11.70	1.78	10.10	7.90	7.60		6.90	6.80	395	17.61
	104				9.90	8.70			6.50			16.92
	105	1277	11.50	1.30	10.10	8.70	8.10	455	7.30			17.58
	106				9.90	8.20			6.50			18.00
	107	1409	11.20	1.06	9.60	8.10	7.30		6.40	6.40		18.13
13-May	108	1386	11.10	0.53	9.20	7.70	8.30	7	7.00	6.80	395	17.64
	109				9.60	8.40			7.30			18.21
	110	1147	11.30	0.73	9.80	8.40	8.30	620	7.20			17.75
	111				9.50	8.40			6.80			18.14
	112	1245	11.00	0.60	9.90	8.90	7.50	657	6.10	6.40	399	16.80
	113				9.50	7.60			6.90			17.47
	114	1221	11.50	1.49	10.10	9.90	8.50		6.10			12.64
	115	1274	11.50	1.37	10.10	8.20	8.20	439	6.90	6.60	412	17.34
	116	1522	11.40		10.10	9.50	7.90		7.10			19.36
14-May	117				9.90	8.60			6.50			17.51
	118		11.80	1.06	10.40	9.00	8.90		7.00	6.70	300	17.53
	119				10.10	8.60			7.10			18.26
	120				10.30	8.60	8.50		6.70			16.82
	121				9.80	8.50			7.20			16.84
	122	1148	11.50	1.11	10.60	9.60	9.20	604	7.30	7.30	388	17.91
	123				10.40	8.80			6.60			17.93
	124	1323	11.80	1.61	10.80	9.70	8.90		6.60			17.34

Date	Sample No.	Raw melt Colour	Limed melt pH	%Cao	Primary pH	Secondary pH	Clarified Liquor pH	Clarified Liquor Colour	Sulphited Liquor pH	Fine Liquor pH	Fine Liquor Colour	%CO ₂
14-May	125	1460	11.40	1.40	10.10	8.80	8.40	374	6.60	6.40	329	16.69
	126				10.20	8.60			6.70			17.16
	127	1376	11.40	1.36	10.00	9.00	8.60		7.40			17.47
15-May	128	1374	11.60	1.44	10.60	9.50	9.30	632	7.40	7.20		17.35
	129				10.20	9.30			7.40			17.89
	130				10.20	9.10			7.00			17.31
	131	986	11.20	1.37	9.90	9.90	8.50	385	7.10	5.30	271	17.91
	132				10.10	9.30			6.70			18.78
	133	940	11.30	1.51	10.30	8.60	8.90		8.80			18.15
	134				10.20	10.20			7.50			
	135	812	11.30	1.19	9.90	8.60	7.90	356	6.70	6.80	322	11.39
	136				10.00	8.80			6.40			17.87
	137	1012	11.40	1.06	10.00	8.90	8.30		8.40			17.58
16-May	138				9.90	8.70			6.40			17.53
	139	1232	11.70	1.12	10.60	9.40	9.30	538	7.40	7.00		17.14
	140				10.30	8.80			6.60			18.08
	141	1165	11.90	0.97	10.20	8.50	8.60	493	6.90			17.78
	142				10.10	8.40			6.80			16.78
	143	1141	11.30	1.35	10.40	9.70	9.40		6.90	6.40		17.75
	144				9.80	7.60			6.10			17.14
	145	922	11.50	1.19	10.30	8.50	6.90		7.40			18.06
	146				10.50	9.30			7.30			17.42
	147	1107	11.30	1.30	10.10	8.40	8.40	383	6.50	6.30		18.26
	148		11.20	1.39	10.20	8.70	8.40		7.10			18.15
17-May	149				9.70	7.90			6.70			18.13
	150				9.90	8.70			7.10			20.00
	151	1195	11.30	0.76	10.00	8.50	8.20	560	7.20			17.11
	152				9.90	8.80			7.00			18.75
	153	1214	11.20	0.93	9.80	9.40	8.50	688	6.60	6.50		17.56
	154				9.70	8.10			7.20			18.24
	155	1178	11.80	2.07	10.60	9.50	8.30		7.50			17.70
	156				9.30	7.60			7.40			18.54
	157	1122	11.60	1.21	10.00	7.90	7.90	414	7.50	7.30		17.90
	158				9.80	7.70			7.40			16.50
	159	1215	11.30	0.71	10.20	7.70	7.70		7.50			15.40
18-May	160				10.00	8.40			7.30			18.77
	161	1033	11.10	0.69	9.90	8.80	8.00	569	7.40	7.10		17.23
	162				10.30	9.40			7.10			
	163				9.90	8.20			6.80			
	164	1130	11.60	1.18	10.30	8.10	8.30		6.70	6.40		
	165				10.00	8.00			6.60			
	166	1208	11.50	0.98	10.30	8.40	8.30	394	6.60			
	167				10.00	8.70			6.60			
	168	1291	11.50	0.86	10.20	8.30	8.40		6.60	6.60		
19-May	169				10.10	8.70			6.40			
	170	1118	11.40	0.91	10.30	9.40	8.80	580	6.80	7.20		
	171				10.00	8.40			6.00			
	172	1036	11.30	1.04	10.10	8.90	8.40	494	6.90			
	173				10.30	8.70			7.10			
	174	1059	11.60	1.26	10.30	9.70	8.60	655	7.00	6.50		
	175				10.10	8.50			6.80			
	176	1558	11.60	0.56	10.20	8.00	8.00		6.90			
	177				10.50	7.50			6.70			
	178	1357	11.40	0.67	10.00	7.60	8.00	472	7.20	6.80		
	179				10.00	8.10			7.00			
	180	1272	11.50	0.95	10.00	7.90	8.10		7.10			
20-May	181				9.80	7.60			7.00			
	182	1211	11.40	0.72	9.90	7.80	7.80	471	6.90	6.80		
	183				9.90	8.10			7.20			
	184	1027	11.30	0.53	9.90	8.40	7.80	505	6.80			
	185	1058	11.10	0.69	9.90	7.80	7.70	454	7.10			
	186				10.20	9.20			6.90			
	187	1139	11.90	1.68	10.30	8.10	8.00		7.30	7.30		

Date	Sample No.	Raw melt Colour	Limed melt pH	%Cao	Primary pH	Secondary pH	Clarified Liquor pH	Clarified Liquor Colour	Sulphited Liquor pH	Fine Liquor pH	Fine Liquor Colour	%CO ₂
20-May	188				10.00	9.40			7.10			
	189	886	11.60	1.14	10.30	8.20	8.20	331	7.00			
	190	978	11.70	0.98	10.10	7.50	8.10		7.00	7.00		
21-May	191				9.90	7.80			6.90			
	192	1141	11.00	0.74	10.30	9.20	8.20	666	7.30	7.30		
	193	1060	11.40	0.88	10.10	9.20	8.00	593	6.90			
	194				10.00	8.10			7.10			
	195	988	11.20	0.97	9.70	7.60	7.40		6.80	6.60		
	196				9.70	7.70			7.40			
	197	1064	11.00	0.95	9.80	7.80	7.60		7.60			
	198				10.20	9.20			6.70			
	199				10.40	7.80			8.00			
	200	1245	11.60	1.04	10.40	8.90	8.60	421	7.60	7.40		
22-May	201				10.30	9.30			7.20			
	202	1063	11.60	1.05	10.30	9.40	8.70	671	7.30	7.00		
	203				10.10	8.20			7.40			
	204				9.90	7.40	7.20		6.80	6.70		
	205				9.30	7.20			6.50			
	206	1259	11.40	1.13	10.40	8.60	7.50		6.50			
	207				10.00	7.50			6.60			
	208	1140	11.80	1.18	10.40	8.40	8.00	390	7.10	6.80		
	209				9.60	7.20			6.90			
23-May	210				10.20	8.40			6.80			
	211	1276	11.40	1.02	10.40	9.50	8.30		7.20	6.90		
	212				10.00	8.30			7.00			
	213	1070	11.60	0.91	10.20	9.80	8.50		7.50			
	214				10.00	7.90			7.40			
	215	1175	11.50	0.95	10.40	8.40	8.10	688	7.50	6.90		
	216				9.80	8.40			7.30			
	217	1344	11.70	0.88	10.30	8.70	8.40		7.20			
	218				9.90	8.00			7.10			
	219	1124	11.40	1.02	9.90	8.10	8.00		7.30	7.50		
	220				10.00	9.00			6.40			
	221	1035	11.50	1.15	10.30	8.70			6.40			
24-May	222	1066	11.80	1.52	10.20	9.80	8.10		7.20	7.00		
	223				10.20	8.40			7.20			
	224				10.20	9.40			6.70			
	225	990	11.20	0.60	11.00	7.80	7.80		7.50	7.60		
	226				10.50	7.50			6.50			
	227				9.20	7.50	7.30		6.20			
	228				9.60	7.50			6.60			
	229	1050	11.70	1.44	10.40	10.60	8.30		7.40	7.00		
	230				8.50	9.40			7.30			
	231	968	11.30	0.77	10.00	9.30	8.30	520	7.40			
25-May	232	1308	11.40	1.20	10.10	8.80	8.70	397	6.90	6.80		
	233				10.00	7.90			6.60			
	234	1359	11.10	1.11	10.10	8.60	8.00	386	6.70			
	235				10.00	9.40			7.80			
	236	1049	11.70	1.27	10.20	8.70	8.20	439	6.90	6.80		
	237				10.00	7.70			6.80			
	238	1080	11.70	0.95	10.30	9.50	8.10		7.00			
	239				10.20	7.50			6.60			
	240	934	11.70	1.16	10.20	8.80	7.90	548	6.80	6.60		
26-May	241				10.10	8.10			6.90			
	242	1286	11.10	0.85	9.60	7.50	7.50	319	6.50			
	243				9.70	7.20			6.60			
	244	1304	10.80	0.53	9.60	7.70	7.50		6.90	6.80		
	245				9.60	8.80			6.70			
27-May	246	1688	11.50	1.34	10.00	7.20	7.30	468	7.30	7.50		
	247				9.60	8.70			7.10			
	248	1339	11.50	1.04	10.20	8.80	8.10		6.80			
	249	880	11.30	0.49	10.00	8.30	7.90	460	7.30	7.20		
	250				9.50	7.60			7.30			

Date	Sample No.	Raw melt Colour	Limed melt pH	%Cao	Primary pH	Secondary pH	Clarified Liquor pH	Clarified Liquor Colour	Sulphited Liquor pH	Fine Liquor pH	Fine Liquor Colour	%CO ₂
	251	985	11.60	0.70	10.10	8.00	8.20	504	7.50	7.60		
	252				9.90	7.90			7.10			
	253	900	11.70	1.01	10.10	8.40	7.90	409	7.80			
	254				9.90	7.90			7.10			
	255	900	11.70	1.01	10.10	8.40	7.90		7.80			
28-May	256				9.70	7.60			7.00			
	257	1015	11.20	0.64	9.60	7.40	7.00	436	6.70			
	258				9.40	8.20			6.80			
	259	1355	10.80	0.61	9.80	9.40	7.50		6.40	6.40		
	260				9.80	9.00			6.70			
	261	1295	11.60	0.95	10.40	8.50	8.50	443	6.90			
	262	1113	11.40	0.89	10.20	7.80	8.20	411	7.00	7.00		
	263				9.90	8.00			7.10			
	264	927	11.50	0.84	9.90	7.80	7.90	579	7.30	7.20		
	265				10.50	8.10			7.40			
	266	967	12.00	1.24	10.60	9.40	8.30		7.60			
29-May	267				10.20	7.70			7.50			
	268	1259	11.60	0.96	10.30	8.00	7.70	399	7.20	6.90		
	269				10.20	8.40			7.80			
	270	1041	11.60	1.16	10.40	8.60	7.60		6.90			
	271	957	11.90	0.99	10.60	8.40	8.40	495	7.30	7.10		
	272				10.30	8.90			7.30			
	273	1243	11.40	0.63	9.80	9.00	7.60		7.20			
30-May	274				9.40	7.40			7.00			
	275				10.00	8.40			6.90			
	276	1310	11.60	1.29	9.60	7.50	7.00	481	6.90			
	277				10.10	9.60			7.00			
	278		11.80	1.19	10.30	9.00	8.80		7.20	7.00		
	279				10.20	8.20			7.60			
	280		11.90	1.13	9.80	8.10	8.30		7.90			
	281				10.10	9.00			7.60			
	282		11.50	0.98	10.30	9.60	9.00		7.40	7.00		
	283				9.90	7.90			7.50			
	284		11.80	1.09	10.20	9.40	8.40		7.60			
31-May	285				10.30	8.60			7.60			
	286	1074	11.10	0.79	10.00		7.00	409	6.50	6.30		
	287				10.10	8.10			7.00			
	288	1246	11.40	0.93	9.90	7.70	7.60	345	7.00			
	289				10.10	9.20			7.10			
	290	1305	11.80	0.98	10.70	8.80	8.60		7.50	7.40		
	291				10.30	8.00			7.50			
	292	1171	11.80	0.93	10.40	8.80	8.70		7.90			
	293				10.10	8.40			7.40			
	294	1218	11.90	1.62	10.40	10.00	8.10	304	6.50	6.00		
	295	1093	11.50	1.08	9.80	7.90	7.70		7.20			

2. Field instruments pH Data

Date	Time	Limed melt pH	Primary pH	Secondary pH
2-May	0200	14.37	9.20	7.18
	0400	10.66	9.13	7.04
	0600	12.68	8.64	6.44
	0800	13.09	9.02	6.45
	1000	12.69	9.08	6.72
	1400	11.81	9.20	7.16
	1600	11.87	9.43	7.72
	1800	11.74	9.17	6.94
	2000	11.35	9.06	6.76
	2200	11.47	9.24	7.94
3-May	0000	11.56	9.23	7.46
	0200	11.46	9.16	7.08
	0400	11.86	9.11	6.95
	0600	11.76	9.37	6.99
	0800	11.68	9.43	7.32
	1000	14.37	9.59	7.75
	1200	11.35	9.35	6.85
	1400	11.07	9.11	6.83
	1600	10.93	9.18	6.87
	1800	14.37	9.69	7.09
	2000	14.37	9.22	6.95
	2200	14.37	9.50	6.87
	4-May	0000	12.23	9.41
0200		11.16	9.16	7.00
0400		10.76	9.02	6.96
0600		10.76	9.02	6.95
0800		10.62	9.12	7.08
1000		10.82	9.12	7.14
1200		11.61	9.18	6.99
1400		11.21	9.09	7.10
1600		9.76	9.25	6.86
1800		10.67	9.38	6.97
2000		11.20	9.47	7.95
2200		11.19	9.56	7.63
5-May		0000	11.15	10.02
	0200	11.09	9.95	7.79
	0400	11.47	9.96	8.19
	0600	11.09	10.15	8.19
	0800	11.09	9.91	8.50
	1000	11.82	9.64	8.40
	2000	11.60	9.74	8.96
	2200	11.60	10.15	8.54
6-May	0000	10.96	9.39	6.98
	0200	10.92	9.52	7.14
	0400	13.37	9.50	8.00
	0600	11.82	9.12	7.42
	0800	12.08	9.17	7.99
	1000	9.51	9.41	7.31
	1200	10.58	9.37	7.01

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Date	Time	Limed melt pH	Primary pH	Secondary pH
	1400	10.82	9.34	7.01
	1600	10.89	9.44	7.47
	1800	11.34	9.77	7.11
	2000	11.40	9.93	7.15
	2200	11.40	9.93	7.45
7-May	0000	11.29	9.91	7.56
	0200	11.16	10.08	8.08
	0400	11.15	10.07	7.29
	0600	11.19	10.11	7.69
	0800	11.17	10.07	7.35
	1000	12.22	10.03	7.01
	1200	11.34	9.78	6.98
	1400	11.61	9.35	6.93
	1600	11.56	9.36	7.19
	1800	11.28	9.32	7.17
	2000	11.26	9.35	6.94
	2200	11.12	9.92	7.89
8-May	0000	11.40	9.76	7.48
	0200	9.80	9.91	7.66
	0400	10.94	9.43	7.01
	0600	10.89	9.31	7.20
	0800	10.97	9.27	7.13
	1000	10.66	9.93	7.68
	1200	11.04	10.05	7.67
	1400	11.83	10.15	8.06
	1600	11.30	9.24	7.34
	1800	11.46	9.31	7.13
	2000	11.60	9.37	6.90
	2200	14.37	9.25	6.97
9-May	0000	11.16	9.26	6.91
	0200	10.73	9.25	6.83
	0400	10.79	9.46	7.03
	0600	11.44	10.12	7.25
	0800	10.16	10.18	7.35
	1000	10.12	9.10	7.24
	1200	9.52	8.79	6.82
	1400	9.41	9.64	7.09
	1600	9.10	7.74	6.52
	1800	9.65	9.50	7.02
	2000	11.07	10.00	7.12
	2200	10.99	9.62	7.83
10-May	0000	10.74	9.56	7.48
	0200	10.74	9.49	7.12
	0400	10.78	9.68	7.03
	0600	10.85	9.66	7.55
	0800	11.21	9.75	7.23
	1000	11.42	9.16	7.13
	1200	10.92	7.97	7.16
	1400	9.77	6.88	6.61
	1600	10.21	9.40	7.67

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Date	Time	Limed melt pH	Primary pH	Secondary pH	
10-May	2000	10.23	9.89	7.07	
	2200	10.22	9.62	7.10	
11-May	0000	10.34	9.37	7.02	
	0200	10.48	9.35	7.20	
	0400	12.88	9.24	6.94	
	0600	10.96	9.23	7.16	
	0800	12.54	9.32	6.64	
	1000	11.12	9.22	6.68	
	1200	12.79	8.94	6.49	
	1400	10.44	9.75	6.67	
	1600	10.36	9.38	6.84	
	1800	10.47	9.39	6.86	
	2000	10.41	9.38	7.07	
	2200	10.24	8.88	6.99	
	12-May	0000	10.16	9.10	7.25
		0200	13.82	8.66	6.89
0400		13.56	8.81	6.74	
0600		9.53	7.89	7.07	
0800		12.31	9.39	7.61	
1000		10.25	9.28	7.19	
1200		10.18	9.31	7.20	
1400		10.96	9.78	6.84	
1600		10.40	9.83	7.23	
1800		10.56	9.87	7.49	
2000		10.62	9.83	7.16	
2200		10.68	10.00	7.61	
13-May		0000	10.65	9.88	7.54
		0200	10.66	9.24	6.88
	0400	12.36	9.31	7.18	
	0600	12.23	9.33	7.11	
	0800	11.90	9.15	7.05	
	1000	12.04	9.17	6.81	
	1200	10.63	9.43	6.41	
	1400	11.28	10.22	7.68	
	1600	14.37	10.10	6.66	
	1800	10.66	10.11	6.96	
	2000	10.68	9.99	6.98	
	2200	10.91	9.86	6.99	
	14-May	0000	11.31	10.00	7.51
		0200	11.05	10.04	7.32
0400		11.18	9.99	6.88	
0600		11.28	10.05	6.80	
0800		10.33	9.53	6.74	
1000		10.43	9.89	7.93	
1200		11.14	10.19	7.26	
1400		10.98	10.29	7.36	
1600		10.04	10.25	6.87	
1800		9.76	9.91	7.45	
2000		10.93	9.43	6.85	
2200		10.63	9.35	7.14	

A9

Date	Time	Limed melt pH	Primary pH	Secondary pH
15-May	0000	10.60	9.44	7.46
	0200	10.52	9.59	7.83
	0400	11.26	9.54	7.11
	0800	10.44	9.49	7.43
	1000	10.27	9.49	7.82
	1200	10.25	9.45	7.69
	1400	10.28	9.50	6.83
	1600	10.16	9.40	6.66
	1800	10.16	9.50	7.34
	2000	10.18	9.44	7.43
	2200	10.13	9.43	7.51
	16-May	0000	10.10	9.41
0200		10.15	9.49	7.76
0400		10.22	9.28	7.34
0600		10.57	9.26	6.88
0800		10.25	9.46	7.79
1000		10.29	9.79	7.57
1200		10.51	9.69	6.51
1400		9.97	10.13	7.12
1600		9.97	10.20	7.52
1800		10.02	10.16	7.63
2000		9.97	9.57	7.26
2200		9.97	9.76	7.69
17-May	0000	9.87	9.14	6.77
	0200	14.37	8.05	7.32
	0400	9.82	9.31	6.87
	0600	9.87	9.47	7.03
	0800	9.89	9.28	7.09
	1000	9.74	9.37	7.02
	1200	9.84	9.57	6.59
	1400	10.17	10.22	7.24
	1600	9.69	9.36	6.47
	1800	9.90	9.51	6.45
	2000	9.91	9.58	6.42
	2200	9.57	9.40	6.54
18-May	0000	9.82	9.02	6.87
	0200	10.52	6.87	6.54
	0400	14.37	7.14	6.80
	0600	9.66	9.12	6.61
	0800	9.93	9.68	7.75
	1000	9.53	8.48	6.47
	1200	10.22	9.69	6.60
	1400	9.74	9.81	6.66
	1600	9.95	9.80	6.60
	1800	9.79	10.04	6.76
	2000	9.72	9.71	6.99
	2200	9.77	9.58	6.88
19-May	0000	9.69	9.63	7.01
	0200	9.74	9.65	6.89
	0400	9.71	9.73	6.65

A10

Date	Time	Limed melt pH	Primary pH	Secondary pH
19-May	0600	9.67	9.76	6.49
	0800	9.84	9.77	7.04
	1000	9.82	9.95	6.96
	1200	10.08	9.21	8.07
	1400	10.20	9.29	7.83
	1600	10.30	10.03	7.59
	1800	9.66	9.46	7.75
	2000	9.84	9.55	7.81
	2200	9.82	9.43	7.61
20-May	0000	9.47	9.13	7.84
	0200	9.78	9.20	7.74
	0400	9.80	9.37	7.66
	0600	9.71	9.23	7.63
	0800	9.71	8.96	7.54
	1000	9.63	8.90	7.75
	1200	10.13	9.29	8.10
	1400	10.05	9.31	8.19
	1600	10.00	9.19	7.69
	1800	9.84	9.09	8.11
	2000	10.25	7.31	7.39
	2200	10.00	9.58	7.41
	21-May	0000	9.87	9.57
0200		9.77	9.28	7.89
0400		9.73	9.4	7.62
0600		9.69	9.31	7.56
0800		9.76	9.52	7.62
1000		9.83	9.55	7.50
1200		9.84	9.53	7.69
1400		9.68	9.22	7.65
1600		10.00	10.17	9.14
1800		7.57	7.99	8.20
2000		9.85	9.88	8.00
2200		9.74	9.92	8.44
22-May		0000	9.79	9.89
	0200	9.74	9.99	7.80
	0400	9.73	9.86	7.57
	0600	9.80	9.87	7.68
	0800	9.83	9.84	7.83
	1000	10.17	9.49	7.63
	1200	9.61	9.14	7.77
	1400	9.91	9.97	8.32
	1600	9.85	9.79	7.65
	1800	9.97	9.80	7.66
	2000	10.03	9.54	7.61
	2200	10.30	7.36	7.45
	23-May	0000	10.09	9.36
0200		9.91	9.74	7.85
0400		9.87	9.77	7.73
0600		10.00	9.74	7.60
0800		10.00	9.87	7.5

A11

Date	Time	Limed melt pH	Primary pH	Secondary pH
	1000	9.57	9.83	7.97
	1200	9.63	9.84	7.71
	1400	9.66	9.81	7.65
	1600	9.53	9.66	7.59
	1800	9.64	9.67	7.79
	2000	9.66	9.74	7.90
	2200	9.70	9.68	7.86
24-May	0000	9.57	9.57	7.73
	0200	9.65	9.83	7.79
	0400	9.59	10.04	8.11
	0600	11.80	7.49	8.54
	0800	9.80	9.78	9.47
	1000	9.47	9.73	7.69
	1200	9.52	9.40	7.71
	1400	9.52	8.66	7.85
	1600	9.69	9.40	7.92
	1800	9.72	9.68	7.83
	2000	9.40	7.43	7.74
	2200	9.47	9.27	7.82
25-May	0000	9.50	9.24	7.81
	0200	14.37	7.05	8.67
	0400	10.28	8.36	9.44
	0600	9.82	9.72	8.84
	0800	9.78	9.43	7.85
	1000	9.74	9.48	8.21
	1200	11.18	9.24	8.49
	1400	11.21	9.18	8.36
	1600	11.13	8.93	8.59
	1800	11.10	9.27	8.20
	2000	11.16	9.23	8.15
	2200	11.10	9.18	7.79
26-May	0000	11.05	9.21	8.00
	0200	11.05	9.27	8.15
	0400	11.04	9.00	7.99
	0600	11.03	8.88	8.18
	0800	11.08	8.97	8.78
	1000	14.37	7.8	9.52
	1200	14.37	8.29	10.55
	1400			
	1600			
	1800	14.37	11.70	11.70
	2000	11.19	8.80	8.80
	2200	10.98	9.05	9.05
27-May	0000	11.30	9.44	8.18
	0200	11.30	9.44	8.18
	0400	11.16	9.10	8.46
	0600	11.04	8.00	8.57
	0800			
	1000	12.22	9.61	10.46
	1200	12.29	9.31	7.48

Date	Time	Limed melt pH	Primary pH	Secondary pH
27-May	1400	11.04	9.01	8.35
	1600	11.09	8.63	7.83
	1800	11.22	8.96	7.42
	2000	11.26	8.99	7.39
	2200	11.32	9.11	7.37
28-May	0000	11.29	9.04	7.37
	0200	11.28	8.84	7.48
	0400	11.37	8.70	7.83
	0600	11.60	8.68	7.98
	0800	13.26	8.59	7.86
	1000	14.37	8.64	10.18
	1200	11.45	6.99	8.28
	1400	10.25	8.59	9.00
	1600	11.02	8.52	7.94
	1800	10.98	5.60	8.05
	2000	10.62	6.04	7.40
	2200	10.37	7.26	6.93
	29-May	0000	10.34	8.06
0200		10.30	8.11	7.56
0400		10.38	8.38	8.35
0600		10.39	8.10	8.24
0800		11.53	8.22	9.00
1000		10.31	9.04	7.84
1200		10.89	9.07	8.00
1400		11.18	7.76	7.62
1600		11.61	9.31	7.91
1800		11.42	9.77	8.42
2000		10.67	9.08	9.12
2200		10.48	8.45	8.00
30-May		10.56	8.71	7.78
	10.66	9.08	8.56	
	11.10	9.24	8.03	
	11.15	9.47	7.88	
	11.31	8.75	8.23	
	11.04	9.27	8.29	
	10.32	9.29	8.98	
	10.66	7.29	8.82	
	9.93	9.23	9.23	
	9.89	9.07	8.72	
	10.01	9.16	8.56	
	9.97	9.08	8.50	

Appendix B**1. Calculation of sample size, process mean and Rm(bar)**

Primary pH

1) Sample size calculation

Sample no.	Primary pH
1	9.70
2	10.10
3	9.90
4	9.90
5	10.10
6	10.00
7	10.30
8	10.60
9	10.10
10	10.10
11	10.20
12	9.80
13	9.90
14	9.50
15	9.90
16	9.90
17	9.80
18	9.90
19	10.20
20	9.70

Sample mean	9.98
Sample standard deviation	0.24
Sample size N (K=0.5%)	92

ii) Calculation of Process mean and Rm(bar)

Sample no	Primary pH	Rm	UCL(Rm)	Centreline	3 Sigma		2 Sigma		1 Sigma	
					UCL	LCL	UCL	LCL	UCL	LCL
1	9.70		0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
2	10.10	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
3	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
4	9.90	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
5	10.10	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
6	10.00	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
7	10.30	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
8	10.60	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
9	10.10	0.50	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
10	10.10	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
11	10.20	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
12	9.80	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
13	9.90	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
14	9.50	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
15	9.90	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
16	9.90	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
17	9.80	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
18	9.90	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
19	10.20	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
20	9.70	0.50	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
21	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
22	9.70	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
23	10.00	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
24	9.70	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
25	10.00	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
26	9.90	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
27	9.70	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
28	9.40	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
29	9.70	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
30	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
31	10.30	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
32	10.50	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
33	9.90	0.60	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
34	10.30	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
35	10.10	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
36	10.00	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
37	10.00	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
38	10.30	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
39	9.60	0.70	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
40	9.90	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
41	10.10	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
42	10.50	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
43	10.10	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
44	10.00	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
45	9.30	0.70	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
46	9.30	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
47	10.10	0.80	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
48	10.40	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
49	9.70	0.70	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
50	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
51	9.50	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
52	9.80	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
53	9.50	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
54	9.40	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
55	9.70	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
56	10.50	0.80	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
57	9.90	0.60	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
58	9.70	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
59	10.30	0.60	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70

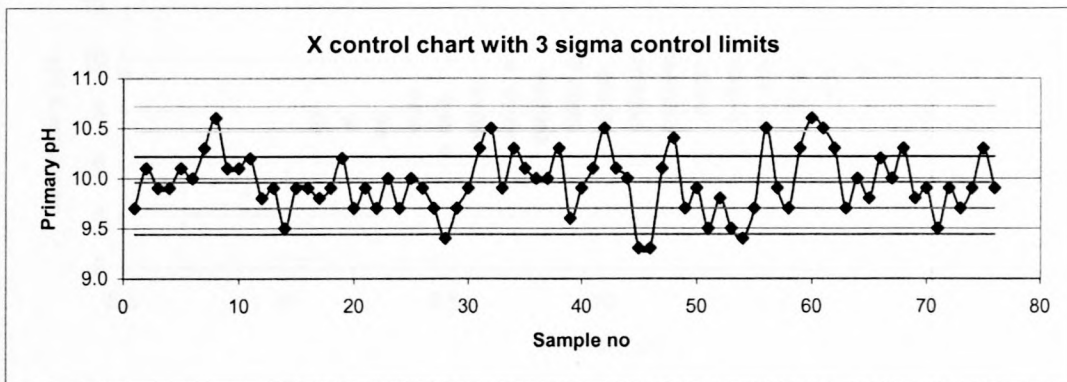
Sample no	Primary pH	Rm	UCL(Rm)	Centreline	3 Sigma		2 Sigma		1 Sigma	
					UCL	LCL	UCL	LCL	UCL	LCL
60	10.60	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
61	10.50	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
62	10.30	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
63	9.70	0.60	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
64	10.00	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
65	9.80	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
66	10.20	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
67	10.00	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
68	10.30	0.30	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
69	9.80	0.50	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
70	9.90	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
71	9.50	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
72	10.00	0.50	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
73	10.00	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
74	10.10	0.10	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
75	10.10	0.00	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
76	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
77	9.70	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
78	9.90	0.20	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
79	10.30	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70
80	9.90	0.40	0.94	9.96	10.72	9.19	10.47	9.44	10.22	9.70

Mean	9.96
Rm	0.29

Control limits	3 sigma	2 sigma	1 sigma
UCL	10.73	10.47	10.22
LCL	9.18	9.44	9.70

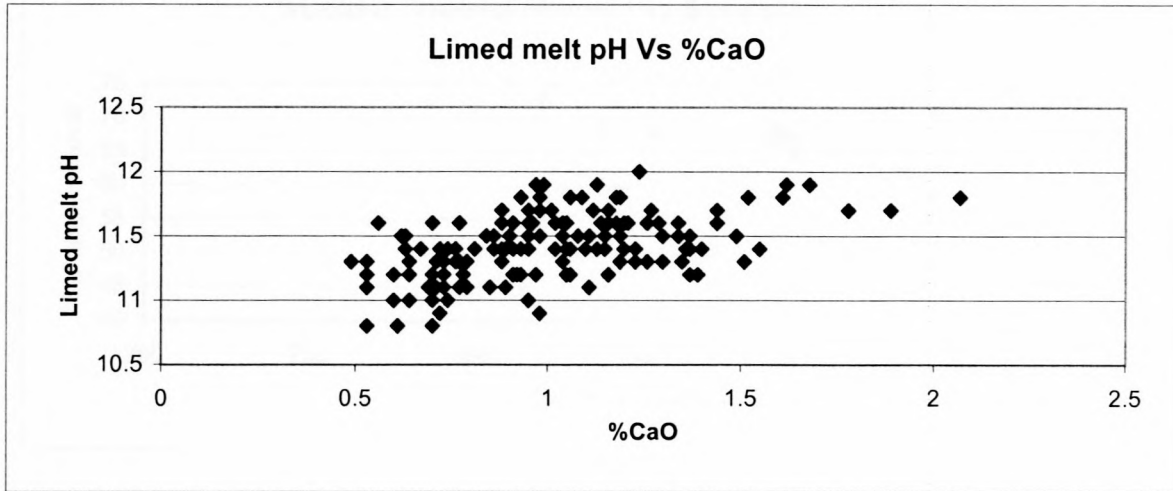
UCL(Rm) 0.95

X control chart



SCATTER DIAGRAMS- CORRELATION

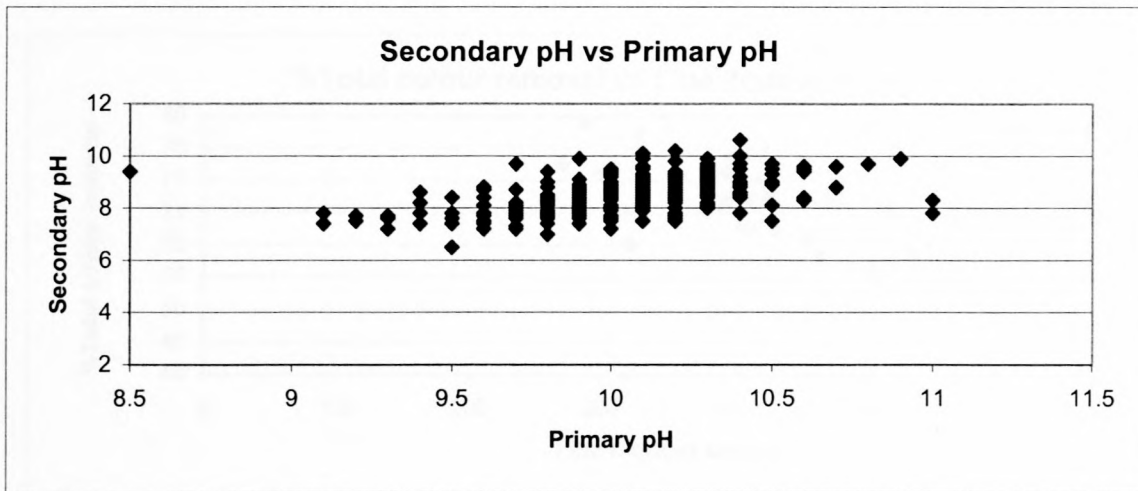
1. Limed melt pH vs %CaO on limed melt



The Limed melt pH shows a weak positive correlation with %CaO on limed melt. The %CaO increases with increasing pH thus a low pH is expected to have a low %CaO and vice versa

$$\text{pH} = f(\% \text{CaO})$$

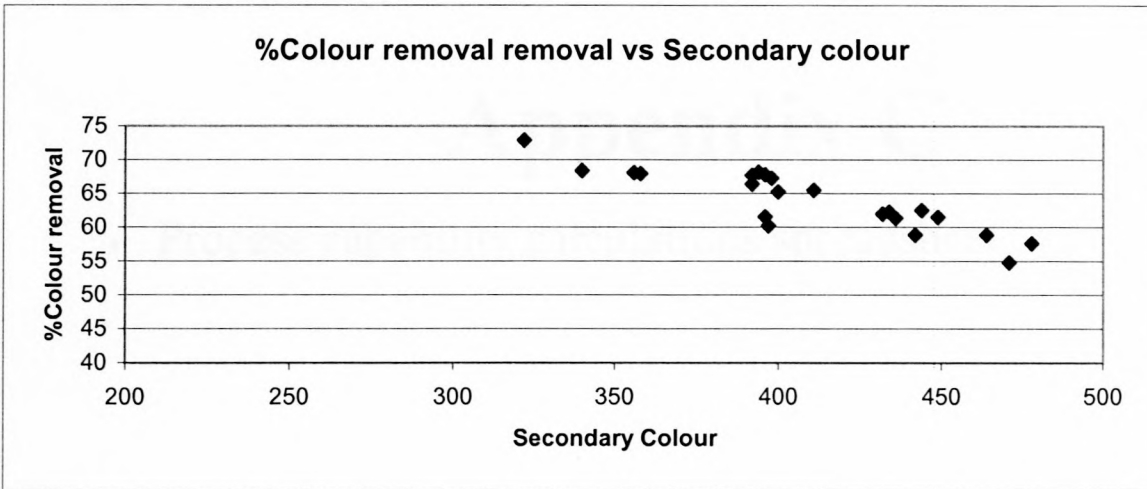
2. Secondary pH vs Primary pH



The Secondary pH shows a weak positive correlation with Primary pH

$$\text{Secondary pH} = f(\text{Primary pH})$$

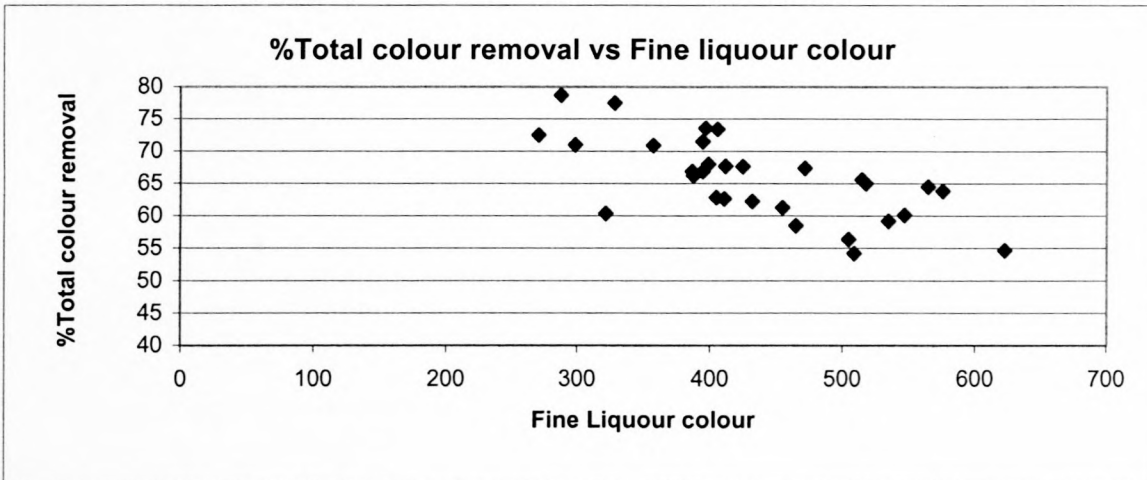
3. Carbonation process: %Colour removal vs Secondary colour



The %Colour removal shows a negative correlation with the secondary colour, meaning high secondary colours are a result of poor colour removal and low colours a result of good colour removal

$$\% \text{Colour removal} = f(\text{Secondary colour})$$

4. Carbonation + Sulphitation processes: %Total colour removal vs Fine Liquour Colour



Similar to graph no.3. The %Total colour removal shows a negative correlation with final liquor colour

Appendix C

- Process capability calculations spreadsheet

APPENDIX C

2. Process capability calculations

Process	Mean	Rm(bar)	sigma hat	USL	LSL	Cp	Cpk min		Zupper	Z lower	Zupper %	Z lower %
1 Liming	11.34	0.22	0.20	11.40	11.00	0.34	0.58	0.10	0.31	1.74	37.83	4.09
2 Primary	9.96	0.29	0.26	9.70	9.20	0.32	0.99	-0.34	-1.01	2.96	84.38	0.15
3 Secondary	8.41	0.56	0.50	8.60	8.00	0.20	0.28	0.13	0.38	0.83	35.20	20.33
4 Sulphitation	6.90	0.34	0.30	7.20	6.80	0.22	0.11	0.33	1.00	0.33	15.87	37.07
5 Fine liquor	6.82	0.45	0.40	7.20	6.80	0.17	0.02	0.32	0.95	0.05	17.71	48.01
6 Liming (%CaO<1)	11.27	0.22	0.20	11.40	11.00	0.34	0.46	0.22	0.67	1.38	25.14	8.38
7 Liming (Lab-FI)	11.40	0.17	0.15	11.40	11.00	0.44	0.88	0.00	0.00	2.65	50.00	0.40
8 Primary (low tpt)	9.39	0.26	0.23	9.70	9.20	0.36	0.27	0.45	1.34	0.82	9.01	20.90
9 Primary (%CaO<1)	9.83	0.28	0.25	9.70	9.20	0.34	0.85	-0.17	-0.52	2.54	69.85	0.55
10 Primary(%CO2>15)	9.96	0.28	0.25	9.70	9.20	0.34	1.02	-0.35	-1.05	3.06	85.31	0.11
11 Primary (Lab-FI)	9.97	0.22	0.20	9.70	9.20	0.43	1.32	-0.46	-1.38	3.95	91.62	0.00
12 Secondary(%CO2>15)	8.42	0.489	0.43	8.6	8.0	0.23	0.32	0.14	0.42	0.97	34.09	16.60
13 Secondary(%CaO<1)	8.34	0.464	0.41	8.6	8.0	0.24	0.28	0.21	0.63	0.83	26.43	20.33
14 Secondary(lab-FI)	8.44	0.23	0.20	8.60	8.00	0.50	0.73	0.27	0.80	2.20	46.81	1.39
15 Sulphited (%CaO<1)	6.88	0.31	0.27	7.20	6.80	0.24	0.10	0.39	1.16	0.29	12.30	38.59