ABSTRACT

VANGALA, RAVIKANTH. Dynamic Process/Quality Control System using Structural Equations – Applications in Ring Spinning and Continuous Dyeing. (Under the direction of Dr. Moon W. Suh).

Real-time diagnosis of abnormal variations in processing has always been a challenging task for most manufacturers with continuous/contiguous processing sequences. Despite the rapid advancements in technology in quality monitoring systems, attaining quality as per customer requirements is still a predominant issue for these companies. Hence, there is an urgent need for development of a new and better method for modeling and monitoring of abnormal variations to optimize quality costs in production, and consequently improve profits. This research study is a part in response to this call. A *dynamic quality control system* was developed, by integrating and enabling three key concepts, namely – *concept of bias separation and estimation through structural equations*, *concept of variance tolerancing*, and *concept of dynamic control limits*. According to this novel system, the changes observed in prior processes update process averages and control limits of the current process through structural relationships that link those two stages. By applying the concept of variance tolerancing, a new set of control limits are obtained, which are functions of dynamic process averages and variances.

$$C.L = f(\mu_y, \sigma_y) \pm kf(\mu_y, \sigma_y)$$

As a case study, this novel concept is applied to ring spinning and continuous dyeing processes that are serially connected with time lags. Structural equations based on key process parameters – *mass variation* and *amount of dye absorbed* for ring spinning, and continuous dyeing processes respectively have been scouted-out from literature. By consolidating and tolerancing these structural equations, a set of dynamic control limits are obtained. Using these accurate control limits, the root causes of the out of control situations can be determined precisely, and unnecessary corrective actions that are detrimental to quality of the output product can be minimized.

Dynamic Process/Quality Control System using Structural Equations
– Applications in Ring Spinning and Continuous Dyeing

by
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DEDICATION

To my wonderful family, mentors and friends for their loving support and understanding

BIOGRAPHY

Ravikanth Vangala, born and raised in Hyderabad, India received his Bachelor of Technology degree from University College of Technology, Osmania University in Textile Technology in 2006. Aspiring to pursue his education at a highly reputed institution, he joined NCSU, and earned his Master of Science degree in Textile Technology from the College of Textiles with a minor in Statistics in 2008. During the Master's program, Ravikanth worked on Design of a Dynamic Quality Control System for Textile Processes under the direction of Dr. Moon W. Suh.

In Fall 2009, Ravikanth decided to pursue his Ph.D. in Textile Technology Management. As a graduate student at College of Textiles, NC State, Ravi has been working in the area of Quality Management and Control for the past six years. During his graduate study, he had opportunity to intern at Buhler Quality Yarns, GA as a Process Improvement Specialist and Lean Six Sigma Black Belt Consultant at Arden Companies, Sanford, NC. He received his certification and training in leadership through Graduate Leadership Development Seminar Series, a part of Preparing Future Leaders initiative started by the Graduate School at NC State. Throughout his Doctoral study, he was actively involved in many non-academic initiatives. He served as a Co-President of Textile Entrepreneurs Club, active, volunteered in many community service activities and is currently serving as a Department Ambassador for TATM Department, College of Textiles.

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Chapter 1

Introduction

Analysis of materials, processes, and products is a part of the current emphasis on continuous quality improvement found in many industries worldwide. Textile industry is not an exception to this trend as the concept of quality has become very important within the textile and apparel industry in the recent past. With the advent of fully automated/computerized modern machinery and emergence of global marketplace, the expectations and demands of consumers have increased at an alarming rate (Hohener, 1990). Although the textile marketing chain is long and complex, globalization of the textile industry has resulted in closer integration of supply and demand of textile manufacturing and associated dyeing and finishing services, in any region of the world. This increased competition directly or indirectly affects materials producers, manufacturers, retailers, and consumers.

Quality has definitely become the most predominant factor in determining the international competitiveness of all industrial products especially as the economic war among nations intensifies globally. Companies that do not meet the international standards such as International Organization for Standardization (ISO), British Standards Institution (BSI), American Society for Testing and Materials (ASTM), International Wool Textile Organization (IWTO), etc. and/or expectations of the consumers do not survive. Hence, in order to improve their ability to survive, companies need to find an effective and efficient way of improving their product quality. However, it has been observed by researchers that there is very less application of the vast amounts of research work and scientific knowledge developed in past 50 years in textile quality monitoring and control (Suh, 1994). When input units such as machine-hours, man-hours and production costs are applied in dividing the utility outputs, profitability and productivity provide the alternative measures of quality.

Because of the large machine –material and human interaction, the textile manufacturing processes have more variables than any other industrial process and hence, the product qualities and products are highly variable, difficult to define, and expensive to measure for several reasons. Statistical tools such as histograms, pareto charts, regression analysis, trend charts, control charts, etc. have been in use from a long time in the textile dry and wet processing industry as they are widely employed for monitoring, forecasting and evaluating properties of raw and processed materials. However, as identified by researchers earlier, the most significant factor that limits the value of statistical quality and process control in textile processes is that statistical control is often impracticable owing to the biases and variances (errors) of previous processes and other interacting factors. The statistical control of random components in the complete absence of physical and structural relationships often generate an endless amount of data that cannot be converted to cost or productivity figures.

Despite the advancements in technology and production-monitoring systems, attaining these quality requirements seem to be a distant task as on-line systems for monitoring the quality of material at different stages of processing have not yet received due importance. Thus, there is a need and requirement for development of new methods for modeling and automated monitoring of key parameters in the textile dry and wet processing industry in order to optimize quality control in production, which consequently will improve profits. This research study is a part in response to this call.

1.1 Problem Statement

A rapidly changing economic environment and global free trade initiatives that provided unrestricted competition to low-cost manufacturers across the globe have had a significant impact on U.S. textile manufacturers, decreasing their domestic production and profitability drastically. The consequence has been the movement of virtually all textile production to developing countries, altering the structure of the domestic textile industry. Although, socio-economic factors play a significant role in determining and driving sustainability in profits for all textile operations, the survival and further growth of a manufacturing plant or a dye house depends on their efforts in addressing other key issues such as, reducing total cost of quality, increasing value-added manufacturing such as adaptation of newer technology and improving productivity (both machine and labor) (Lyford; Welch, 2004).

In a complex and dynamically changing production environments such as spinning and dyeing, there is a paramount danger in focusing on just one of the two prerequisites to success: high productivity and high quality. But, in today's business environment, the drive to introduce new technologies has been stimulated mainly by the need for increased production. In the textile industry, the low-cost competitors have forced many manufacturers to compromise on quality to be more cost competitive in the face of the global competition (Dinsdale, 2004). However, the importance of quality cannot be understated. Better quality products have always been in demand and despite, the production costs being higher, these manufacturers have been able to compete in international markets. For example, the combed Supima cotton yarn from the United States represents high quality product that can compete over low labor cost products from across the globe. With the competitiveness in low-wage countries, products with high quality have made the European manufacturers an example of a major exception in competing with low-price products (Sabanci, 2005).

In addition, the textile industry faces a unique challenge today. Across the globe, the average spending per household on clothing has decreased significantly in the last decade. We can now buy the same, or even larger, amount of clothing, but spend substantially less as compared to the previous two decades. In the U.S. alone, consumers spent as little as 2.98% of their income on clothes in 2009, which is a significant decrease as compared to 4.78% in 1988 and 9% in 1950 (Ravasio, 2012). However, the fast fashion trends are accompanied by lower product quality standards. The continuous demand for newer and more fashion patterns and designs means the manufacturers have lesser time to manufacture the yarn, the dyers have lesser time to dye the fabric and the pattern makers have lesser time to assemble the garment. Making more items in a shorter period of time can only mean one thing: less time per item, and therefore, forcing the manufacturers and dyers to ignore more mistakes and imperfections either by offsetting or by widening the existing control limits to the extent that they become irrelevant. Hence, it can be said that contemporary fashion consumption patterns have a direct correlation with lower garment quality.

According to Ravasio (2012), the average life span of a garment has reduced significantly in the past few years because of poor quality and if the same trend continues, it can be safely speculated to decrease even further in the years to come-by. Thus, it has become more important than ever to provide an effective system to accurately control and continuously monitor the quality of production. The continuous flow of new innovations in terms of process methods in production in textile industry over the past few decades have definitely led to increased automation and increased speed of operations. However, in order to gain cost competitiveness over the low labor costs in developing countries and to respond quickly to the global customer demand, many spinning mills and dye houses have invested mostly in advancements in technology that yield significant benefits in productivity, and made adjustments in their deficiencies in quality by offsetting or widening the control limits (Dicken, 2003). This certainly leads to a situation where the manufacturer fails to detect a true out-of-control situation resulting in frequent false alarms and unwarranted process calibrations. Hence, despite the widespread use of statistical tools and standard procedures alongside appropriate well advanced equipment and personnel, most manufacturing and processing plants have not been able produce quality products with desirable profits to thrive and compete in domestic as well as international markets (Jordan, 2001).

The Global Textile & Apparel trade speculated to reach around USD 800 billion by 2015, and around USD 1 trillion by 2020 (Gugnani and Sunny, 2012). In the present scenario, with higher production, yarn quality requirements have become stringent and demanding such as 0.5 breaks per million meter of yarn in weaving and CV% (10m) for knitting. With the current static quality control systems, it is very difficult for manufacturers to produce goods that meet these quality requirements in the first time or without losing a considerable share of profits. Currently, due to the inefficient quality monitoring systems, the cost of poor quality (which ranges anywhere between 5% and 20% of sales for most manufacturing companies) is at an average of 14% of sales for textile and apparel industries. With the aid of the dynamic quality control system, the cost of quality for an average manufacturer (sales turnover of $20 million USD) can go down to as low as 6% of sales, thus improving profits by almost $1 million USD and as high as 50% (Bheda, 2010). Thus, a small reduction in quality costs at each stage of textile processing may easily double or triple the current profit margins, especially for the U.S. domestic textile industry, which is currently operating at low profit margins.

As Suh et al., (2006) pointed out the root cause for the failure of existing quality and monitoring systems have to be pointed out accurately and investments have be made in developing newer and efficient methods that can improve the quality in both spinning and dyeing processes. One of key issues for failure that has been identified is the incongruent application of current static control systems in the complex textile production environment, which is dynamic and interactive in nature. This has not only resulted in lower quality products but also in loss of production time, materials and consequently profits. Hence, there is an immediate need to replace the existing static and inflexible control systems with an automated dynamic quality control system.

1.2 Research Objectives

RO I: To develop a working model of dynamic process/quality control system based on known structural equations that predicts process average of the current process from the prior processes.

RO II: To provide a set of dynamic control limits based on the means and variances of the prior processes around the dynamic process average.

RO III: To effectively illustrate the dynamic process/quality control system developed by using application examples in spinning and continuous dyeing processes through a newly developed control software.

1.3 Significance of this Research Work

There is a need to reverse the current trend of shorter processing sequences accompanied by reduced quality safeguards that increase the risk of producing an unacceptable product. The common assumption in textile industry is that random variation in processing occurs inherently and there is no way it can be controlled. However, the signal that generates these biases is being ignored completely. Valid structural equations can be used to relate the signals to biases and variances generated, thus providing a way to understand the root-causes for out-of-control situations that arise frequently during continuous/contiguous processing. Need for a dynamic control system in textile processes is evident from the fact that it is one of the only few manufacturing sequences where a static control system is still being used to monitor, control and reduce the amount of variations that occur during processing.

Although, manufacturing sequences currently employ online quality control systems, the static control limits at a given stage of continuous processing sequence mode are fixed and non-reactive to any dynamic changes that occur due to the previous processing stages. Hence, the use of such static target reference in a continuous, dynamic production environment causes frequent false alarms when the changes in process averages originate from the prior process stages. Moreover, since biases and variances get introduced at each and every processing stage in a continuous process, use of dynamic and flexible control limits is mandatory in a rapidly changing production environment.

This novel dynamic quality control system aims to minimize the unnecessary corrective actions (false positives), loss of production time, materials and profit, and determine the root-causes of out-of-control situations. By incorporating structural equations (that are based on certain key process parameters) in its core design, process averages and control limits based on the biases and variances generated at the current and prior processing stages are derived. It is really difficult to determine the root causes of the out-of-control situations precisely in any continuous/contiguous production environment.

However, because of incorporation of structural equations, this new system provides a way to back-tracking of the responsible factors and processing conditions that may have produced the specific out-of-control situation, thus providing an effective solution rather than a disappointing guess work. The prototype of this system can also be widely applied for quality control in various other manufacturing environments where the processing sequence is either continuous or contiguous in nature.

By monitoring quality using this novel technique of Dynamic Quality Control System, manufacturers will be able to produce high quality textile products at lowest price. One of the prime functions of a dynamic quality control chart in spinning is the separation of biases and variances generated in the previous stage from the current stage. By separating and acting upon the biases and variances at each stage results in minimization of false positives and unnecessary corrective actions, as root cause of 'out-of-control' situations can be easily traced, generating an optimal control strategy at each stage of processing. The feedback and feedforward control schemes used so far in the spinning process have been mechanically driven only. Hence, by incorporating structural equations in the design of a combined feedforward-feedback control scheme over-all control at spinning is achieved. The dynamic control chart technique not only helps to ensure that the over-all quality is maintained and but also helps the manufacturer to lower his processing costs, minimize the expenditure on testing and produce better quality goods.

This research study is an attempt to aid the textile producers and manufacturers (both domestic and international) to increase their competitive position in the globe by focusing on ways of reducing quality costs in their respective unit operations especially in a competitive market or in a recession environment. The quality control tool presented in this research study is not without limitations, but it is an attempt to create a novel technology to address and improve the current quality issues and challenges faced by the U.S. textile industry as it continues on its journey into a competitive landscape and also on a path to recall and improve its domestic manufacturing.

Chapter 2

Literature Review

2.1 Definition of Quality, Process Control and Quality Control

The concept of "Quality" has been contemplated throughout history and continues to be a topic of intense interest today. 'Quality' presently is the buzz-word among managers and executives in contemporary organizations and according to Feigenbaum (1982), "*Quality is the single most important force leading to the economic growth of companies in international markets*". In a survey conducted in the year 1990, executives ranked the improvements of service and product as the most critical challenge facing U.S. business (Zeithaml, Parasuraman & Berry, 1990).

According to Clapp et al. (2001), a search for definition of 'Quality' will yield inconsistent results as it has several definitions given by various researchers during a span of over 50 years. For example, Quality has been defined as *'Value'* by Feigenbaum in 1951 and Abbott in 1955; as *'Conformance to Specifications'* by Levitt in 1972 and Gilmore in 1974; as *'Fitness for Use'* by Juran in 1974; as *'Conformance to Requirements'* by Crosby in 1979; as *'Meeting and/or Exceeding Customers Expectations' by* Gronroos in 1983, Parasuraman, Zeithaml & Berry in 1985 and as *'Loss Avoidance'* by Taguchi, cited by Ross in 1989.

About a couple of decades ago, 'Quality' was used only to refer to product quality, but today it has become an essential part of our daily life. The intense competition between manufacturers has left no place for the concept of "Acceptable Quality Level" (AQL). The goods with 5%, 2% or even 1% defectives do not satisfy today's customers who would have accepted them in the past. The production error levels are now measured in *parts per million* (ppm), *parts per billion* (ppb) or *zero defects* (ZD). The trend towards greater accuracy is a characteristic of modern industry that can be found in all production processes and studies associated with technical evaluations.

According to Box, et al. (1976), *‘Control’* in industrial/manufacturing environment, refers to “o*ur desire to affect the outcome of some process or set of conditions*” and in these environments knowledge of how the process should behave under normal conditions is used to identify and eliminate the process variations. From a purely statistical perspective, we may interpret *‘control’* to mean *achievement of control via the quality control techniques*. From a control engineering perspective, we may tend to think of *‘control’* in terms of *feed-forward* and *feedback control loops*, the dynamics and stability of the system and of particular types of control devices required to carry out the control action.

Box, et al (1976), also defined *‘Process Control’* as “*the regulation or manipulation of variables influencing the conduct of a process in such a way as to obtain a product of desired quality and quantity in an efficient manner*.” *‘Process Control’* in general terms refers to eliminating the special causes of variation from the process and to achieve desired target values and it is one of the most important and critical aspects of quality assurance. Feigenbaum (1951) gave an excellent definition of *‘Quality Control’* keeping in view the consumer satisfaction aspect long before the concept of customer satisfaction started playing a prominent role in world trade: “*Quality Control is an effective system for coordinating the quality maintenance and quality improvement efforts of the various groups in an organization so as to enable production at the most economical levels which allow for full consumer satisfaction*”.

To guarantee 100% quality through examination is quite impossible for any manufacturing industry and especially for Textile Industry. Hence, manufacturers prefer controlling the system that produces the product to control of products. The production of quality goods consistent with standards with the aid of standardized quality control systems has not only increased the revenue of the manufacturers but also the world trade (Atilgan, 2007).

2.2 History of Quality & Quality Management in Textile Industry

Today quality is such an important commodity to both consumers and producers that it has become a goal within many companies. However, Quality Control is not a new concept to the textile industry. Even during the ancient times quality control in the textile industry always had its own importance. The earliest quality engineer was probably the first Homo sapiens who smoothened a wheel or sharpened a tool to free it from blemishes thereby improving its rolling ability or increasing its cutting power (Gunter, 1998). Quality and its management have always been important in human life since ancient civilizations and their standardization policies can be regarded as the first step towards quality. In ancient Rome, a uniform measurement system was introduced for manufacturing bricks and pipes; and regulations were in force for the construction of buildings. Water clocks and sundials were used in ancient Egypt and Babylon (15th century BC). The Chinese Song Dynasty (10th century) had specifications on the quality factors such as shape, size, and length etc., of products in handicrafts. Socrates, Sun-Tzu and Aesop are also among those few prominent people around the world who emphasized the importance of quality management. (Reeves & Bednar, 1994).

The modern quality movement started on May 16, 1924, when Walter A Shewhart, an employee of Bell Labs, sent a one page memo to his higher authorities describing a method for improving the quality of telephone manufacturing using statistics which also included the drawing of probably the first control chart (Brocka & Suzanne, 1992). Prof. Walter Shewhart and Harold Dodge were the two most influential people during the mid-twenties who not only laid stress on the importance of quality but also played a prominent role in implementation of statistical methods for quality in the USA. It is also believed that the extensive use of statistical quality control methods started during the Second World War for improving America's war time production and some of these statistical quality control methods were even classified as military secrets. Later, Dr. Kaoru Ishikawa, a well-known Japanese quality philosopher speculated that the Second World War was won by quality control and by utilization of statistical methods.

2.2.1 *History and Evolution of Quality Control in Spinning*

The yarn manufacturing area of the textile industry offers a wealth of data for statistical analysis. Articles on the statistical quality control of textile yarn manufacturing products such as sliver, roving, and yarn date back to the late 1940s and 1950s. In these articles, the emphasis is on product quality and defect detection rather than on defect prevention through process control and quality improvement. Unfortunately, even in those articles which focused on quality control, there has been hardly any usage of the structural equations or relationships between the input and output factors. In spun yarn manufacturing, quality control and quality assurance has been and continues to be, in most cases, a very much-departmentalized function. It is also very much dominated by production concerns for the majority of textile operations. Quality testing has predominantly focused on three areas: 1) end product testing of characteristics such as linear density (sliver weight, hank roving, or yarn count), twist, strength and elongation, short-term evenness, and count variation; 2) inspection (defects such as thick and thin places, slubs, and neps; repeating faults such as mechanical errors or drafting waves); and 3) frequency checks for end breaks during spinning.

For faster feedback, some yarn manufacturers are beginning to move some test equipment (e.g., yarn boards, reels, skein winders, and balances) to the production floor. This is a process-oriented quality feedback that allows an operator to determine the key processing factors that affect the internal and external customer requirements of the product, control and optimize these factors on the shop-floor itself. Inspection for spun yarn manufacturing is directed toward finding defects such as thin places, thick places, or slubs that can cause further problems in yarn preparation or fabric forming. In addition, it is done to reduce the chance for off-quality fabric resulting from irregular yarns. Warp yarns for weaving are typically graded more critically than filling yarns or knitting yarns. Package build, knot quality, and package density are other factors graded during inspection to ensure good running performance in later processing. Given the quality levels of the past, the need for yarn inspection is warranted.

It is however, very costly, and when unacceptable levels are found and lots rejected, losses are great in terms of raw materials, wasted manpower, and improper utilization of processing equipment. Furthermore, the cost of unproductive inspection is far too high. As the focus moves toward process control, defect prevention, and quality improvement, the need of inspection markedly reduces.

Electronic controls and monitoring, when used correctly and effectively, can be a valuable asset in defect prevention and SPC. The problem with most continuous electronic controls (for example, feed-control autolevellers for carding and drawing) is that adjustments are made on predetermined target values. This is in contrast to properly using statistical control limits to determine when to take corrective action. This leads to far more variation through over-control than would occur were the process controlled manually through the use of control charts. Dhillon (2007) states that quality assurance still remains as much a departmentalized function as it was since its first application, dated back to late 1940's. He further expressed concerns about the fact that quality control in yarn manufacturing has not changed much in the past 50 years or so as the emphasis still remains on product quality and defect detection rather that defect prevention.

2.2.2 *History and Evolution of Quality Control in Dye Processing*

Dyeing is one of the most complicated processes in any textile production sequence as it combines the sciences of chemistry, physics, mechanics, physical chemistry, fluid mechanics, thermodynamics and others. History of dyeing can be traced back to as early as primitive age when people attempted to create color to apply on them. Although it is very difficult to determine the precise time when coloring of fibers first occurred, both historians and scientists have determined that substances obtained from *"ochre"* such as *"black, white, yellow and reddish pigments"* that were used by the primitive man in cave paintings around was used to add color to textiles (nicDhuinnshleibhe LS, 2000). On the other hand, some archeologists believe that the practice of adding colors to textile fragments can be traced back to first century AD as dye analysis on textile fragments excavated from archaeological sites in Denmark showed the use of a blue dye wood along with an unidentified red dye (Grierson, 1989). For most parts of the 20th century, treating fibers, yarns and fabrics with mordants before dyeing was the process followed dyers from Middle-east, Asia and parts of North Africa used mordants such as Alum, Iron, Copper, Cream of tartar and Common salt as these regions were rich with deposits of these minerals (nicDhuinnshleibhe LS, 2000).

About 150 years ago, W H Perkin unexpectedly discovered the first aniline dye called *"mauve"* and this incident, best described as the 'chemical miracle' was well documented by many researchers (Holme, 2006). This discovery by Perkin had a significant impact on textile and apparel industry as it led to the establishment of the synthetic dye-manufacturing industry worldwide. Soon after this discovery, both manufacturing and educational institutions put-in huge efforts in researching and developing newer dyestuffs, which later became the characteristic of the industry. Also, research conducted by fiber producers and other industries such as pharmaceuticals and agrochemicals contributed a lot to technology of dye application and formation of dye intermediates, which in turn helped in the growth of other smaller industries (Park and Shore, 2007). As Hauser (2006) points out, economic forces, market demands and environmental concerns have been the key factors that have driven innovation and automation in the wet processing, which still remains a very important component of the textile industry.

The dye processing technology has evolved pretty rapidly from simple manual operations that were used for several decades to sophisticated computer controlled machines that came into prominence in the late 20th century. When the concept of 'Zero Defect' production was translated to the textile-dyeing sector, it led to the concept of 'Right-First-Time' (RFT) processing (Park and Shore, 2009). In early 1980's, research in dyeing involved development of control application methods, use of dyeing machine control systems, and research on short dye-cycle times (Rattee, 1985). During the same time, effect of dye properties and control systems on dyeing reproducibility was also an important area of research (Keaton and Glover, 1985). The development of sophisticated computer programs that produced high quality recipe predictions were also developed by 1980's (Park, 1993).

Researchers have also discussed quality control of yarn package dyeing based on circulating liquor machines and automation (Gailey, 1975 and Park, 1983). The development of ‘Parallel Sided Dyeing Package’ (PSDP) improved the quality and productivity for yarn package dyeing (Mason, Park, Thompson, 1980). During the mid 90’s, development of circulating-fabric machines and instrumental methods of color assessment helped in acquiring RFT dyeing production which is considered as a benchmark in quality control by most dye houses. Towards the end of the 20^{th} century, rapid technological developments combined with the advent of globalization necessitated the development of reliable dyeing methods with a high degree of precision to achieve reproducible high standards of levelness. With companies competing globally, there is more demand than ever before to produce the highest quality material in the shortest time possible (Shamey, 1998).

Although, these developments have led to a considerable improvement in dyeing process quality, the dyeing and finishing industry is still desperately in the need of newer and efficient methods of quality monitoring and control in dye processing and functional treatments of textiles. Controllers for dyeing have been using predetermined set points and not statistically calculated control limits to make adjustments, signal alarms and /or stop the operation. This leads to an over-control situation and increased variation for the process. In order for dye-houses to effectively use the monitoring and controlling equipment available today, the following items must be addressed:

- Statistical control of raw materials (including dyes, chemicals, water, fabric)
- Statistically calculated control limits for key process parameters
- Use of spectrophotometers to establish dye formulas, determine color additions, and evaluate the final shade, or color of the fabric.

The processing technique whether employed in laboratory or plant is subjected to a greater extent of variation when the same operating sequences are repeated. Also, the resultant degree of variation in the quality of a manufactured product, and the tolerances resulting therefore, are determined largely by experience and are only rarely defined on a statistical basis. However, this is a necessary requirement for optimization of the production sequences and therefore it is essential to improve the accuracy by means of statistics. Therefore, there is an urgent need to promote new technologies in textile dyeing and finishing, injecting new thoughts to the industry.

2.3 Evolution of Quality Principles in Textile Industry

Figure 1. Evolution of Quality Principles over the years

Quality Control is not a new concept to the textile industry. Even during the ancient times quality control in the textile industry always had its own importance. Clapp et al (2001) discussed about the earliest standards that were set in quality control for textile industry which date back to about 5000 BC. The paper suggests that the Zhou Dynasty (11^{th} to 8^{th} century BC) in China was so particular about the quality of cotton and silk fabrics produced that it issued a decree that stated "*Cottons and silks of which the quality and size are not up to the standards are not allowed to be sold on the market*". The fabric producers who did not meet these standards had to pay hefty fines as a punishment.

Also, these standards varied depending on the location of manufacturer, especially as the weather varied significantly in the Southern parts compared to Northern territory. The paper also discusses the quality assurance and control in textile manufacturing in the West. Germany was one of the first states that followed quality assurance methods. A group of experts inspected the entire cloth/fabric manufacturing process and only those fabrics produced under this expert supervision were allowed to be sold in the market. This unique process was called *"Tuchshau" (Showing of Cloth)*. The evolution of quality principles in dry textile processing can be primarily classified into four stages. They are:

Artisan/ Inspection: The age old concept of quality assurance in the textile manufacturing was based on inspection of 100% of product items to sort the good from the bad before the products reached the consumers. According to Kadolph (1998), several companies continued employing the concept of quality assurance until early 80's, viewing quality as a factor or a group of factors that can be controlled by inspecting finished products. In these inspections the satisfactory or acceptable products that passed were sold at normal prices while unacceptable products were sold as seconds at a lower price. This process was tedious, time consuming and laborious, and moreover, to guarantee 100% quality through examination is quite impossible for any manufacturing industry and especially for Textile Industry. Companies then defined a level of quality for any output, a set of inspection procedures and product specification rules, referred to as acceptance sampling which ensures that all efforts are directed toward achieving these specific goals. In simple terms, a set of communication tools between the user and the producer of the product were developed (Dodge & Romig, 1959).

Statistical Quality Control (SQC)/ Statistical Process Control (SPC): The second generation of quality assurance development in textile manufacturing started with the advent of SQC/SPC techniques. The main objectives of the SQC/SPC programs were to keep the variability of a process or product within the customer specification limits. Much progress has been made in the application of SQC/SPC in textiles over the past three decades. The first reports of application of SQC methods in yarn manufacturing products appeared to be during the late-1940s and 1950s (Clapp et al., 2001). These methods focused on defect detection rather than defect prevention. The majority of companies to first practice quality improvement utilized Crosby based principles and many employed the use of quality circles in their organizations. This was followed in the mid-1980s by an increased emphasis on Shewhart control charts, Deming practices for continuous improvement and the Juran's approach to quality improvement.

According to Bona (1994), Shewhart control charts were warmly received in textile quality control as they kept output of individual processes in control. Clapp et al. (2001)

point *"end product testing of characteristics, count variation* and *frequency checks for end breaks during spinning"* as the key areas in spun-yarn manufacturing where statistical process control was applied predominantly during the last decade. In recent years, almost every sector in textile industry started implementing SPC as technologies in textile machinery and product specifications have been changing rapidly imposing new quality demands. Also, increasing computing power, availability of numerous SPC software programs and the increasing competition at both local and international levels permit real-time control charts. These online quality control systems are used to describe the statistical process control concepts such as control charts, cause and effect diagrams and process capability studies, which led to the successful minimization in rejections.

According to Engin (2004), the latest trends in quality and process control in yarn manufacturing and processing is *Offline/Online Process Control,* which is implemented either by means of sampling process control (also called *offline* process control) or by an automatic process control (also called *online* process control) at every processing stage. Some of yarn quality characteristics such as yarn breaking force, yarn elongation and yarn hairiness, cannot be measured by online process control. The process of dyeing a textile fabric is one of the most monitored and automatically (online) controlled processes in the entire textile manufacturing chain. The finishing processes, however, are at the other end of the spectrum with fewer controls and heavy reliance upon inspection and testing. In fact, most mechanical finishing processes are considered to be much more art than science. This leads to a great deal of subjectivity whenever evaluating finishing processes. Process parameters such as temperature, pH, rate of temperature rise and cooling for the dyeing process have been widely known, documented and monitored through sampling (offline) process control for many years. Hence, even in the most technologically advanced manufacturing plants, a combination of sampling and automatic process control techniques are employed (El Mogahzy, 1992).

Total Quality Control (TQC)/ Total Quality Management (TQM): As the use of statistical process control grew in the 1980's, industry saw the need to monitor and improve the entire system of providing a quality product or service. Sensing that meeting customer needs, requirements, and expectations involved more than providing a product or service, industry began to integrate quality into all areas of operations. This integrated approach, involving all departments in a company in providing a quality product or service, became known as *Total Quality Control (TQC)* (Ishikawa and Lu, 1985). *Total Quality Management (TQM)* is a management approach that places emphasis on continuous process and system improvement as a means of achieving customer satisfaction to ensure long-term company success. From 1981, Milliken & Co. started implementing the flat organization structure to address specific problems and to change and improve processes in all areas of the company. Since then, most of the textile companies have been following the concept of TQM. With the introduction of ISO series of standards in the United States and across the globe, the textile industry has quickly adapted the new quality assurance systems as they found value in using these standards for their quality systems, thus increasing both imports and exports of fiber, textile and apparel from U.S. (Clapp et al, 2001).

Six Sigma / Lean Six Sigma: Six Sigma method is a project-driven management approach to improve the organization's products, services, and processes by continually reducing defects in the organization (Kwak and Anbari, 2004). There have been two major perspectives about Six Sigma. First, discusses the origin of Six Sigma from statistics (Hahn et al., 1999; Montgomery, 2001). From a statistical perspective, Six Sigma is defined as 'having less than 3.4 defects per million opportunities or a success rate of 99.9997% where sigma is a term used to represent the variation and the process average' (Anony and Banuelas, 2002). Second, from a business perspective, Six Sigma is defined as a 'business strategy used to improve business profitability, to improve the effectiveness and efficiency of all operations to meet or exceed customers' needs and expectations' (Antony and Banueals, 2001).

General Electric defines Six Sigma as a 'systematic, data-driven approach using the define, measure, analysis, improve, and control (DMAIC) process, utilizing design for Six Sigma method (DFSS) (Kwak and Anbari, 2004). The Six Sigma phenomenon, which followed quality initiatives such as Total Quality Management (TQM) and Continuous Quality Improvement (CQI), is viewed as a more comprehensive method for many companies seeking to improve their performance and effectiveness (Anbari, 2002). It has gained an avid following among executives and managers not only for its ability to reduce cycle time, eliminate product defects, and dramatically increase customer involvement and satisfaction but also since it includes measured and reported financial results, and uses advanced data analysis and project management tools (Pande and Holpp, 2001).

The rapid developments in sensors, microprocessors, and computing storage technologies together with ever-declining costs for these provide the textile industry with both enormous opportunity and a dilemma. Researchers advocate that these new applications call for a new approach to quality based on design aspects. Many companies in industries other than the textile industries started implementing Six Sigma quality programs in their management strategy and reaped the benefits. According to Kumar, R.S (2010), although textile industry being a field dealing with lots of variations and defects in each process was an ideal platform for application of Six Sigma quality programs, many companies in industries other than textiles started implementing Six Sigma quality programs and reaped benefits much before DuPont made Six Sigma a key component of their management strategy. Later on other leading fiber, textile and apparel companies such as Burlington Industries, Unifi, Collins and Aikman, PGI etc., started implementing Six Sigma initiatives. A combination of Lean methods with Six Sigma approach is called *Lean Six Sigma*, which focuses on reducing costs through process optimization (IBM Institute for Business Value, 2007).

2.4 Statistical Quality Control (SQC)/ Statistical Process Control (SPC)

Statistical process control, better known by its abbreviation SPC, has become an important part of quality control activities. There have been many articles written on the subject of SPC/SQC as a new technique for transforming management. However, these techniques are not new. Deming (1939) encouraged the use of basic statistical formulas to identify, control and ultimately eliminate special causes of variation in the process, referring to these methods as Statistical Quality Control (SQC).

According to the American Society for Quality (2004), the most frequently used SQC/ SPC methods are:

- *Cause and Effect* – A chart used to examine factors that influence a given condition
- *Flow Chart* – A chart used to delineate the steps in a process
- *Pareto Chart* – A chart used to determine priorities indicating the most significant factors
- *Trend or Run Chart* – A plot of the data used to determine patterns of behavior
- *Histogram* – A chart used to measure the frequency of occurrence
- *Scatter Diagram* – A chart which demonstrates the relationship between two variables
- *Control Chart* – A trend chart with statistically determined upper and lower limits on either side of the process average

Deming identified several different charts to achieve statistical control of a process and most manufacturing companies implement Deming's SPC/SQC via use of the *Control Chart*. SPC/SQC assumes that every process has variation and a c*ontrol chart,* which help us to identify, analyze and control variations in each process. A process is said to be in control when no points fall outside the upper and lower control limits and there are no special patterns observed in the points. SPC/SQC seeks to minimize that variation via these *control charts* by assisting us in identifying and ultimately deciding which control actions should be taken to eliminate the source of that variation. The successful SPC/SQC programs utilize statistics to identify and eliminate special causes of variation, thereby driving the process into a steady state of control. Once control has been achieved, the use of *control charts* is continued to monitor the process so that aberrations can be quickly identified and resolved maintaining a steady state or controlled process (Walton, 1986).

In any production process, there exists certain amount of inherent or natural variability depending upon the number of process and input variables. Hence, to minimize the variability in quality, proper screening actions on input variables and other pre-production planning activities and application of industrial experimentation are generally recommended. In other words, the variability in quality that occurs in an actual production process should be either '*error*' or '*natural/inherent variability*'. Hence, it is very important to monitor this '*error*' variability and necessary measures should be taken so as to maintain this '*error*' constant over a time, across various machines.

Over a period of time variations owing to special causes are bound to occur due to changes in raw material or operatives or sudden machine failures. Therefore the process is usually sampled over time, either in fixed or variable intervals. The presence of special causes can be monitored by considering a control statistic such as the mean ($\overline{X}$) of a sample of units taken at any given time. The approximate probability distribution of the control statistic can then be used to define a range for inevitably common cause of variation, known as control limits. This allowable variation can also result in false alarms. That is, even when no special causes are present, we may be forced to look for the presence of special causes. This false alarm probability is usually kept low by using a signal rule for special causes.

2.4.1 Control Chart Technique

Rudnick (1950) defined a *Control Chart* as a graphic tool, which displays the summary statistic of the characteristics of interest and tests the existence of a state of statistical control in the process. Control limits on a control chart are fixed using probability laws and are different from the specification limits as the specification limits represent the extreme possible values of a quality characteristic for conformance of the individual unit of the product. They are not intended for checking the quality of each unit produced but as a basis for judging the significance of quality variations from time to time, sample-to-sample, or lot-to-lot. If all the special causes are eliminated, then practically all the plotted points will lie within the control limits. The long-term variability and bias are controlled using the control chart procedure, which is designed to be implemented in real time after the baseline and control limits have been established (NIST/SEMATECH, 2008).

The application of the control chart technique in the presentation and interpretation of inspection data has increased the effectiveness of quality control in textile manufacturing. In applied textile research the control chart method can make a valuable contribution. The advantage in the application of this technique lies in increasing the personal efficiency of the research worker. Characteristic of reproducibility can be judged by the establishment of a criterion, which specifies that variation in the data exists due to chance alone or which specifies whether or not a state of controlled conditions has actually been obtained. The knowledge of quality control chart methods facilitates the planning of the comparison. The principles to follow in sampling are emphasized in discussions of the control chart technique, the use of rational subgroups, frequent small samples instead of infrequent large ones and the grouping of data on the basis of the order of production.

Tague (2004) defines control chart as "*a graph used to study how a process changes over time".* Further, she states that in any control chart there is always a central line and upper and lower lines for the averages, upper and lower control limits respectively and these lines are obtained by utilizing the historical data. A process can be determined whether it is in control or out of control based on the position of the process average with reference to upper and lower control limits. A process is said to be out of control if the process average is above or below the upper and lower control limits respectively. According to Tague, pairs of control charts are generally used for variable data with the top chart monitoring the average and the bottom chart monitoring the range. However for attribute data, control charts are used singly.

2.4.2 When to Use a Control Chart

One of the most essential purposes of control chart is to distinguish between the 'common causes' of variation and the 'assignable causes' of variation in order to prevent over-reaction and under-reaction to the process. To first use a control chart in practice, no assumptions of normality or independence over time need to be made. Samples are to be taken over time and values of a statistic have to be plotted. The American Society for Quality (2010) has given a few instances/situations when a control chart can be best used. ASQ

(2010) suggests that a control chart can be used to find problems and correct them on a continuous basis, to predict expected range of outcomes from a process. In addition, control charts help determine if the process is in statistical control, analyze special and common causes of variation in process and help determine if there is a need to prevent these problems or make fundamental changes to the process.

2.4.3 Comparison of Control Chart Methods

With rapid advancements in data acquisition and computing technologies in last two decades, many researchers such as Woodall and Montgomery (1999), Stoumbos et al. (2000), Woodall (2000) points that multivariate control charts would play a greater role in monitoring and improving manufacturing processes. Hence, there is a need for conducting more research to develop new control charts. In order to carry out new research, the available control charts have to be thoroughly studied, compared and analyzed first and developments have to be based on the drawbacks in the existing systems. Reynolds Jr. et al (2011) suggests that large and transient shifts could be effectively and efficiently detected only through the traditional Shewhart control charts and hence, they have widespread applications in manufacturing even today. However, claims made by researchers such as Ben-Gal et al. (2003) clearly indicate that Shewhart control charts are completely ineffective for detecting small changes in process parameters and hence, other types of control charts, such as Exponentially Weighted Moving Average (EWMA) charts, Dynamic EWMA charts, Cumulative Sum (CUSUM) charts, Q-charts came into prominence as they are effective for detecting small parameter changes. In addition, they also state that among these different types of charts, EWMA and CUSUM charts are the most effective for detecting small-sustained shifts.

The first real comparison of control charts can be traced back to the work done by Roberts (1959) who evaluated different control chart schemes available to develop a new control chart called the *geometric moving average chart*. Based on his observations, Roberts suggested that while selecting a control chart for a particular application or a group of applications, the ease and understandability for computing, plotting and testing operations is the most important aspect to be considered. Also, he concluded that the ability of a control chart to provide clues and detect the special causes of variations in a process plays a significant role for its selection and the extent to which a control chart is compatible with corresponding applications has to be considered while selecting control charts. Lucas (1982) declared that beneficial effects can be obtained by adding Shewhart limits to a basic CUSUM, thus creating a new combination of Shewhart-CUSUM scheme.

However, the use of this combined Shewhart–CUSUM scheme was limited to clinical studies and other non-manufacturing applications. Lucas and Saccucci (1990) stated that it was possible to design a Shewhart–EWMA scheme similar to the Shewhart-CUSUM scheme. However, there was not enough literature available to aid in the design of this new scheme. The effect of pictorial representation of different quality control schemes namely Shewhart, EWMA and CUSUM control charts on human (operator) performance has been evaluated in a study conducted by D'Souza and Greenstein (1999). However, they found no experimental validations to show a clear advantage for different types of SPC charts with respect to operative performance based on graphical characteristics. Thomas (2000) studied the *alternatives to Shewhart charts* in his book on statistical methods. He mentions that few researchers considered Shewhart charts to be superior to other types of control charts/procedures. However, he concludes that CUSUM procedures have better overall properties when compared to Shewhart charts and also are not prone to become ARL biased.

According to a study conducted by Ong et al (2004), Shewhart control charts were perceived to be inferior compared to EWMA and CUSUM charts based on their statistical performance. They noted that although Shewhart control charts have been in use for a very long time, EWMA and CUSUM charts gained prominence very rapidly as they had a statistical advantage in detecting small mean shifts. Moreover, they found a distinction in the way the data points are pointed and the out-of-control points are interpreted amongst Shewhart control charts, EWMA and CUSUM charts. Traditionally control charts are designed with respect to statistical criteria (sample size, control limits). According to Rahim et.al, (2002) the use of statistical criteria and practical experience has led, in many cases, general guidelines for the design of control charts.

Woodall and William (2000) claimed that the use of the classical control charts is not widespread in the industry as expressed or implied by some practitioners. Instead of Shewhart control charts, there are other customized control charts suitable for requirements of the industry considered. This theory was re-emphasized by Engin (2004), who stated that although classical Shewhart control charts are heavily used in the textile industry, they are generally used in adapted to suit the needs of the manufacturer, with control limits that are varying around generally accepted as $\pm$ 2% of nominal value of quality characteristic. Whether classical Shewhart charts or some other special charts are used, the application of the control chart technique in the presentation and interpretation of data increased the effectiveness of quality control in textile manufacturing. He claims that, the superintendents and over-seers closely observed the trends several times a week and interpreted the data by giving the percent of "Good," "Warning Region," and "Out of Control" points so that the over-all quality records of a department could be compared from week to week.

Yeh et al. (2004) proposed a new control chart model to effectively monitor small changes of variability of multivariate normal processes. For designing the new control chart, they first studied the evolution of multivariate control charts to monitor and analyze the variability of multivariate normal process. In this study, it was found that the first multivariate control chart originated from the works of Hotelling in 1947. During the 80's there were only a few researchers who working on Shewhart control chart models detecting various changes in the variance-covariance matrix of the related distribution while others worked in areas related to development of control charts that can monitor small shifts in the process mean (Yeh et al, 2004). It was observed that most of the research on development of Multivariate Cumulative SUM (CUSUM) control charts occurred during the late 80's and early 90's (Woodall and Ncube, 1985; Crosier, 1988; Pignatiello and Runger, 1990; Hawkins, 1993), and during the mid 90's researchers shifted focus towards development of Multivariate Exponentially Weighted Moving Averages (EWMA) control charts (Runger and Prabhu, 1996; Prabhu and Runger, 1997). Starting early 2000's researchers started working on proposing new and modified CUSUM/EWMA procedures to detect very small/minor shifts in the process mean (Qiu and Hawkins, 2001).

Literature suggests that there have been many studies carried out to compare Shewhart charts with EWMA and CUSUM charts in the past decade. However, it was observed that most of these comparisons considered only those cases in which a special cause produced sustained shifts in a particular process parameter and ignored sample size '*n*' and sampling interval *'d'* values (Reynolds Jr. and Stoumbos, 2004). On the other hand, there is literature available citing works of different researchers who compared control charts based on values of *n* and *d*. For example, Hawkins (1992) recommended using $n = 1$ as a choice of *n* in a CUSUM chart that is used to detect sustained shifts in μ. Almost after a decade, researcher Montgomery (2001) conducted a similar study and gave recommendations on using $n = 1$ as a choice of *n* in the CUSUM charts. Although both these research works had similarities in terms of work conducted and results claimed, both these works did not provide any numerical results to validate their hypothesis. $n =1$ is the most preferred choice for a CUSUM chart (Hawkins and Olwell, 1998). However a value of $n > 1$ being a more efficient choice has been stated by Prabhu *et al.* (1997). In case of CUSUM charts, Stoumbus and Reynolds (1996) suggested various values of *n* and *d* that can detect sustained shifts in μ. Reynolds (2004a) recommended using $n =1$ for both non-normal as well as normal process data after studying choice of *n* in various CUSUM charts used to detect sustained shifts in μ.

Feng and Kapur (2009) discussed in detail why Shewhart control charts are not effective at all times especially in textile manufacturing. He explained this through an example by discussing the inspection of defects in a fabric with varying sample size. In a roll of fabric, some areas may have higher number of defects compared to the other areas and thus if you consider a variable sample size for inspecting a dyed fabric, the number of defects would vary from sample to sample within the fabric/ selected. Thus, he claims, for applying Shewhart control charts the only feasible option is to monitor the average number of defects per inspection unit in a sample. He then discussed how effectively EWMA and CUSUM control charts can be applied in the cases where there is a need to detect these small, variable process parameter defects. He also suggests, as other researchers pointed out earlier, that Shewhart control charts is a memory less process as it ignores the previous information given by a sequence of points and hence, it is insensitive to small shifts in a process.

Table 1 below provides the Pros and Cons of the most frequently used control chart methods in textile manufacturing. It can be clearly observed that in all of the control chart methods, there is a common disadvantage – which is absence of structural equations in the design. This clearly indicates that none of the control chart methods that are extensively applied in textile manufacturing today have utilized any scientific/research findings in textiles from the past 100 years that is available. Also, it is observed that most of control chart methods are not custom built to suit the dynamic nature of textile processing, where biases and variances occur both intrinsically and extrinsically. The table also indicates that there are more disadvantages in each of the control chart methods when compared to the advantages, which can be partially attributed to the lack of profits gained by manufacturers despite spending huge amounts of money on these quality control systems.

Table 1. Pros and Cons of the most frequently used Control Chart Methods in Textile Manufacturing

Chart	Pros	Cons
SCC	• Simplistic • Effective for detecting large sustained shifts and transient shift • Uses immediate control for statistical testing	• Static • Ineffective for detecting small changes in process parameters • Memory-less process – Ignores past information from the process • Produces frequent false alarms • Unwarranted process calibrations • No usage of structural equations involved in the design
EWMA	• Flexible, similar to CUSUM Chart Highly effective for detecting small parameter changes and sustained shifts • More sensitive to Out-of-control conditions Dynamic in nature – 'Prior' process knowledge can be incorporated • Increase in number of early false-alarms • Can be used for forecasting/feed-forward control	• Loss of information can be significant when 'n' is small • Ineffective for detecting large sustained shifts • Can be misleading under even a low degree of time dependency • Observations should be independent and uncorrelated • No usage of structural equations involved in the design

Table 1. Pros and Cons of the most frequently used Control Chart Methods in Textile Manufacturing (cont'd).

Modified EWMA	• Effective for detecting small parameter changes and sustained shifts • Useful in short-production runs • Dynamic in nature – 'Prior' process knowledge can be incorporated • Detects shifts much faster than SCC and EWMA • Provides clean picture of process chang	• Loss of information can be significant when 'n' is small • Ineffective for detecting large sustained shifts • Can be misleading under even a low degree of time dependency • Observations should be independent and uncorrelated • No usage of structural equations involved in the design
Q-Chart	• Effective for detecting small parameter changes and sustained shifts • Effective for short-production runs • Maintains false-alarm rate even when parameters are unknown	• Cannot detect large shifts • Hard to analyze special patterns • Yields relatively wide control limits • Ineffective in early detection of process disturbances • No usage of structural equations involved in the design
CUSUM Chart	• Effective for detecting small parameter changes and sustained shifts • Highly effective for short-production runs • Powerful in detecting small shifts	• Complex and difficult to interpret • Ineffective for detecting large parameter changes and sustained shifts • Special patterns are hard to be seen and analyzed • Poor power for early and late structural changes • No usage of structural equations involved in the design

2.5 Investigation of Quality/ Process control parameters that influence textile processing sequences

Several studies have been published in the literature that discuss the influence of quality/process control parameters on processing performance and production capabilities of textile dry and wet textile-processing sequences. However, most of these studies are still far from providing a comprehensive list of all or atleast most significant parameters that have a major influence on dry and wet textile-processing sequences. One of main reasons for this inadequacy is that these studies are generally carried out using empirical models or regression analysis to describe the influence of a particular quality/process parameter or in some cases, a select few parameters that influence processing. An abundant amount of studies can be found in the literature that demonstrates the relationship between cost of raw material and overall processing costs and/or profits. However, many other parameters such as properties of raw material, level of technology, machinery and skill of machine operators etc. are not covered in the literature extensively as they are considered to be not so significant by many researchers as it is difficult to create an empirical model describing the relationship between these parameters and over all profits.

Quality attributes that define raw material properties significantly influence the overall production costs or profits of entire textile chain as they can lead to yarn imperfections (neps, thick and thin places), an important yarn parameter that affects both yarn and fabric processing. A yarn with more imperfections will exhibit poor appearance grade, lower strength and poor performance in weaving and is likely to produce fabric with low quality. This leads to inconsistent dye uptake in fabric causing defects such as visible streaks in the final garment (Hebert et al 1986, 1988; Ochola. J et al, 2012). Hence, it is of paramount importance to investigate extensively quality and process parameters such as raw material, level of technology, machinery, skill of machine operators, mass variations, imperfections etc. to be able to understand the actual causes of biases and variances occurring in both dry and wet textile processing sequences.

2.5.1 Quality/ Process control parameters that influence Spinning process

The simplest definition of spinning according to Marsh (1953) is the joining of short fibers by drawing them from a loose fibrous mass and twisting them together. Although the yarn production process differs depending on the spinning system, it primarily involves opening, cleaning, blending, carding, drawing, spinning and winding. Various fiber parameters are of high significance in processing and end use, and hence fibers with the required properties should be selected and processing should accommodate these parameters adequately. For example, fiber diameter is important in dyeing behavior; fiber length determines the choice and adjustment of machinery and is important in producing uniform; strong yarns with less ends down in spinning from low staple length fibers; fiber immaturity in cotton leads to inferior spinning performance and lower-quality yarns and fabrics; color is important, since the presence of discoloration has a detrimental effect on dyeing etc.

Especially at the mixing stage the fiber properties play a key role during processing. At mixing the basic requirement for implementing a reliable fiber selection technique is the quality of the parameters describing a cotton bale and this quality is determined by several factors, including the measuring technique used, data produced and reliability and reproducibility of the data. The parameters to be determined at the mixing stage are: fiber fineness (micronaire value), fiber length, length uniformity, strength, break elongation, color and trash. Variability in fiber length, short fiber content, trash particle distribution and nep distribution are also determined. Population variability is a critical factor in determining blend uniformity.

Fine fibers can be spun to fine counts, giving more uniform, stronger yarns for the same count, with less processing difficulty than inferior fibers. Quality control assists in the selection of fibers, the verification of fiber properties, the selection of the appropriate processing sequence and the blending of fibers. Various fiber properties provide the necessary input process averages and variances of the subsequent output processes. The literature has been surveyed and the most important and essential properties of fiber clusters at each processing stage of spinning have been listed in the table below (Table 1).

Based on the factors involved, structural equations between the input and output parameters were identified. Well-known properties of fiber clusters are considered and their changes are traced between any two successive stages through the established relationships.

Table 2: Key fiber parameters that influence the spinning processes.

Process	Input Parameters	Output Parameters
Mixing	1. Fiber fineness variation 2. Fiber length 3. Strength 4. Maturity 5. Trash Content 6. Color	1. Material variation 2. Length uniformity 3. Breaking elongation 4. Short fiber content 5. Nep distribution 6. Color
Blow room	1. Fiber web thickness 2. Fiber web density 3. Fiber alignment 4. Flock sizes 5. Quantity of material 6. Cleaning resistance	1. Material quantity variation 2. Quantity of material
Carding	1. Impurities 2. Neps 3. Fiber length distribution 4. Fiber orientation	1. Sliver mass 2. Fiber orientation 3. Linear Density 4. Waste %
Drawframe	1. Sliver properties – Fiber orientation, Mass, Linear density, Uniformity 2. Grams/meter of sliver fed 3. Neps 4. Hook distribution 5. Number of doublings 6. Cohesive friction between fibers 7. Total draft	1. Linear density of the strand 2. Fiber orientation 3. Waste % 4. Drafting waves

Table 2: Key fiber parameters that influence the spinning processes (cont'd).

Speed frame	1. Feed uniformity of fiber to the creel rollers 2. Drafting arrangement 3. Total draft 4. Cohesive friction between fibers 5. Delivery speed	1. Twist & mass uniformity of roving 2. Amount of twist 3. Output speed 4. Centrifugal tension formation 5. Piecing variation 6. Strength of sliver
Ring frame	1. Required count 2. Roving properties 3. Uniformity of yarn-twist, mass, strength	1. Yarn characteristics – count, twist, strength, hairiness etc 2. Uniformities 3. Amount of yarn delivered 4. Number of stoppages

2.5.2 Quality/ Process control parameters that influence Dyeing process

Dyeing is the last stage in the manufacturing of yarns and fabrics, which plays an important role on the final appearance of goods. Process control is highly essential in any continuous processing and more-so in a process as complex and dynamic as dyeing, where several factors could possibly affect the uniform distribution of a shade within a dyed yarn/fabric. Factors such as *raw material characteristics*, *equipment design* and *environmental conditions* influence the process (Vickers, 1954). Also, *variations in materials*, *equipment*, *controls*, *process*, *human factors*, and *logistics* affect the distribution of dye in the dyebath resulting in a non-uniform yarn/fabric.

The fiber composition and variation of textile/raw materials need efficient and effective process optimization methods to adjust the fluctuating input of the materials.

Consider the classic case of mass variations in a yarn sample that needs to be dyed. These variations in mass create nonrandom periodic irregularities causing visible streaks on the woven fabric appearance. Limit of each step in the process is reflected in the results of final dyeing and any failure to control the dyeing operation may be disastrous for dyeing. Therefore, it is critical to monitor and control the dyeing process by identifying and evaluating the quality and process control parameters that influence dyeing as objectively as possible to achieve uniform and optimum dyeing (Gunay, 2009).

Dyeing process parameters such as *temperature, pH, rate of temperature rise and cooling, rate of uptake, dwell time* and *liquor ratio* have been widely known, documented and monitored for many years. Casselman (1980) discussed about the influence of *amount of water used*, *amount of chlorine* added to treat water on the *pH* of dye bath in the dyeing process. Aspland (1981) suggests that the three major variables involved in the complex dyeing process are the *physical and chemical natures of the dye*, the *dyebath (including pH)*, and the *textile material*. In addition to these, he remarked that the quality of the final product is also affected by factors such as *dyeing time*, *temperature, rate of temperature increase*, and *machine type*. The chemicals used in the dyeing process are mostly *complex organic compounds,* which are capable of influencing the absorption capability of a dye. Also, hardness of water and temperature of water used in dye bath have an influence on the *pH* of dye bath (Datye and Vaidya, 1984).

Nobbs (1991) states that *pre-defined variation of temperature, flow, addition of dye* and *other process chemicals* are the essential process controls in a conventional dyeing process. As per Perkins (1991), *temperature* is the most influential parameter in the dyeing process. He discussed how cotton, rayon, and nylon dye well at temperatures 100°C or lower, while polyester and several other synthetic fibers dye more easily at temperatures higher than 100°C. *Structure of the dye* used and *particle size of the dye* can also considered as significant factors that could influence the *dye bath pH* and hence, the dyeing process (Weatherall and Needles, 1992).

Koksal et al. (1993) suggest that the controllable factors for dyeing control include *dye concentration, pH, temperature, pressure, process time, amount of fabric, characteristics of dyes, chemical and water*. They used the case study approach to propose a method to identify the optimal batch dyeing process parameters and stated *liquor ratio, amount of dye, salt concentration, alkali concentration, dyeing temperature, time before adding alkali and agitation rate* as the factors that have the most influence on dyeing process and which are controlled by the design engineer. Smith and Lu (1993) discussed about the influence of controllable factors such as *dye concentration, pH, temperature, pressure* and *process time* on the *control and uniformity of dyeing*. Further, they listed the typical properties that were being monitored/ controlled by most control systems listed below in Table 3.

Table 3. Typical properties monitored/ controlled by most control systems

Material	**Machine**
Weight	Pump speed
Moisture content	Width
Density (cloth/package)	Number of actions
Pre-shrinkage	Volume of bath
Twist (fabric)	Temperature
Liquor ratio	Humidity
Tension	Flow direction
pH	Cycle time
Affinity to Dyes/Chemicals	Over/under feed rate
	Nip/ Differential pressure

Gilchrist and Nobbs (1997) devised a new method of dyebath analysis in which they studied the factors that affect the measured absorbance of dye. In this study, they concluded that *dye concentration, dye bath temperature, electrolyte concentration* and *pH* have a significant influence on state of aggregation of the dye. However, the factors *dye concentration*, *pH,* and *temperature* have the highest effect on the shade and coloration uniformity of dyed goods (Huang & Yu, 1999). Xin et al., (2000) investigated the influence of a number of parameters such as *dyebath pH, amount of salt, immersion time, number of dips*, *oxidizing temperature, concentration of wetting agents,* and *soaping temperature* on the color variation in the dyeing of denim yarn with indigo. They concluded that each of these parameters had varying influence on the resultant color obtained on the samples dyed.

Michel K-H (2000) stated that *heat* is the catalyst that could hasten the dyeing process. Factors such as *type of material to be dyed, type of dyes used* and *type of water* (depending on location of plant) plays a key role in deciding this critical range of temperature. *Temperature, pH of dye liquor, addition of leveling agents and/or agitation agents* influences evenness or levelness of dyeing. Also, c*hanges in dye-liquor concentration*, *temperature, time* and *liquor ratio* significantly impact the color change during processing. Moreover, process parameters such as *thermal gradient, pH product concentrations,* and *characteristics of the circulation cycles of baths in the presence of builders* influence the efficiency of dyeing operations. According to him, when heat is supplied for certain period of time fibers swell allowing better dye penetration and thus the rate of transfer of dye molecules to the substrate is improved. He experimented with effect of varying temperatures on dye-uptake by fibers and concluded that uptake of dyes by textile fibers occurs at temperature called as critical range of temperature.

Factors such as *selection of dye*, *aggregation*, *degradation*, *sedimentation*, *weight of auxiliaries*, and *washing time* may have some influence on the pH of the dye bath and hence, on the dyeing process (Iksender et al, 2005; Kim et al, 2005; Saraf et al, 2007). Zhao et al (2006) state that the *rate of dye uptake by fibers* and *the levelness of dye distribution throughout the package* are the two important parameters which have to be studied in order to evaluate the quality of dyeing. Smith (2007) reviewed a large body of work related to the control methods, modeling, analysis, and dyebath monitoring that can ensure consistent results for dyeing processes.

Based on the literature search, he came up with a large fish-bone diagram of variables that affect shade repeatability in yarn dyeing. According to him, the parameters that influence the *dyeing process are bath ratio, rate of circulation, dyeing velocity, micronaire/maturity or denier of fiber, shape of fiber, distribution constant of dye, standard affinity of dye, absorption and desorption rates of constant for dyes, fabric construction, fiber content in fabric and yarn type*.

Gorensek et al., (2008) conducted research on the parameters that influence the dyeability of cotton warp for dip-dyeing process. Their research shows that *dyebath temperature*, *dyebath pH*, and *addition of a salt to the dyebath* have significant influence on the color, color yield, and rub, wash, and lightfastness of indigo dip-dyed cotton warp. Huheey (2009) discussed about the importance of *variety of auxiliaries* that are added to disperse the dye molecules in a solution and to enhance the rate of dyeing. Further explaining the mechanism, the researcher claimed that either through circulation of the dyebath or circulation of the textile, these auxiliary substances move to the surface of the textile fiber and attach to the porous surface of the fiber. In case of reactive dyes, *alkali concentration, temperature* and *time* are the most important parameters that affect the color yield (Beech, 1970).

Park and Shore (2009) identified the numerous factors, which have to be controlled to achieve satisfactory reproducibility in dyeing. They classified these factors into two categories based on the level of their importance. Table 5 below gives a list of some of the factors of major and minor importance. Some of these factors could be controlled directly within the dyehouse whereas others cannot be influenced by dyer or in the dyehouse. Gunay (2011) researched a group of principal factors that affect the dyeing reproducibility at various stages of dyeing processing and concluded that while *dyebath temperature and pH, dye concentration, conductivity, exhaustion profile and time of dyeing* were the most influential parameters during the dyeing process, *weight of substrate, moisture content of the substrate, weight of dyes, dyebath color, liquor-ratio, amount of salt, weight of chemicals and auxiliary products* can be considered the most significant amongst all parameters during pre-dyeing stage. He classified these parameters into two categories – factors of major and minor importance that require control in the dyeing.

A list of key process parameters that influence the dyeing process and respective factors that are influenced in the dyeing process have been summarized in the Table 6 below. From this table we can conclude that among these process parameters, ***Raw material characteristics, Temperature, Dwell time, Dye concentration, Liquor ratio*** and ***Dyebath pH*** can be considered as the most important or the most influential parameters. The theories and claims made by researchers across the globe about the influence of these key parameters on the dyeing process and the need to control these controllable parameters in order to achieve desirable quality and uniformity in the final dyed products can be easily validated with the help of structural equations. The use of structural relationships and functions in mathematical modeling and computational analysis of the dyeing process provides a powerful tool to investigate and understand the link between the factors that significantly influence the dyeing process. This provides valuable information regarding factors that influence the final outcome of the dyeing process.

Table 4. List of Process Parameters that influence and factors that are influenced in the Dyeing

Researcher	Parameters which can influence dyeing process	Factors which are influenced in dyeing process
Vickerstd, 1954	**Rawmaterial characteristics**, Equipment design, Environmental conditions	Process
Beech, 1970	Alkali concentration, **Temperature**, **Time**	Color yield
Aspland, 1981	Physical and chemical natures of the dye, **Dyebath pH**, Rawmaterial, **Time**, **Temperature**, Rate of temperature increase, Machine type	Quality of final product
Datye and Vaidya, 1984	Chemicals used in dyeing	Absorption capability of dye
Nobbs, 1991	**Variation in temperature**, Flow, Addition of dye and other process chemicals	Process controls
Perkins, 1991	**Temperature**	Process
Smith and Lu, 1993	**Dye concentration**, **pH**, **Temperature**, **Pressure**, Process time	Control and uniformity of dyeing
Koksal, 1993	**Dye concentration**, **pH**, **Temperature**, Pressure, **Process time**, Amount of fabric, Dye characteristics, Chemicals and water used, **Liquor ratio**, Amount of dye, Salt concentration, Alkali concentration, Time before adding alkali, Agitation rate	Control of dyeing
Gilchrist and Nobbs, 1997	**Dye concentration**, **Dye bath temperature**, Electrolyte concentration, **pH**	State of aggregation of the dye
Huang and Yu, 1999	**Dye concentration**, **pH**, **Temperature**	Shade and coloration uniformity of dyed goods
Xin et al, 2000	**Dyebath pH**, Amount of salt, **Immersion time**, Number of dips, Oxidizing temperature, Concentration of wetting agents, Soaping temperature	Resultant color obtained
Michel K-H, 2000	**Type of material to be dyed**, Type of dyes used, Type of water	Critical range of temperature
	Temperature, **pH of dye liquor**, Addition of leveling agents and/or agitation agents	Evenness or levelness of dyeing
	Changes in **dye-liquor concentration**, **Temperature**, **Time**, **Liquor ratio**	Color change during processing
	Thermal gradient, **pH**, Product concentrations, Circulation cycle characteristics	Efficiency of dyeing operations
Zhao et al, 2006	**Dye uptake rate**, Levelness of dye distribution throughout the package	Quality of dyeing
Smith, 2007	**Bath ratio**, Rate of circulation, Dyeing velocity, **Raw material characteristics**, Dye distribution constant, Affinity and Enthalphy of dyeing, **Absorption and Desorption rate constrants**, Activation energy	Dyeing consistency and process efficiency
Gorensek et al., 2008	**Dyebath Temperature**, **Dyebath pH**, Additional salt in the dyebath	Color, color yield, rub, wash and lightfastness
Huheey, 2009	Variety of auxiliaries/ chemicals	Rate of dyeing
Park et al, 2009	**Liquor to goods ratio**, Weight of electrolyte, Weight of Auxialiary products, **Time of dyeing**, **dyebath pH**	Reproducibility in dyeing
Gunay, 2009	Variations in Materials, Equipment, Controls, Process, Human factors, Logistics	Distribution of dye in the dyebath
Gunay, 2010	Dyebath temperature and pH, Dye concentration, Conductivity, Exhaustion profile and Time of dyeing	Reproducibility during dyeing
	Weight of substrate, Moisture content of the substrate, Weight of dyes, Dyebath color, **Liquor-ratio**, Amount of Salt, Weight of chemicals and auxiliary products, **Temperature**, **pH**, Rate of temperature rise and cooling, Rate of dye uptake	Reproducibility during pre-dyeing stage

2.6 Current Scenario of Quality Control Systems in Textiles

Textile, apparel, and furnishing companies are currently competing in a market that has changed considerably in the past few decades. Post WTO agreement in Textile and Clothing that ended the quota regime in 2005, the global marketplace has increased competition throughout the textile industry. In a world of global marketing, compliance with international standards for quality in conjunction with various international certification standards has become of paramount importance to manufacturing companies across the globe. Textile companies are more than ever faced with the challenge to produce better quality products, faster and at reduced costs. Now-a-days quality is such an important commodity to both consumers and producers that it has become a goal within many companies. These companies are making every effort to achieve control of their manufacturing processes from dyes and chemicals usage to machine efficiency to operator performance; from inventories to on-time deliveries. Every aspect of the process is being analyzed in an effort to improve quality and to optimize productivity. This is true whether they are involved in producing materials or finished products or they are involved directly with the customer. Hence, manufacturers now prefer controlling the system that produces the product to control of products.

Suh (1992), in one of his earlier papers criticized the textile manufacturing and processing industry which has been over-emphasizing the need for quality control on product quality and defect detection rather than defect prevention through process control and quality improvement. He coined the terms: a '*random-walk' processing sequence* for textile processing sequences which are independent of one another and which do not affect the process averages and variances of the subsequent stages at any given stage and a *'non-random walk' processing sequence* as the one where the process averages are structurally tied to each other through dimensional and physical relationships and the magnitude and direction of the process error at a given stage are likely to influence those of the subsequent stages. Fabric width, shrinkage, and mass per unit length of fiber assemblies in multistage textile processing constitute *non-random walk* processes.

According to Glowacki (1970), methods for statistical quality control (SQC) are applied broadly in many industries and in textile industry these methods were successfully introduced in 1924 in the United States of America, in 1929 to 1932 in Germany. In his study, he observed that the control chart methods are widely employed for *"controlling raw material*, *irregularity of semi-finished products (sliver, roving, yarn)*, *ends-down* (*roving, yarn*), *faults* (*sliver, roving, yarn*), *yarn quality and spindle stoppages*, *yarn breakages on winding machines*, *operator efficiency*, *production/shift-hr"* in a spinning mill. Moreover, he discussed that traditional Shewhart control chart methods (such as $\overline{X}$ *& R*) have been employed in a cotton-spinning mill for applications such as *"monitoring the weight of laps*, *monitoring lengths of sliver delivered into cans*, *monitoring fineness of sliver, roving and yarn*, *count of yarn"*. Besides, he also pointed out that application of control chart methods is far-too less in a weaving shed when compared to a spinning plant. Nevertheless, he observed that control charts are applied for *"testing incoming lots of yarn*, *analyzing and controlling the faults in grey goods*, *qualitative classification of yarn packages from winding machine* and *analyzing stoppages of looms*, *yarn-breaks during weaving*, *operator efficiency*, *production/shift-hr."* in a weaving shed.

As EWMA charts are generally useful for detecting small changes, he indicated that they were mostly used in situations when small lots of material were processed and when there was a need for frequent changes in scale of a control chart. Hence, EWMA methods were recommended for worsted spinning mills, especially where there is a frequent change of the nominal count in production on a given machine. With the advent of affordable computers, sensors, fast testing equipment, and control technologies, a new and innovative system aimed at improving the profitability of textile operations is the need of the hour. Suh (2002) further suggested that if the profit margins of the U.S. textile industry have to be improved then the industry has to learn how to reduce and contain the huge variations imbedded in the *random walks* of textile processing. Also, he believes that a drastic change has to be made in the way the quality is measured, controlled, accounted, and optimized in order that a textile operation may be competitive regionally and globally.

In textile manufacturing industry, loss resulting from high variability can be defined as a loss to society, which can be associated with every product that is shipped or transferred to a consumer. The user of the fiber is the spinner, the user of yarn is the weaver, and the chain continues down to the consumer of the apparel or any textile product. Thus, each intermediate operation in a textile manufacturing line should be considered as an independent entity even though they are contiguous in nature.

Historically the producer's perspective of quality has always been in terms of product process performance, while the consumer's perspective has been and continues to be, in respect to overall quality attributes that have significant impact on product performance or application (Kadolph, 1998). Hence, accurate measurements and efficient quality control systems have become the key elements in meeting customer requirements and achieving the overall company business objectives for almost every textile manufacturing company. According to Dunn (2003), automation and a push towards on-line quality control systems have taken root in the textile industry. The capacity to implement on-line based quality control systems in manufacturing of textiles can be attributed to the tremendous progress achieved in the development and implementation of electronic instrumentation and sensor technology over the last two decades.

Due to global demands for quality textile products, an array of on-line technologies is used in wet processing, fabric and yarn inspection, winding, spinning preparatory, fiber blending, and so forth. The large amount of data involved in on-line tests presents a challenge to textile firms, and to address this problem, Suh (1994) proposed using fingerprinting techniques to capture only extreme deviations. A combination of on-line and off-line tests are recommended for spinning firms due to sampling inadequacy in off-line tests and lack of availability of on-line tests on a number of yarn quality characteristics. According to Atilgan (2007), Uster® Statistics have become the most important and widely used quality standards in spun yarn manufacturing as these standards are specific to yarn markets for consistent use in yarn process control and market transactions. However, on-line quality evaluations currently in use in the yarn manufacturing industry i.e., Uster® Ring

Expert systems and similar competing technologies, are limited only to monitoring yarn end breaks and efficiency for a single process at a given time.

Despite using these systems, manufacturers have not been able to efficiently combat the rising costs of production, pushing them towards deploying additional on-line measurement systems. Unfortunately, control on quality and cost are a must in textile production to be able to sustain today's competitive global markets pressure. According to Peters (2003), most of the current on-line systems lack the provision of real and quick opportunities for detection of off-target production units while allowing for timely machine adjustments within the product quality and productivity specifications. He further states that there is a need for on-line measurement and continuous monitoring of yarn quality parameters in real time to reduce the need for expensive off-line quality tests.

Adopting an efficient and effective quality management system in spinning mills requires quality characteristics and reference values in order to assess the quality levels. Quality characteristics belong to those of fibers and yarns which form the input and output of any spinning mill and the reference values belong to those of the processing itself, irrespective of whether it is an online or offline monitored process. The literature, which has been collected during the course of many years in the textile industry, must also not be underestimated. According to Azzam et.al (2005), the most important yarn quality characteristics where variations occur are "*nep content in cotton fibers, count variation, mass variation, thin places, thick places, neps, hairiness variation, tensile force variation (which are measured offline) and actual efficiency value, production per spindle hour, yarn breaks /1000 spindle hr., production loss due to yarn breaks, break-free yarn length, mean yarn break duration, splice and knot frequency (which are measured online)*". These variations could be influenced by variation between samples, measuring sensor calibration and accuracy, and environmental conditions. The factors that could cause variations in these quality characteristics in a spinning plant could be lack of quality systems and quality ethic, ineffective maintenance systems, ineffective process and operational control systems and ineffective investment and replacement policy of quality control systems.

Moreover, within the spinning process, there have been changes during the last few years. Azzam et al., pointed out that personnel having less knowledge about the raw material are being employed which was not the case earlier. They believe there is a need for people with sound technical knowledge in both operations and management in a spinning mill as there has been a rapid increase in automation of machinery in the past two decades. Furthermore, spinning mills have become capable of producing twice the amounts of their current production capacities in half the time. Although, there is a need to increase the production capabilities because of the global competition, higher and quicker production leads to severe stress on fiber than it was ever before. They further claim that, owing to sky-rocketing of raw material prices in the past few years and increase in competition at global level, there is a definite demand for "*production of zero defects within a batch delivered according to specifications"* from the yarn buyers.

Also, in the last 20 years there have been significant changes in the weaving and knitting processes. The production of woven or knitted fabric per machine increased by 2-3 folds because of the increase in machine speeds and fabric widths. However, high production does not necessarily imply good product quality as increase in production rate sometimes has adverse effects on quality of goods manufactured. In order to maintain low costs and achieve high efficiency, it is quite necessary to decrease the unproductive downtimes, such as stops due to end breaks. Also, it is quite necessary to ensure production is achieved under better economic conditions. Zhu et.al (1996) pointed out that the problem of weak places has gained more and more importance in this recent past, especially after the advent of high-production spinning and weaving mills as they negatively influencing the running efficiency. Despite several investigations being carried out in the past few years, single conclusive evidence could not be traced out to find why this problem occurs and what needs to be done to solve this issue. Importance of this issue has grown because the weak spots produce machine stops later during weaving or knitting processes.

According to Gopalakrishnan et.al, (2010), there are many aspects of garment quality characteristics based on which the garment exporters work. Quality related problems in garment manufacturing such as overall look, formation, feel and fall, physical properties, color fastness and finishing properties should not be overlooked. The quality parameters that generally affect the quality during dyeing and finishing of garments are poor color fastness properties, staining, tendering, yellowness and improper finishing effect (Parmar et.al, 2010).

2.7 Reasons for the Failure of Quality Control Systems in Textile Manufacturing

Although the production efficiencies in most of the continuous processes have gone up substantially as they are being equipped with automation modes such as sensors, microprocessors and control software and hardware, the process qualities have not improved significantly. As mentioned earlier, many researchers believe the main reason behind this is the '*static control'* systems and methods wherein each processing stage is controlled independent of other stages in the multi-stage control units. Under a static control mode, the control limits at a given stage are fixed and non-reactive to the dynamic changes of the previous stages. Thus, an error or bias introduced in one stage may cause all of the subsequent stages to be out of control, often shutting down the entire unit. Experiences have shown that the only practical remedy for this situation is to widen the control limits for all of the subsequent stages. By continuing the practice, however, all control limits become so wide which make the so-called statistical limits useless.

In textile manufacturing, the most common procedure employed to deal with an out-of-control situation is backtracking of the problem to determine where the problem began and in the cases where the problem is identified at a previous processing stage, necessary corrective actions are taken. This method of identifying and determine the causes of variation is known as feedback control. Friauf (1998) termed feedback control as mere guesswork rather than an effective corrective action and further stated that feedback control although helps in determining the cause of a particular problem, is often accompanied by over control and unwarranted process calibrations due to the contiguous nature of textile manufacturing. The Dynamic EWMA control chart procedure was considered as an immediate remedy to the problem of frequent false alarms and unwarranted process calibrations caused due to the application of static control systems in a continuous and dynamic textile processing environment by researchers such as Wassermann (1994). However, different researchers Olorunniwo (1989); Chellamani and Chattopadhyay (2000) pointed out that EWMA control chart procedure was effective only for a short-run process control situations. In addition, as there was no reference to the biases generated by prior process, this procedure forces one to examine the current process average only against the target completely ignoring the biases generated from prior processing stages in a contiguous/continuous manufacturing environment. This undoubtedly is a completely inefficient control process.

Research shows that there has been a significant development in the textile science and engineering areas for last 10 decades. Articles on the statistical quality control of textile yarn manufacturing products such as sliver, roving, and yarn date back to the late 1940s and 1950s. In these articles, the emphasis is on product quality and defect detection rather than on defect prevention through process control and quality improvement. Unfortunately, the same is generally true even today. Electronic controls and monitoring, when used correctly and effectively, can be a valuable asset in defect prevention and SPC. However, the problem with most continuous electronic controls (for example, feed-control autolevellers for carding and drawing) is that adjustments are made on predetermined target values. This is in contrast to properly using statistical control limits to determine when to take corrective action. This leads to far more variation through over-control than the variation, which would occur when the process is controlled manually through the use of control charts. This is typical of why SPC has not been more successfully implemented in textile manufacturing operations.

The final and the most important reason for the failure of SPC methods is the lack of application structural equations in the design of the control systems. Unfortunately, in most cases, researchers consider the non-structural form of equations, i.e., regression models which actually are not structural and functional equations or any reduced form of structural model to explain and analyze the effect of various fiber properties on the different processing stages. As the regression models are atheoretical they cannot be equated with the ordinary structural/ functional relationships and equations of any form. The “models” so-called, are not truly models in the sense that they are often population dependent, remote from physical modeling, not suitable for repeated predictions and most of the times are based on invalid assumptions (Devore and Peck, 1996). The traditional regression analyses assume that there is no specific numerical relationship linking the so-called independent and dependent variables.

But, we often know a lot more about the process or product in terms of the physical science and engineering relationships/equations only. To summarize, the following are some of the most common shortcomings in above-mentioned most frequently used quality control systems:

- Memory-less processes
- No structural equations/models incorporated in the design
- Produce frequent false alarms, generate unwarranted process calibrations
- Either ineffective in detecting small shifts or large shifts
- Feed-back control leads to instability and guess work rather than an effective corrective action.
- No significant cost reduction or increased benefits
- Based on process variances only

Hence, a novel method that can determine the exact root-cause for every out-of-control situation is the current need of the hour. Moreover, using the existing systems it is highly impossible to provide early warning to operators and manage out-of-control situations in processes, as the existing systems do not handle continuous output value

Chapter 3

Research Methodology

3.1 Purpose of the study

In order to address the above-mentioned shortcomings in most frequently used quality control systems in the textile industry, it is necessary to develop newer technologies as well as optimize the use of available technologies. The current trend of shorter processing sequences, higher productivity and more automation accompanied by removal of many quality safeguards that increase the risk of producing an unacceptable product has to be reversed. This research study is an attempt to aid the textile producers and manufacturers (both domestic and international) to increase their competitive position in the globe by focusing on ways of reducing quality costs in their respective unit operations especially in a competitive market or in an environment a recession. The quality control tool presented in this research study is not without limitations, but it is an attempt to create a novel technology to address and improve the current quality issues and challenges faced by the U.S. textile industry as it continues on its journey into a competitive landscape and also on a path to recall and improve its domestic manufacturing.

3.2 Research Design

This novel system incorporates structural equations based on certain key process parameters from the literature, application of a combined feedback-feedforward system and simulation techniques in its design. It provides process averages and control limits based on the biases and variances generated at the current and prior processing stages. The prototype of this system can also be widely applied for quality control in various other manufacturing environments where the processing sequence is either continuous or contiguous in nature.

This research work was divided into three key phases. In the first phase, a huge amount of literature was surveyed to critically evaluate the quality control charts that are currently in use in continuous manufacturing and the key loopholes in each of those systems was identified.

This has already been discussed in detail in Chapter 2. Phase II of the research involved identifying the key theories and concepts that would address those drawbacks and loopholes in existing systems. These theories and concepts are then systematically incorporated into the design of the dynamic quality control system. Section 3.4 below discusses in detail the development of theoretical framework of the dynamic quality control system and section 3.5 details the schematic representation of the newly designed control chart system. Accurate illustration of this novel quality control system was carried out using application examples in Ring Spinning and Continuous Dyeing processes in the last phase.

In Chapter 4, a complete description of the application of this control system to Ring Spinning and Continuous Dyeing processes is illustrated. Chapter 5 discusses about the validation of this system and graphical representation of the concept. A structural equation that forms a relationship between key input and output variables in continuous dyeing process has been selected and data is simulated that reflects real-time dye-house processing data. Variance of output parameter determined through mathematical calculations and computer program MS Excel were then compared using the simulated data. As the mathematical calculations are based on the concept of Dynamic Process/Quality control, the comparison of output parameter variances serves as a validation factor.

Lastly, a computer program was written in HTML5 programming language and a dynamic application programming interface (API) Highcharts has been used to demonstrate the graphical representation of Dynamic Process/Quality Control Chart.

Phase I: Review of Literature

Review of existing quality control systems – Drawbacks of the current systems – Identifying structural equations based on key process parameters

↓

Phase II: Development of theoretical framework

Incorporating 5 key concepts into the design of Dynamic Quality Control System – Schematic representation of Dynamic Quality Control System

↓

Phase III: Illustration of DQCS using case study examples

Application of Dynamic Quality Control System to Ring Spinning and Continuous Dyeing processes

Figure 2: Research Design for Development of a Dynamic Quality Control System

3.3 Definition of a Dynamic Quality Control System

Monitoring the unpredictable and fluctuating quality variations, diagnosing these variations and adjusting the process at the right moments are one of the key challenges faced by quality personnel and plant managers in a continuous manufacturing sequence. An ideal way to deal with such quality and process control challenges is to implement a dynamic quality control system. "*A dynamic control system is a system that responds to normal and abnormal system conditions continuously, acting upon the system quantities as determined by measurement of system parameters, thus enhancing the system stability*" (NPCC, Document C-33).

King (1989) proposed a dynamic control method that combined concepts from *"statistical control principles, time-series analysis using exponentially weighted averages, projection pursuit and limit-cycle engineering ideas"* as he believed that conventional Shewhart charts either overestimate inherent process variation and/or underestimate true process capability. Both of these cases are undesirable as they either result in non-optimum control or result in loss of control sensitivity. A key feature of a dynamic control system is that it does not assume the process to be stable and hence, local estimates for mean and standard deviation are made for each sample. According to King (1989), the main difference between traditional Shewhart charts and his dynamic chart was in the assumptions about *"behavior of real-time data"* and *"associated improvement in timeliness of result"*.

For a continuous/contiguous production process, a dynamic quality control method individualizes and customizes control limits for each time period of production based on the actual/current process average. Dynamic control systems are already in use in various fields such as chemical engineering, semi conductor devices, electronic chip designs, assembly systems, networked manufacturing, food industry, heavy machine manufacturing industry and most recently in supply chain as well. To cope with the challenges of monitoring dynamic and variable quality variation into supply chain, Jiang et al (2009) integrated quality prevention, analysis and diagnosis and put forward a Dynamic Process Quality Control method, enabling technologies such as the theory of similarity manufacturing, Statistical Process Control (SPC), neural network. This on-line based quality analysis/control method diagnoses the abnormal variation at the right moment, which is the most difficult problem that a enterprise in supply chain faces in process quality control. Similar methods (Xingyu et.al, 2007, 2008; Lei, 2009; Chen, 2002) were put forward that provide an opportunity to monitor and control the material being processed on a minute-to-minute basis at any stage during processing. This continuous quality monitoring of process-flow results in maximization of production and minimization of costs incurred. However, such a control system is difficult to incorporate in textile manufacturing and processing industry because of the nature and number of processes involved. Hence, an alternate method of monitoring based on similar theoretical principles has been developed as a part of this research work.

3.4 Development of theoretical framework for Design of Dynamic Quality Control System

Dynamic Quality Control System for textile processing, a novel method to overcome the defects and problems faced using existing quality and process control systems, was first conceptualized by Suh (1994). He pointed-out the lack of progress and improvement in process quality in spun yarn manufacturing despite significant increase in production efficiencies over the last five decades.

He manifested that the main reason behind failure of existing systems is the '*static control'* methods adopted in quality monitoring, wherein each processing stage is controlled independent of other stages in the multi-stage control units. According to him, an error or bias introduced in one stage may cause all of the subsequent stages to be out of control, often leading to false alarms and even shutting down the entire unit in the worst-case scenario. The only practical remedy, which most of the industries have been employing to counter this problem has been to widen the control limits for all of the subsequent stages. By continuing this practice, all control limits may become so wide that it would make the so-called statistical limits useless. To overcome this problem, he recommended development of a control system that is reactive to the dynamic changes of the previous stages.

Based on failures of the existing quality control systems, a thorough framework for designing such a system has been developed. The key strategy used in designing the system is *"estimation of output process averages and variances as functions of input process averages and variances originating from prior process stages"*. The concepts incorporated to achieve this strategy were:

- Concept of Bias Magnification and Separation through "structural or functional relationships"
- Concept of Additive Biases and Variances
- Concept of Variance Tolerancing
- Concept of Dynamic Control Limits
- Concept of Combined Feedback-Feedforward system

3.4.1 Concept of Bias Magnification and Separation through Structural/Functional Relationships

In any continuous manufacturing operation, one of the fundamental problems in measurement of data is distinguishing ***noise*** from ***signal*** and further eliminating it. Signal is the "important" part of the data that needs to be measured while noise is the fluctuation/variation from the signal, i.e., the non-essential part of data that needs to be filtered out.

The quality of output obtained depends entirely on the signal-to-noise ratio, which is the ratio of the true average or true mean of signal to the standard deviation of the noise. Measurement of signal-to-noise ratio is much easier if the noise can be measured separately, in the absence of signal. In any continuous/contiguous manufacturing setting, it is almost impossible to acquire readings of the noise alone on a segment of baseline before or after the occurrence of signal. However, it is possible to model the shape/magnitude of the signal exactly by means of a structural equation and thus, the error term can be estimated by calculating its expectation value.

Various researchers (Suh, 1994; Beck et al, 1998; Nobbs, 1999; Gilchrist et al, 2000; Shamey et al, 2000; Draper et al, 2001) have discussed the need and importance of structural equations and proved that mathematical modeling could lead to a better understanding of the role of variables in any processing sequence. Structural and functional relationships can form the link between any two stages of a continuous/contiguous manufacturing and processing industry. These equations also explain the relationship between the input and output process variables in a better and efficient way when compared to regression and prediction equations. Moreover, a structural and functional relationship uncovers unique processing parameters that govern economic behavior.

The study of structural relationships and models leads to a precise knowledge of the kinetics of a processing sequence, in-turn improving the process control, reliability and, perhaps most importantly, lead to understanding and estimating the impact of various factors/process parameters on the process itself. They can be used in mathematical modeling and computational analysis of a process, thus providing a powerful tool to investigate and validate the theories and claims made by researchers across the globe. Structural equations not only form the link between input and output variables, they also help in estimating the output process biases and variances as functions of the input process biases and variances. This in-turn helps in magnifying the variances that originated from prior and current process stages.

Bias-Variance decomposition

As mentioned earlier, in order to identify the root-causes for out-of-control situations in a processing sequence, *biases* and *variances* have to be separated out from the actual signal and estimated. "*Bias*" in simplest terms is a systemic deviation from true mean. It is the structural error of a model i.e., bias occurs when a known or unknown constant is added to existing process signal (average). If a function is sine wave, say $f(x) = sinx,$ then there will be a systematic errors (*Bias*) at each "bump" in sine wave.

The "*bump*" or "*deviation from mean*" is caused because of inherent characteristics of raw materials being processed or nature of processing itself. Figure 3 below illustrates how an addition of a constant value (*bias*) to an existing signal. It can be observed that even with an addition of bias, the end result is still remains a sine wave. However, the relative position has been altered vertically by a distance that is a function of *bias*.

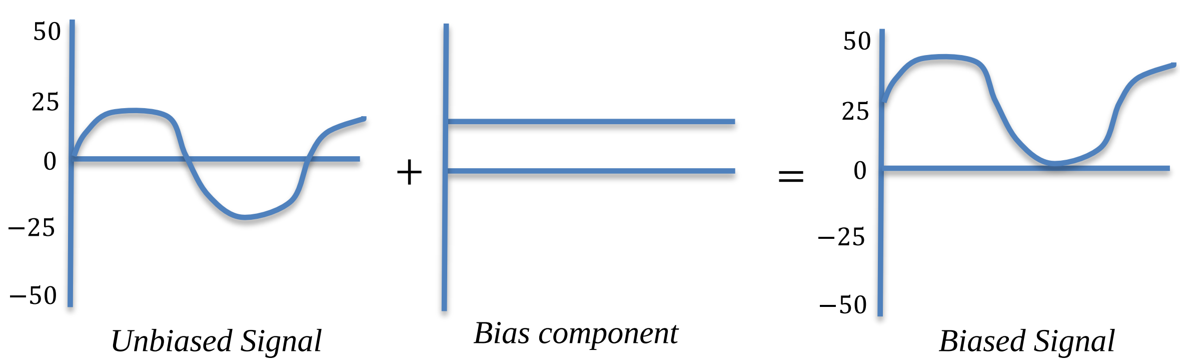

Figure 3: Unbiased and Biased Signals

On the other side, *variance* characterizes the amount of random variation at a given data point on the process average. In other words, it is a measure of inconsistency in signal / process average, i.e., it measures the average distance of signal from its closest systematic component. Variances are generated due to processing errors, differences in speeds between moving parts, wearing out of various components and sometimes due to external factors. These variances get carry-forwarded and get amplified as they move further down in the processing sequence. Hence, a significant difference can be observed between the predicted output signal and actual output signal with inherited variance components.

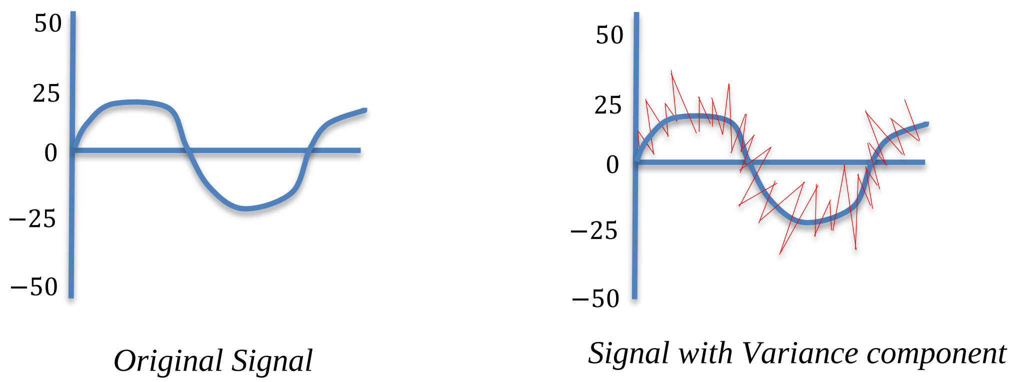

Figure 4: Signals without and with Variance component

These biases and variances when combined together constitute the *error* component of a structural equation. However, since the *bias* is already inherited into the signal, it cannot be further channelized. On the other hand, since *variance* is generated due to processing errors, it can be channeled and estimated into two sub components – *variances* generated in current processing stage and *variances* inherited from previous processing stages. In any continuous manufacturing sequence, the additive effect of these *variances* leads to an out-of-control scenario (Section 3.4.2 provides detailed description on additive effects of biases and variances in continuous manufacturing and processing sequences). Hence, it becomes quintessential to estimate the *error* component accurately in a continuous processing sequence in order to separate and decompose the *variances* generated in processing.

Various researchers have proposed different techniques for bias-variance decomposition (Geman, Bienenstock & Doursat, 1992; Kong & Dietterich, 1995; Kohavi, Wolpert, 1996; Geurts, P, 2009). Although, these studies primarily focus on handling large datasets, minimizing *biases* and *variances* and generating an optimal bias/variance tradeoff using algorithms, they provide an insight about how the biases and variances can be separated and measured approximately. Consider a structural equation with any function $f(x)$, where the input variable x is fixed. By calculating the expectation value of error term ε, which is normally distributed with zero mean and standard deviation σ, *bias* and *variance* can be decomposed and estimated separately.

$$y = f(x) + \varepsilon \text{ ------------ (1)}$$

$$\Longrightarrow \varepsilon = y - f(x)$$

$$E(\varepsilon) = \mathrm{E}\left[\left(y - f(x)\right)^2 \mid x\right]$$

$$\mathrm{E}\left[\left(y - f(x)\right)^2 \mid x\right] = E\left[\left((y - E[y \mid x]) + (E[y \mid x] - f(x)\right)\right)^2 \mid x\right]$$

$$= E\,[(y - E[y \mid x])^2 \mid x] + \left(E[y \mid x] - f(x)\right)^2$$
$$+ 2E[(y - E[y \mid x]) \mid x]\left(E[y \mid x] - f(x)\right)$$

$$= E\,[(y - E[y \mid x])^2 \mid x] + \left(E[y \mid x] - f(x)\right)^2$$
$$+ 2\left((E[y \mid x] - (E[y \mid x])\right)\left(E[y \mid x] - f(x)\right)^2$$

$$= E\{(y - (E[y \mid x])^2 \mid x\} + \left(E[y \mid x] - f(x)\right)^2 \text{ ------------ (2)}$$

i.e., Expected Prediction Error = [variance] + [bias] ^{2}

As discussed above, both *bias* and *variance* contribute to the poor performance of the signal and depending on the amount of contribution of *bias* and *variance*, the root-causes for out-of-control situation can be identified. *Variance* describes how much the signal (process) is varying from its original path because of errors that might arise either in the early stage of processing and get carry-forwarded in a processing sequence or get generated in the current stage of processing. It is determined by calculating the expectation value of difference between the original signal and expectation value of output variable y w.r.t x

$$Var\ (y) = E\{(y - (E[y \mid x]))^2 \mid x\} \text{------------ (3)}$$

Bias gives the average amount of error in the signal (process) that arises due to inherent variations in raw material being processed. It is determined by calculating the difference of expectation value of output variable y w.r.t x and original signal $f(x)$.

$$Bias^2(y) = \left(E[y \mid x] - f(x)\right)^2 \text{------------ (4)}$$

According to Yu et al (2006), with an ideal number of parameters in a structural equation/model, the amount of *biases* and *variances* generated in a process can be estimated accurately. The number of ideal parameters can be identified with their amount of significance on the output variable and overall processing sequence. True values of bias and variance can only be estimated approximately, because it is impossible to calculate those values for an infinite set of data points. Obviously, the bigger the data set, the better will be the approximation. For a better understanding of estimation of *biases* and *variances*, consider a structural equation that defines the relationship between output variable y in terms of input variable x.

Using a simple structural equation $\{(x+1)^2\}$ example, estimation of error component (i.e., bias and variance components) can be explained as follows:

$$y = x^2 + 2\,x + 1 \text{ ------------ (5)}$$

Using the Taylor series expansion, a generic approximation of the estimation of output y can be obtained. In this approach, the derivatives with respect to the random variables in the measurements evaluated at their mean values are employed. The expectation value of y thus obtained can be used to estimate *bias* and *variance* values as functions of *means* and *standard deviations* of input factors. The above equation (5) is expanded by using a Taylor's series expansion $\sum_{n=0}^{\infty} \frac{(x-a)^n}{n} f^n(a)$ with a = μ to obtain the estimate of output variable:

$$f(x) = f(a) + \frac{(x-a)}{1!} f'(a) + \frac{(x-a)^2}{2!} f''(a) + \frac{(x-a)^3}{3!} f'''(a) + \cdots$$

$$\Rightarrow f(\mu) = f(\mu) + \frac{(x-\mu)}{1!} f'(\mu) + \frac{(x-\mu)^2}{2!} f''(\mu) + \frac{(x-\mu)^3}{3!} f'''(\mu) + \cdots$$

$$f(\mu) = \mu^2 + 2\,\mu + 1,$$

$$f'(\mu) = 2\,\mu + 2, f''(\mu) = 2$$

$$\{f^2(\mu)\} = \mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1,$$

$$f'^{(\mu)} = 3\,\mu^3 + 12\,\mu^2 + 12\,\mu + 4\ , f''(\mu) = 9\mu^2 + 24\,\mu + 12$$

$$E[f(\mu)] = E[\mu^2 + 2\,\mu + 1] \ + \ E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + \ E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \cdots$$

$$= (\mu^2 + 2\,\mu + 1) \ + \ 0 \ + \ \frac{\sigma^2}{2}(2) + \ldots$$

$$= \mu^2 + 2\,\mu + \sigma^2 + 1$$

$$E[\{f(\mu)\}^2] = E[\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1] \ + \ E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + \ E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \cdots$$

$$= (\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1) + 0 \ + \ \frac{\sigma^2}{2}(9\mu^2 + 24\,\mu + 12) + \ldots$$

$$= (\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1) + \left\{\frac{\sigma^2}{2}(9\mu^2 + 24\,\mu + 12)\right\}$$

From above, we know variance can be obtained using expected value of $f(x)$ and $f(x^2)$

$$V(y) = E[f(x^2)] - (E[f(x)])^2$$

$$V(y) = \left((\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1) + \left\{\frac{\sigma^2}{2}(9\mu^2 + 24\,\mu + 12)\right\}\right) - (\mu^2 + 2\,\mu + \sigma^2 + 1)^2$$

$$= \left((\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1) + \left\{\frac{\sigma^2}{2}(9\mu^2 + 24\,\mu + 12)\right\}\right) - (\mu^2 + 2\,\mu + \sigma^2 + 1)^2$$

$$= \left((\mu^4 + 4\,\mu^3 + 6\,\mu^2 + 4\,\mu + 1) + \left\{ \frac{\sigma^2}{2} (9\mu^2 + 24\,\mu + 12) \right\} \right) -$$

$$((1 + 4\,\mu + 6\,\mu^2 + 4\,\mu^3 + \mu^4 + 2\sigma^2 + 4\mu\sigma^2 + 2\mu^2\sigma^2 + \sigma^4))$$

$$= \left(12 + 24\,\mu - 2\sigma^2 - 4\mu\sigma^2 + \frac{5\mu^2\sigma^2}{2} - \sigma^4 \right) \quad \text{------------ (6)}$$

$$Bias^2(y) = (E[f(x)] - [f(x)])^2$$

$$= [(\mu^2 + 2\,\mu + \sigma^2 + 1) - (2\mu + 2)]^2$$

$$= (1 - 2\mu^2 + \mu^4 - 2\sigma^2 + 2\mu^2\sigma^2 + \sigma^4) \quad \text{------------ (7)}$$

Equations 6 and 7 give the *bias* and *variance* components of the structural equation y (equation 5). Using a range of values input variable x takes, the exact amounts of contribution of both components to error can be calculated accurately. Thus, the amount of noise contributed within a process stage can be identified and separated from the noise being carry-forwarded through various stages of process.

3.4.2 Concept of Additive Biases and Variances

Consider a bias B_n entering at the n^{th} stage of a contiguous manufacturing process. This is a sum of all biases generated from the process at that particular stage and biases generated from the *(n-1)* previous processes. Similarly, at each stage the input variances of the previous processes or the pre-existing variances in the process sum up with the variance components generated from that processing stage and the variance components from the external causes which are not associated with the machineries.

By considering the total bias from the random component and the total error variance at a particular stage, control limits for any given processing stage can be determined accurately. Suh, et.al, explained the above concept clearly using an example of density profiles of a sliver and the resulting roving and yarn in three successive processing stages.

We can observe from figure 5 below, that at each stage the input variances of the previous processes i.e., the pre-existing variances in the process sums up with the variance component generated from that process itself and also the variance from the external causes which are not associated with the machineries. In order to analyze, these variances a system that separates and estimates each of these variances has to be used.

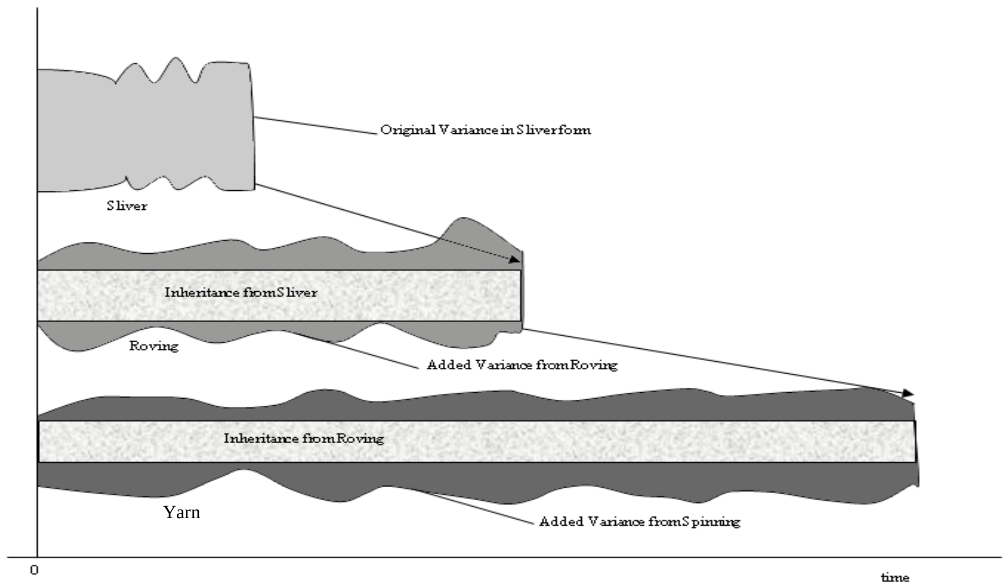

Figure 5: Schematic Diagram of Inheritance of Variance from Previous Process Stages

3.4.3 Concept of Variance Tolerancing

In any continuous manufacturing, large variation in process and product characteristics is not well understood due to lack of an effective way to separate random variations from structural or known scientific relations that are often unknown or hidden. Thus, the traditional quality control techniques based on variance analysis alone have failed due to the large number of unaccounted variations in raw materials and processes in addition to the complex structural relationships that are largely unknown or difficult to verify in the presence of huge process variations. In this situation, an improvement in signals cannot be easily verified without reducing and estimating the random noise.

Utilizing the structural equations based on yarn strength, Suh and Koo (2001) proposed a novel concept to "*separate and estimate random errors associated with raw materials and yarn structures from process-induced errors"*. They claim that, analysis of variances of simple structural equations that form the links between different stages of a contiguous process via input and output variables provide the necessary means to device the control and improvement strategies. Evans (1975) pointed out that the application of Statistical Tolerancing technique (devised by Tukey, 1957) could be used to determine the probability distributions of output characteristics using a set of input component variances. However, according to Suh and Koo (2001), as the knowledge of structural relationships in textile products and processes is minimal and limited, conventional application of *statistical tolerancing* methods although highly effective is inadequate for textile manufacturing and processing. Hence, they devised a new technique called the *Variance Tolerancing* technique, that utilizes known structural equations/functions and relationships that form the link between two processing stages. The variance of output variable is obtained in terms of summation of variances of several input subcomponent variables.

By applying a set of variance ranges for each of these input subcomponents, the out-of-control situations can be easily detected and also, component(s)/ factor(s) that lead to the out-of-control situation can be easily identified and necessary corrective actions can be taken. Securing statistical distributions for suitable input quality components with the objective of quantifying a desirable output quality characteristic statistically is practically more meaningful as well as academically more challenging than trying to achieve a desired average characteristic of the output product by selecting or adjusting the average characteristic of input factors. To explain this proposition further, Suh and Koo (2001) illustrated the tolerancing and channeling process of variances with the help of a simplistic stochastic model that is function of a *"set of intrinsic components X's"* and "*a set of intercepts H's*". However as the variances of intercepts would equal to zero, they considered a textile product characteristic, *Y*, expressed as:

$$Y = g\ (X_1 ... X_m),\ m \leq n,$$

Here 'g' is a geometrical/probabilistic/structural model, $x_1 \ldots x_m$ are the intrinsic components. As the model is expressed in terms of input components, variance of the output can be obtained by calculating the variances of those individual components, which can be estimated from their statistical distributions. According to Suh and Koo (2001), on certain occasions a structural model or a probabilistic equation may not have all of the required input components that have a direct impact on the process and in such cases tolerancing of variances does not yield the desired results. Hence, it is really important to ensure that the best possible input components represent key factors such as input materials, process conditions and prediction/ characterization of product characteristics in a structural / geometric equation. Further, they applied the classical statistical tolerancing formula to the above equation and obtained the following

$$Var\ (Y) = \sum \left(\frac{\partial f}{\partial x_i}\right)_0^2 Var\ (X_i) = \sum f_i^2 Var(X_i) \text{ ------------ } (8)$$

3.4.4 Concept of Dynamic Control Limits

In any continuous manufacturing industry, there is a need for continuous monitoring at each stage of processing to make sure that the acceptable quality (customer defined quality standards) is achieved at the end. In most continuous/contiguous manufacturing processes, quality is monitored through a set of pre-determined control limits/ specification limits, obtained either through theoretical assumptions or by conducting various trial-and-error methods that suit the current operations in the manufacturing plant. In a dynamically changing manufacturing environment, these control limits often cause false alarms and prompt unnecessary corrective actions, leading to decrease in productivity. Hence, a set of control limits that are flexible, accommodating and most importantly, which adjust to the inherent variations that occur are required. For deriving such dynamic control limits, analysis and estimation of biases and variances that flow through the process are required. The above mentioned concepts of utilizing structural equations for separating and estimating biases and variances generated at each stage of the manufacturing process and tolerancing and channeling of those biases and variances generated in the previous processing stage and the current processing stage, helps in determining a set of dynamic control limits for each processing stage in spinning. This new set of dynamic control limits obtained will be a function of dynamic process averages and variances as shown below:

Control Limits based on Static Process Average and Variance are given by:

$$CL = \mu \pm k\sigma \text{ ------------ } (8)$$

Control Limits based on total Biases and Variances generated in the process are given by:

$$CL = \sum_{i=0}^{k} B_i \pm t_{\alpha}\sqrt{\sum_{i=0}^{k} \sigma_i^2} \text{ ------------ } (9)$$

Control Limits based on Dynamic Process Average and Variance are given by:

$$CL = f(\mu_x, \sigma_x) \pm kf(\mu_x, \sigma_x) \text{ ------------- } (10)$$

This new set of control limits aids in monitoring the performance of a process over time in order to detect any unusual events that may occur at any random instant of time. These control limits are different from the most widely used Shewhart control limits as they can accommodate and adjust to the inherent raw-material and process variations that keep occurring in any continuous manufacturing industry. As these limits are derived from the structural equations that connect different stages of a processing sequence, additive effects of biases and variances throughout various stages of spinning process has been clearly accounted for. Moreover, they can aid in determining the root-causes of variations as the control limits are built around the current process average (dynamic mean). As mentioned above, mean and standard deviation obtained are expressed in terms of process averages and process variances.

3.4.5 Concept of a Combined Feedforward-Feedback system

In order to minimize the effect of process disturbances and keep the processes within the desired specification levels, few textile dry and wet processing industries have incorporated either a *feedforward only* control or a *feedback only* control compensative mechanisms in the control systems at certain processing stages. *Feedback* control is used when a known input variable exists which can be manipulated to cancel deviations of the output from its target value (Desborough and Harris, 1993).

Feedforward control is used when knowledge of the value of some measured but uncontrollable variable may be used to partially cancel deviations of the output from target value (Sternad and Soderstrom, 1998). *Feedforward* control allows the control scheme to compensate for variation by making adjustments to related variables in the process loop, while in the *feedback* control scheme, the deviation from target will be *fed back* to decide the appropriate degree of compensation. Several researchers have advocated incorporation of either *feedback* or *feedforward* mechanisms for estimation of process performance in terms of output variance in the past in continuous manufacturing industries such as the textile industry. Many researchers and trained practitioners have been advocating the usage of either a *feedback* or a *feedforward* system to monitor and control the variance contributions due to disturbances and controllers for a very long period of time. Over time, these techniques have evolved from the use of pneumatic and electrical devices to a wide range of intelligent digital devices, and now are an integrated part of processing equipment, providing real-time control actions in response to variations in the process.

Generally, when the machine stops due to an automated control mechanism, it is difficult for operators to determine the root-cause of problem for which the machine stopped and which part of the system is defective. Hence, an enhanced diagnostic tool is required to assist the operators in keeping the system at the normal operation and in finding out the possible faults. By combining *feedforward* logic with *feedback* system, the effect of process disturbances due to unknown variables and external factors can be eliminated, thus stabilizing the process and keeping the process within the desired specification levels. The main advantage using a combined *feedforward-feedback* control system is that it can be utilized even when the source of variation is unknown or its magnitude is unknown. Depending on the controlled output, the *feedback-only* effect or the *feedforward-only* effect contributes to the output variance of the *feedforward-feedback* system. The *feedback-only* control utilizes the deviation from the target to calculate the necessary compensatory changes required to achieve normal processing while *feedforward-only* system measures the input disturbance directly and with that knowledge takes measures so as to eliminate the impact of the disturbance on the process output.

Thus, the combined *feedforward–feedback* control system measures the input disturbance directly and with that knowledge takes measures to eliminate the impact of the disturbance on the process output. This system can significantly improve the stability of the process by minimizing the variances whenever there are rapid shifts or disturbances in the key properties of the material being processed. Also, specific control actions can be automatically executed through this system as it utilizes the deviation from the target to calculate the necessary compensatory changes required to achieve normal processing.

3.5 Design of Dynamic Quality Control System

The design of the dynamic quality control system was first proposed by Suh (1994). The single most important factor for consideration in design of this novel system is the prediction and quantification of biases and variances that get carry-forwarded from one stage of processing to the subsequent stages. This makes the system more responsive to the dynamic and rapidly changing conditions in a continuous manufacturing operation. Another important challenge is the graphical representation of the dynamic control chart, which needs to be easy to understand as well as practical. The above-mentioned concepts were incorporated into a traditional Shewhart control chart system to generate an optimal control strategy at each processing stage. Also they coupled the traditional static process average and its corresponding control limits with dynamic process average and its corresponding control limits in the same control chart for graphical representation purposes. This novel quality control system thus displays two sets of control limits associated with both static and dynamic process averages that are obtained based on the biases and variances generated from the prior and current processing stages, which leads to detection of root causes in out-of-control situations. Thus, minimizing the false alarms and unnecessary corrective actions.

When there is no or minimal variance in raw material, a process tends to perform as designed, with virtually no data points plotted outside the pre-determined or static control limits. However, since such an ideal condition is a rarity in any continuous manufacturing process, especially where no or limited control is possible on the inherent variance in raw material properties, action would be warranted regardless of the decision obtainable from the static control limits. When certain specification limits need to be met closely, the target process average may be compromised if the total process bias exceeds an upper limit. In this decision scheme of control system, three different cases of *out of control* situations arise (shown in Figure 6 below) based on the extent of deviation occurred in the process average. The three different cases of out-of-control situations are:

Out of Control w.r.t. Static Limits: The actual process average is found to be out of control with respect to pre-determined or static control limits. This scenario is common to both static control charts and the dynamic control chart systems. The outliers could be due to variances from material being processed or variances arising from mechanical errors or even manual errors. Although, this scenario is not desirable, taking corrective actions based entirely on this is not required as it leads to false alarms, or unnecessary corrective actions in many cases as discussed earlier. Therefore, no immediate corrective actions are recommended when a process is out-of-control in this case scenario.

Out of Control w.r.t. Dynamic Limits: The actual process average is found to be out of control with respect to dynamic control limits. This is a case scenario, which does not exist in the current quality control systems. Since the dynamic control limits are generated using continuously obtained process data i.e., dynamic process averages, the outliers observed in this scenario can be credited to variations in raw material being processed and the biases and variances that get carry-forwarded during processing. Since the process average is out of control due to the dynamic and sudden variations in material being processed, taking corrective actions in this case scenario is some-what justified as it requires some improvements such as determining the root-causes of variation or the point of origin of variations to control of false alarms.

Out of Control w.r.t both Static and Dynamic Limits: The actual process average is found to be out of control with respect to both static and dynamic control limits. This is the most serious case scenario of all three cases. Immediate action is mandated as any delay in taking corrective actions could lead to detrimental quality finished product, not only resulting in heavy losses but also leaving the entire processing stage or even the plant to shut down. As the dynamic process average provides the trend of material variations, the root-causes of variation or the point of origin of variations can be easily detected. The root cause of this kind of variation can be traced back to both raw material variations as well as mechanical errors at a given stage where the process average is out-of-control.

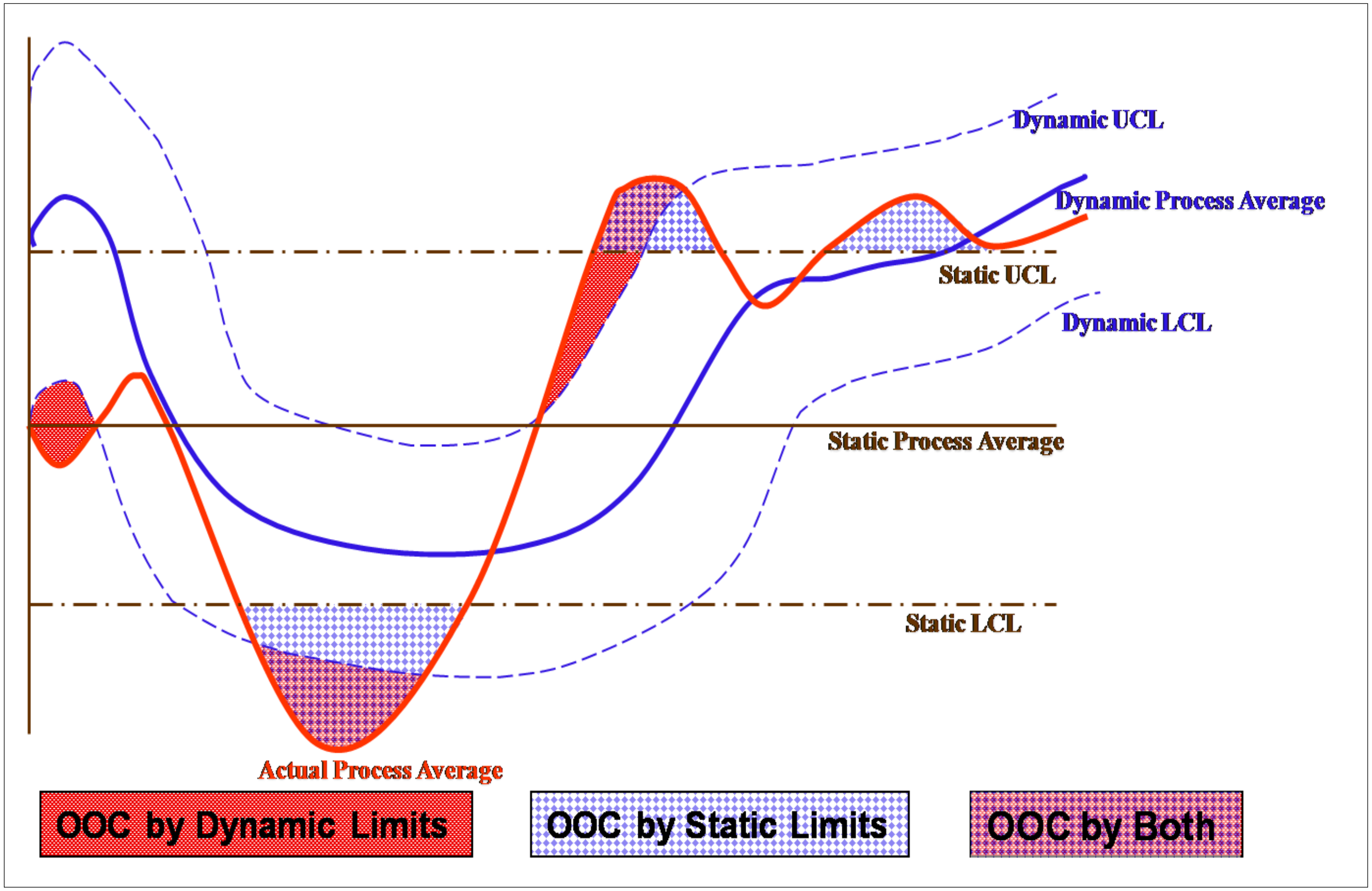

Figure 6: Schematic Diagram of a Dynamic Control Chart

Chapter 4

Application of Dynamic Quality Control System

As discussed earlier, theoretically determined control limits (i.e., static control limits) help in identifying whether a process is in-control or out-of-control. However, when employed, they cause false alarms, unnecessary corrective actions and unwarranted process calibrations that hinder production sequences, as they are static in nature and incompatible with the dynamic and rapidly changing production environment. The concepts involved in construction of a Dynamic Quality Control System have been discussed in-detail in Chapter 3 above. In this chapter, the concept of dynamic quality control is clearly illustrated through a couple of application examples.

In any continuous process type of manufacturing each process stage is tied to the next, as the output material from the previous processing stage is the input feed for the subsequent processing stage. Generally, the input error comes from raw materials, despite taking precautionary measures such as pre-conditioning before processing. Moreover, during processing, slight differences in speeds, humidity, actual drafts, and mechanical imperfections of equipment add additional variations to the material being processed. Hence, two of most common continuous manufacturing/processing operations in textiles domain have been chosen to explicitly explain the concept and working of a dynamic quality control system.

The first example selected is Ring Spinning process, which is essentially composed of five sequential processing stages and each of the processing stages has a correlation with the previous stage. Although, ring spinning can sometimes be considered as a contiguous manufacturing instead of continuous manufacturing, it is selected as an example to illustrate the dynamic quality control system because of the inherent variations generated in the process owing to input and influence of several key processing variables. In any ring spinning processing sequence, biases and variances are generated right from opening and mixing stage and get accumulated and carry-forwarded to the subsequent processing stages.

The second example is Continuous Dyeing process, which is often the last step in the manufacturing processes of yarns and fabrics, and plays an important role in the final appearance of goods. Outcome of a dyeing process is significantly influenced by various input and output factors, such as basis weight, mass uniformity, physical and dimensional properties of raw material, type of raw material, speeds of material and dye flow, moisture contents, liquor ratio, dye concentration, dye injection rate, chemical dyeing auxiliaries, bath temperature, etc. However, more than any of the above-mentioned factors, time is a much more important and dominant factor in a continuous dyeing process and hence, the concept of dynamic quality control can be explicitly illustrated using the example of said wet textile process. Sections 4.1 and 4.2 below illustrate the development and application of a dynamic control chart using simulated data that is generated based on actual industry data. Also, the dynamic control chart will be compared against conventional Shewhart control chart system that has been traditionally employed for the past few decades.

4.1 Application of Dynamic Quality Control System to Ring Spinning process

Consider the classic case of manufacturing of yarn through ring spinning process. Raw material in fiber form is converted into a yarn after passing through a sequence of processing stages, namely opening and mixing, carding, drawing, roving and spinning. As discussed earlier, in any such contiguous manufacturing processes, quality of the product is influenced by many factors, as there are complex interactions and relationships between prior and subsequent processing stages. Variations in raw material properties are bound to occur, especially when natural fibers such as cotton, jute, wool and blends are processed, due to the nature of raw material and inherent variations present in the control elements despite taking several pre-processing precautionary measures.

The most conventional practice of quality monitoring in a ring-spinning mill is that a quality lab operator collects random samples of processed material from each processing stage at periodic time intervals (such as everyday, three times a week, once every week, once in two weeks and once in a month). Once the samples are collected, various tests are performed in the quality lab to determine the quality levels of the material being processed. Among various tests conducted, determining whether each processing sequence is within the specification limits or not using Shewhart control chart method is the most commonly used tool set. By plotting and observing the data generated, a Quality Lab manager or a Plant Manager determines whether the process is within control or out-of- control depending on whether the data falls within the predetermined set-limits or outside of them. However, as mentioned earlier, this is a static control chart method with pre-determined and inflexible control limits leading to false alarms, unnecessary corrective actions and unwarranted process calibrations, thus hindering production and profits for the manufacturing company. Determination of process quality based on pre-determined control limits and randomly selected samples is one of the most inefficient methods of quality monitoring for a contiguous process such as ring spinning. However, with the application of a dynamic control that can synchronously change with respect to variations in mass in raw material, the overall quality can be improved.

Application Example 1: *Obtaining Dynamic Control limits based on key process parameter:* ***Mass Variance***

Theoretically, the mass variation of a sliver/ roving/ yarn can be quantified by the input variance from the previous stage and the variance imparted by the process itself and some external causes. Jeong and Suh (2002) have earlier proved this concept with their numerical results showing only 30 – 60% of variance coming from within process and the rest from the previous processes and other external factors. According to their study, if the mass amplitudes of the sliver length units (X_1, X_2, X_3 … , X_n) are considered, the mean and variance of unit mass X can be expressed relatively as

$$\hat{E}(X) = \frac{1}{n}\sum_{i=1}^{n} X_i \text{ and } \hat{V}(X) = \frac{1}{n}\sum_{i=1}^{n}(X_i - \hat{E}(X))^2$$

And, if the sliver is attenuated to '*d*' times the original length, the mean and variance of the unit mass X of the roving becomes

$$\hat{\mathrm{E}}(\mathrm{X}) = \frac{1}{\mathrm{d}}\,\hat{\mathrm{E}}(\mathrm{X}) \text{ and } \hat{\mathrm{V}}(\mathrm{X}) = \frac{1}{\mathrm{d}^2}\,\hat{\mathrm{V}}(\mathrm{X}) + \sigma^2_{\mathrm{r/s}}$$

where X is the amplitude value of unit length of roving, the term $\sigma^2_{\mathrm{r/s}}$ is the portion of the within-variance associated with the roving process and $\frac{1}{\mathrm{d}^2}\,\hat{\mathrm{V}}(\mathrm{X})$ is the variance component inherited from the sliver (input variance).

In order to illustrate the concept of dynamic quality control system, the first step is to identify a process parameter that is of paramount importance to the spinning process. From Section 2.5, it can be observed that ***mass variation, strength variation*** and ***uniformity*** are one of the key raw material properties that have significant effect on the spinning process. Variations in *mass* of raw material fibers are bound to occur, especially when natural fibers such as cotton are processed, due to the nature of raw material and inherent variations present in the control elements despite strategically selected bale-laydowns and random pickings during opening and mixing stage. Especially, since fibers are fed through chute system in most of modern spinning mills, massive amounts of fibers of varying mass are transported in a very short span of time. Thus, in spite of the rapid advancements in technology, it is difficult to control and monitor these variations in raw material.

As discussed in Section 3.4.1, by identifying various structural equations that can determine mass variation as a function of key several input processing parameters at each stage of the spinning process, the cumulative effect of biases and variances on mass variations in raw material can be distinctly observed and analyzed. Structural equations from each processing stage can then be combined sequentially to form a final structural equation, whose output mass variance can toleranced using the variance tolerancing technique to determine a new set of limits called the dynamic control limits.

Various equations are identified at different stages of spinning process using mass uniformity as key factors from the literature. These 'clean' and 'manageable' structural equations were developed into a single structural equation to obtain the dynamic control limits for the ring-spinning process.

Opening/mixing: Deviation in feed (input) σ_{feed} is derived as:

$$\sigma_{feed} = (V) \times (W) \times (H) \times (d) \text{ ------------ (11)}$$

Also, El Mogahzy *et al.* (1992) proposed that cotton mix uniformity can be enhanced by optimizing a number of critical factors – population variability, location of category break points in the distribution of fiber characteristics, number of categories in the distribution of fiber characteristics, number of bales per mix. According to him, total Within-laydown mass variance can be calculated as follows:

$$\sigma^2_{WLD} = \frac{(n-1)N}{(nN-1)} \sigma^2_{BB} + \frac{(N-1)}{(nN-1)} \sum_1^L \sigma^2_{WB} \text{ ------------ (12)}$$

where n is the number of bales in a laydown, N is the number of observations taken from each bale, σ^2_{BB} is the between bale variance, and σ^2_{WB} is the within bale variance.

And, total mass variance at the mixing stage with 'L' laydowns is calculated as follows:

$$\sigma^2_{total} = \frac{(L-1)n}{(Ln-1)} \sigma^2_{BLD} + \frac{(n-1)}{(Ln-1)} \sum_1^L \sigma^2_{WLD} \text{ ------------ (13)}$$

Carding: Buturovich (1968) proposed the following equation for the measurement of variation in the output web at carding. Let 'X_π' be the variation in web (output), 'X_p' the variation in feed (input), K(t) a function of t, 't' being the instantaneous time, 'c' the expected residence time of fiber in the card, 'q_π' the weight per unit length of web (output), 'q_p' the weight per unit length of feed (input), 'Y_π' the instantaneous variation in 'q_π' and 'Y_p' the instantaneous variation in q_p .

Output mass variation 'V' in carded web is given by equation:

$$\sigma_{web} = \int_0^t K(t) X_p (t-\delta) d\delta \text{ ------------ (14)}$$

$$V = \frac{t}{2c} e^{-t/c} \quad \text{------------ (15)}$$

Drawing: Mass variation in draw frame sliver as per Grishin's 'Law of Drafting' (1954) is given by equation:

$$V^2 = \frac{1}{n} \left[V_o^2 + AN_o(z-1) + BN_o(z-1)^2 z\right] + V_\alpha^2 \quad \text{------------ (16)}$$

where 'V' is the irregularity CV, 'n' the number of doublings, 'V_0' the mass irregularity of the input, 'A' is the coefficient due to the increasing mass irregularity from the reduction of thickness or decrease in the number of fibers in the cross section and 'B' is coefficient due to drafting mechanism, 'N_0' the hank of input, 'z' the draft ratio and 'V_α' be the additional irregularity arising from roving tension at roving frames.

Roving: The relative variance (V_α^2) obtained at roving frame is given by Cavaney and Foster's equation (1955):

$$V_\alpha^2 = \frac{AN_0}{n} \left(\frac{S-\bar{L}}{\bar{L}}\right)(z-1) + d \quad \text{------------------ (17)}$$

where 'N_0' is the hank of the input strand, 'z' the draft ratio, n the number of doublings, 'S' the draw frame roller settings, '$\bar{L}$' the mean fiber length, 'd' a constant and 'A' the source of irregularity of the product.

Consolidation of structural equations from each stage of processing into one final structural equation: A method has been devised to consolidate structural equations connecting various stages of processing by treating opening & mixing, carding, drawing, roving and spinning as continuous but disjoint processes. As mentioned earlier, structural equations form the link between input and output variables between any two stages in a continuous/contiguous manufacturing process and hence, they aid in determination and estimation of biases and variances generated in the entire process chain.

The above-mentioned five stages of spinning were tied to each other based on a certain fiber property (mass variation) using structural and functional relationships. These relationships determined the influence of various input process parameters on output mass variation. By tying these structural equations, a process chain was formed connecting various stages of the spinning process and expected levels of mass variances were computed at the end of each processing stage. The final structural equation obtained after consolidating all of those structural equations was given by the equation below:

$$V^2 = \frac{1}{n}\left[\frac{t^2 e^{-2t/c}}{4c^2} + AN_0(z-1)\left(\frac{S}{\bar{L}}\right) + BN_0(z-1)^2 z\right] + nd \text{ ------------- } (18)$$

where, 'V' is output mass variance at spinning process; 't' is the instantaneous time; 'c' is the expected residence time of fiber in the card; 'N_0' is the hank of the input strand; 'z' is the draft ratio; 'n' is the number of doublings; 'S' is the draw frame roller settings; '$\bar{L}$' is the mean fiber length; 'd' is density of fibers in a bale; 'V_0' is the mass irregularity of the input; 'A' and 'B' are coefficients ('A' is due to the increasing mass irregularity from the reduction of thickness or decrease in the number of fibers in the cross section and 'B' is due to drafting mechanism)

Using the above equation (18), where output mass variance is expressed in terms of input mass variances from each stage of the spinning process, bias and variance components can be calculated using Taylor's series expansion as explained earlier. For the ease of mathematical calculations, consider all input parameters expect instantaneous time 't' and expected residence time of fiber in card 'c' as constants. Now, equation (18) is reduced to:

$$V^2 = \frac{1}{n}[V_i^2 + c]$$

where $V_i^2 = \frac{t^2 e^{-\frac{2t}{c}}}{4c^2}$ and c is a constant.

$$Var[V^2] = \frac{1}{n^2} Var[V_i^2] + c$$

By letting $x = \frac{t}{c}$,

$$Var[V^2] = \frac{1}{n^2} Var[x^2 e^{-2x}] + c \text{ ------------- (19)}$$

As discussed above, the Taylor series expansion can be used to obtain a generic approximation of the estimation of output y. The expectation value of y obtained can be used to estimate bias and variance values as functions of means and standard deviations of input factors. The above equation (19) is expanded by using a Taylor's series expansion $\sum_{n=0}^{\infty} \frac{(x-a)^n}{n} f^n(a)$ with a = μ to obtain the estimate of output variable:

$$f(x) = f(a) + \frac{(x-a)}{1!} f'(a) + \frac{(x-a)^2}{2!} f''(a) + \frac{(x-a)^3}{3!} f'''(a) + \cdots$$

We know, $\textit{Variance}\ [V(y)] = E[f(x)^2] - (E[f(x)])^2$

$$E[f(x)] = E[\mu^2 e^{-2\mu}] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \cdots$$

$$= \mu^2 e^{-2\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + \cdots$$

$$E[\{f(x)\}^2] = E[\mu^4 e^{-4\mu}] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \cdots$$

$$= \mu^4 e^{-4\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + \cdots$$

$$Var[V^2] = \frac{1}{n^2} [\mathrm{E}\,[x^4 e^{-4x}] - (\mathrm{E}\,[x^2 e^{-2x}])^2]$$

$$= \frac{1}{n^2} [\, \mu^4 e^{-4\mu} + \sigma^2 e^{-4\mu}(6\mu^2 - 16\mu^3 + 8\mu^4)]$$

$$- [\, \mu^2 e^{-2\mu} + \sigma^2 e^{-2\mu}(1 - 4\mu + 2\mu^2)]^2$$

Equation (20) below gives us the output variance of the "mass variance of roving" as a function of the input mean μ and input variance σ for x = t/c, as defined.

$$Var[V^2] = \frac{1}{n^2}\left[e^{-4\mu}\left\{ \sigma^4(8\mu - 20\mu^2 + 16\mu^3 - 4\mu^4 - 1)\right\}\right]$$

$$+ \left[\sigma^2(6\mu^2 - 16\mu^3 + 8\mu^4)\right] - \left[\sigma(2\mu^2 - 8\mu^3 + 4\mu^4)\right] \text{ --- (20)}$$

$$E[V^2] = (E[f(x)] - [f(x)])^2$$

$$= [(\mu^2 e^{-2\mu} + 2\,\mu + \sigma^2 + 1) - (2\mu + 2)]^2$$

$$= (1 - 2\mu^2 + \mu^4 - 2\sigma^2 + 2\mu^2\sigma^2 + \sigma^4) \text{ ------------ (21)}$$

Calculation of Dynamic Control limits: The output mass variance obtained at spinning process (Equation 21) is a cumulative sum of input mass variances of all stages of spinning i.e., from mixing and blending to roving stage. Also, the error term will be a cumulative of input biases /variances generated at all stage of spinning process. Using the output mass variance calculated by using Variance tolerancing technique, the dynamic control limits for the spinning process, based on the key process parameter mass variation can be obtained.

The control limits are calculated by plugging the dynamic average means (μ_i) i.e., the instantaneous residence time in cards (c_i) and the dynamic standard deviation (σ_i) (i.e., square root of $Var[V^2]$ from above)

$$\mu_x = \mu^2 e^{-2\mu} + \sigma^2 e^{-2\mu}(1 - 4\mu + 2\mu^2) \text{ ------------- (22)}$$

$$\sigma_x = \sqrt{\frac{1}{n^2}\{e^{-4\mu}[\sigma^4(8\mu - 20\mu^2 + 16\mu^3 - 4\mu^4 - 1) + \sigma^2(6\mu^2 - 16\mu^3 + 8\mu^4) - \sigma(2\mu^2 - 8\mu^3 + 4\mu^4)]\}}$$

--------- (23)

$$Dynamic\ CL = \mu_{f(\mu_x,\sigma_x)} \pm 3\,\sigma_{f(\mu_x,\sigma_x)}$$

The dynamic control chart can be plotted as shown in Figure 6. This new control chart shows that the traditional control limits alongside a new set of dynamic limits, monitoring the manufacturing process continuously.

Application Example 2: *Obtaining Dynamic Control limits based on key process parameter: Strength Variance*

Variations in strength of fiber-strands during the yarn processing are inevitable because of the fundamental nature of fibers, arrangement of fibers during processing and the manufacturing methods. Control of variation in strength of fiber-strands at intermediate stages of yarn manufacturing is essential to obtain a good uniform product. Fibers are subjected to a lot of stress throughout the spinning process and this effect on fiber strength has a significant effect on the yarn strength. For example, consider the process of Drawing where fibers are subjected to roller drafting and doubling in order to separate, straighten and orient them along the strand axis. The draft ratio and number of doublings depend on the desired yarn count, thus making the yarn count a significant factor that effects yarn strength along with fiber strength. As discussed earlier, the inherent biases in fiber strength lead to variations in draw frame sliver strength variations and the drawing process introduces additional variances into the yarn strength during processing. Thus, theoretically, the variation in yarn strength can be quantified by using a structural equation or relationship that can be expressed in terms of Fiber strength and Yarn count.

In order to obtain yarn strength variance, similar set of steps were carried out as discussed above in the case of mass variance. An equation was scouted out from literature that is a function of fiber strength and yarn count. Biases and variances were estimated using this structural equation for variation in strength in yarn after spinning. The variation in the strength of yarn adjusted for the yarn thickness can be represented empirically by the equation:

$$Y_s = \frac{F_S}{C_y} \qquad \text{------------- (24)}$$

where F_s is the Fiber strength, C_y is the Yarn count and Y_s is the strength of yarn adjusted for yarn thickness.

Using the above equation (24), where yarn strength is expressed in terms of inputs fiber strength and yarn count, bias and variance components can be calculated using Taylor's series expansion. For the ease of mathematical calculations, consider $Y_s = Y,\ F_s = F$, and $C_y = C$.

Now, variance of output Y is given by:

$$V(Y) = V\left[\left(\frac{F}{C}\right)\right]$$

We know Variance $[V(y)] = E[f(x)^2] - (E[f(x)])^2$

$$\therefore V\left[\left(\frac{F}{C}\right)\right] = \left\{E\left(\frac{F^2}{C^2}\right) - \left(E\left(\frac{F}{C}\right)\right)^2\right\}$$

$$E(Y) = E\left[\left(\frac{F}{C}\right)\right]$$

$$E\left(\frac{F}{C}\right) = E_F E_C\left(\frac{F}{C} \mid C = c\right)$$

$$= E_c\left(\frac{\mu_F}{c}\right)$$

$$= \mu_F E_c\left(\frac{1}{c}\right)$$

$$E\left(\frac{F^2}{C^2}\right) = E_F E_C\left(\frac{F^2}{C^2} \mid C = c\right)$$

$$= (\sigma_F^2 + \mu_F^2)\, E\left(\frac{1}{C^2}\right) \quad (\because\ E(F^2) = \sigma_F^2 + \mu_F^2\ )$$

Taylor's series expansion can be used to calculate the expectation value of $E_C\left(\frac{1}{c}\right)$ and thus, the variance of output Y. Taylor series provides a means to predict a function value at one point in terms of the function value and its derivatives at another point. A function $f(x)$, which has continuous derivatives upto $(n+1)^{th}$ order, can be expanded using the Taylor series expansion $\sum_{n=0}^{\infty}\frac{(x-a)^n}{n}f^n(a)$ with a = μ as shown below:

$$f(x) = f(a) + \frac{(x-a)}{1!}f'(a) + \frac{(x-a)^2}{2!}f''(a) + \frac{(x-a)^3}{3!}f'''(a) + \cdots$$

Applying the Taylor Theorem:

The above structural equation can be expanded by using a Taylor's series to obtain the Expected value of output parameter-yarn strength (Y_s) in terms of means and variances of input parameters Fiber strength (F_s) and Yarn count (C_y):

$$f(x\,|x = C) = f(C) + \frac{(x-C)}{1!}f'(C) + \frac{(x-C)^2}{2!}f''(C) + \ldots$$

$$= \frac{1}{C} + \left(-\frac{1}{C^2}\right)\frac{(x-C)}{1} + \left(\frac{2}{C^3}\right)\frac{(x-C)^2}{2*1} + \ldots$$

$$E\left(\frac{1}{C}\right) = E\left\{\frac{1}{C} + \left(-\frac{1}{C^2}\right)\frac{(x-C)}{1} + \left(\frac{2}{C^3}\right)\frac{(x-C)^2}{2*1} + \ldots\right\}$$

$$= E\left(\frac{1}{C}\right) + E\left[\left(-\frac{1}{C^2}\right)\frac{(x-C)}{1}\right] + E\left[\left(\frac{2}{C^3}\right)\frac{(x-C)^2}{2*1}\right]$$

$$= \frac{1}{\mu_C} + \frac{\sigma_C^2}{\mu_C^3}$$

$$E\left(\frac{F}{C}\right) = \mu_F\left\{\frac{1}{\mu_C} + \frac{\sigma_C^2}{\mu_C^3}\right\} \text{ ------------- (25)}$$

$$E\left(\frac{1}{C^2}\right) = E\left\{\frac{1}{C^2} + \left(-\frac{2}{C^3}\right)\frac{(x-C)}{1} + \left(\frac{6}{C^4}\right)\frac{(x-C)^2}{2*1} + \ldots\right\}$$

$$= E\left(\frac{1}{C^2}\right) + E\left[\left(-\frac{2}{C^3}\right)\frac{(x-C)}{1}\right] + E\left[\left(\frac{6}{C^4}\right)\frac{(x-C)^2}{2*1}\right]$$

$$= \frac{1}{\mu_C^2} + \frac{3\,\sigma_C^2}{\mu_C^4}$$

$$E\left(\frac{F^2}{C^2}\right) = (\sigma_F^2 + \mu_F^2)\left(\frac{1}{\mu_C^2} + \frac{3\,\sigma_C^2}{\mu_C^4}\right)$$

$$V(Y) = \left\{E\left(\frac{F^2}{C^2}\right) - \left(E\left(\frac{F}{C}\right)\right)^2\right\}$$

$$= \left\{\left(\frac{\sigma_F^2}{\mu_C^2} + \frac{3\sigma_C^2\sigma_F^2}{\mu_C^2} + \frac{\mu_F^2}{\mu_C^2} + \frac{3\sigma_C^2\mu_F^2}{\mu_C^2}\right) - \left(\mu_F\left(\frac{1}{\mu_C} + \frac{\sigma_C^2}{\mu_C^3}\right)\right)^2\right\}$$

$$= \left\{\left(\frac{\sigma_F^2}{\mu_C^2} + \frac{3\sigma_C^2\sigma_F^2}{\mu_C^2} + \frac{\mu_F^2}{\mu_C^2} + \frac{3\sigma_C^2\mu_F^2}{\mu_C^2}\right) - \left(\mu_F^2\left(\frac{1}{\mu_C^2} + \frac{\sigma_C^4}{\mu_C^6} + 2\,\frac{\sigma_C^2}{\mu_C^4}\right)\right)\right\}$$

$$= \left\{\left(\frac{\sigma_F^2}{\mu_C^2} + \frac{3\sigma_C^2\sigma_F^2}{\mu_C^2} + \frac{\mu_F^2}{\mu_C^2} + \frac{3\sigma_C^2\mu_F^2}{\mu_C^2}\right) - \left(\frac{\mu_F^2}{\mu_C^2} + \frac{\mu_F^2\sigma_C^4}{\mu_C^6} + 2\,\frac{\mu_F^2\sigma_C^2}{\mu_C^4}\right)\right\}$$

$$= \left\{\frac{\sigma_F^2}{\mu_C^2} + \frac{\sigma_C^2}{\mu_C^2}\left(3\sigma_F^2 + 3\mu_F^2 - \frac{\sigma_C^2\mu_F^2}{\mu_C^4} - \frac{2\mu_F^2}{\mu_C^2}\right)\right\}$$

$$\sigma_Y = \sqrt{\left\{\frac{\sigma_F^2}{\mu_C^2} + \frac{\sigma_C^2}{\mu_C^2}\left(3\sigma_F^2 + 3\mu_F^2 - \frac{\sigma_C^2\mu_F^2}{\mu_C^4} - \frac{2\mu_F^2}{\mu_C^2}\right)\right\}} \text{ ------------- (26)}$$

From above, the output strength variance obtained at spinning process is a cumulative sum of means and variances of input fiber strength and yarn count. The structural equation provided necessary relationship to obtain the “output strength variance” as a function of key input parameters. Using the dynamic means and standard deviation from above, dynamic control limits for the yarn strength in spinning process can be obtained as follows:

$$Dynamic\ CL = \mu_{Y(\mu_x,\sigma_x)} \pm 3\,\sigma_{Y(\mu_x,\sigma_x)}$$

4.2 Application of Dynamic Quality Control System to Continuous Dyeing process

The practice of evaluation of color levelness based on trail and error methods, visual assessment of a single or multiple observers and other non-quantitative methods are still prevalent in many dye houses across the globe. These methods cause significant deviations in assessment of final appearance of goods as they are highly dependent on the judgment of the observer and do not quantify levelness. A review of 2011 ITMA technology in textile wet processing, clearly indicates that a majority of textile wet processing companies are solely focused on *wise resource management* – processing textiles with less water and energy while achieving greater productivity than ever before (Hauser, 2011). However, optimizing these processes by making adjustments in costs, energy consumption, time and other factors do not help to attain uniformity in shade or required dye levelness in the product as the causes of shade variation may be due to materials, equipment, controls, process, human factors, and logistics.

These factors affect the distribution of dye in the dyebath and/or the ability of a dye to migrate on the fabric for uniform fabric appearance. For instance, the mass variation of yarn could create nonrandom periodic irregularities, which causes visible streaks on the woven fabric appearance. Furthermore, the high rate in dye uptake could lead to unlevel dyeing of the textile. It is therefore critical to monitor and control the dyeing and also evaluate the resulting textile appearance as objectively as possible to achieve optimum dyeing. But, despite the technological advancements in wet textile processing industry, many (perhaps most) dye houses have less than optimum control of these raw material inputs. Hence, there is a clear need for development of a modern quality monitoring and control systems, which have the potential to produce highly efficient, level dyed shade repeats. With proper structural models and simulation techniques, a dynamic control system can be designed in such a way that it diagnoses, analyzes and predicts the variance in output data based on the measured input parameters in a particular time interval (say, after every *'t'* minutes).

Also, this system will help in detecting the root causes for those faults and disturbances that keep occurring in the process due to the inherent variations in the control elements and nature of processing. This on-line real-time dynamic control system will be more suitable to a continuous dyeing or finishing process since the input variable have a significant and immediate impact on the output variable. While the relationships among these variables have been studied in the past, the process averages have seldom been linked in terms of structural relationships. As observed in review of literature, there have been no studies conducted so far to find all or majority of the key process parameters that influence the dyeing process and the structural equations that connect and/or uncover the relationships between these most significant input and output process parameters.

A thorough investigation was carried out and process parameters *Rate of Dyeing, Mass of fabric, Raw material characteristics*, *Temperature*, *Time*, *Dye concentration*, *Liquor ratio, Speed of Dyeing* and *Dyebath pH* were identified as the most influential process parameters in many research studies. Based on these key process parameters, structural equations and mathematical models were researched in the literature. As discussed earlier, these structural relationships and models lead to a precise knowledge of the kinetics of dyeing, and help in understanding and estimating the impact of these key factors/process parameters on the dyeing process. It has been already proved by many researchers that mathematical models lead to a better understanding of the role of variables in real dyeing process. Hence, for the construction of the dynamic control system, models that form a link between key input and output parameters in such a way that they determine the quality of resulting dyed material were identified.

Continuous dyeing is carried out on a dyeing range where fabric (or any other raw material) is continuously passed through a dye solution of sufficient length to achieve initial dye penetration. The dye on the fabric is fixed by subsequent steaming of the substrate. Although a lot of recent developments have led to effectively reducing the dye liquor to fabric ratio and reducing energy and effluent treatment costs, the consistency in dye shade or amount of dye absorbed onto material is by and large an important issue in the dyeing industry across the globe. The influence of the liquor flow rate on the amount of dye absorbed onto fabric has been known for a long time (Ferus-Comelo, 2006).

Two parameters that describe the dyeing properties of raw-material to be dyed in the constant-speed (V) continuous dyeing process are rate of dyeing and mass of raw-material. The rate of dyeing (R) shows how quickly a standard dye exhausts onto the substrate. The mass of raw-material (M) determines the amount of dye that exhausts onto the substrate. Traditionally, dye houses determine the values by carrying out experiments using trial and error methods. A structural model developed by Suh (1992) that links these constraints on the dyeing operation and process variables – *rate of dyeing*, *fabric speed* and *mass of fabric*. This mathematical model predicts the *amount of dye absorbed* by the material based on variations in input factors mentioned above. The mass of raw-material (M) on the other hand is inversely proportional to amount of dye absorbed. Hence, variations in raw-material would entail a risk of unlevelness. In a dynamic control system, real-time monitoring and control of dyeing process is possible as the *amount of dye absorbed onto fabric* in the output material is adjusted based on the variations in input factors using a combined feedback-feedforward mechanism.

The following equation (27) can be used to calculate the amount (fraction) of dye adsorbed onto the material in time 't' seconds:

$$Y = k\left(\frac{R}{V*M}\right) \quad \text{------------- (27)}$$

where Y is the amount of dye absorbed, R, V and M are the input parameters dye bath flow rate ($dm^3 min^{-1} kg^{-1}$), fabric speed ($m\ min^{-1}$), mass of fabric (gm^{-1}) and k is a constant. Assuming that the fabric speed is maintained constant throughout the dyeing cycle or dyeing process, the amount of dye absorbed is dependent only on dyebath flow rate and mass of fabric.

$$Y = k'\left(\frac{R}{M}\right) \quad \text{------------- (28)}$$

$$V(Y) = V\left[k'\left(\frac{R}{M}\right)\right] = k'^2 V\left(\frac{R}{M}\right)$$

$$\textit{We know variance } [V(y)] = E[f(x)^2] - (E[f(x)])^2$$

$$\Longrightarrow \; V(Y) = k'^2 \left\{E\left(\frac{R^2}{M^2}\right) - \left(E\left(\frac{R}{M}\right)\right)^2\right\}$$

$$E(Y) = E\left[k'\left(\frac{R}{M}\right)\right] = k'E\left(\frac{R}{M}\right)$$

$$E\left(\frac{R}{M}\right) = E_M E_R\left(\frac{R}{M} \mid M = m\right)$$

$$= E_M\left(\frac{\mu_R}{M}\right) = \mu_R E_M\left(\frac{1}{M}\right)$$

$$E\left(\frac{R^2}{M^2}\right) = E_M E_R\left(\frac{R^2}{M^2} \mid M = M\right)$$

$$= (\sigma_R^2 + \mu_R^2)\, E\left(\frac{1}{M^2}\right)$$

The Taylor's series expansion can be used to calculate the expectation value of $E_M\left(\frac{1}{M}\right)$ and thus, the variance of output Y. Taylor series provides a means to predict a function value at one point in terms of the function value and its derivatives at another point. A function $f(x)$, which has continuous derivatives upto $(n+1)^{th}$ order, can be expanded using the Taylor series expansion $\sum_{n=0}^{\infty}\frac{(x-a)^n}{n}f^n(a)$ with a = μ as shown below:

$$f(x) = f(a) + \frac{(x-a)}{1!}f'(a) + \frac{(x-a)^2}{2!}f''(a) + \frac{(x-a)^3}{3!}f'''(a) + \cdots$$

For the ease of mathematical calculations, *fabric speed* (V) is considered to remain constant throughout the dyeing process. Hence, for this application example, consider the amount of dye absorbed (Y) to be dependent only on input parameters *rate of dyeing* (R) and *mass of fabric* (M) only.

Applying the Taylor Theorem:

The above structural equation can be expanded by using a Taylor's series to obtain the Expected value of output parameter- amount of dye absorbed (Y) in terms of means and variances of input parameters *fabric speed* (V), *mass of fabric* (M) and *rate of dyeing* (R):

$$f(x\,|x = M) = f(M) + \frac{(x-M)}{1!}f'(M) + \frac{(x-M)^2}{2!}f''(M) + \ldots$$

$$= \frac{1}{M} + \left(-\frac{1}{M^2}\right)\frac{(x-M)}{1} + \left(\frac{2}{M^3}\right)\frac{(x-M)^2}{2*1} + \ldots$$

$$E\left(\frac{1}{M}\right) = E\left\{\frac{1}{M} + \left(-\frac{1}{M^2}\right)\frac{(x-M)}{1} + \left(\frac{2}{M^3}\right)\frac{(x-M)^2}{2*1} + \ldots\right\}$$

$$= E\left(\frac{1}{M}\right) + E\left[\left(-\frac{1}{M^2}\right)\frac{(x-M)}{1}\right] + E\left[\left(\frac{2}{M^3}\right)\frac{(x-M)^2}{2*1}\right] = \frac{1}{\mu_M} + \frac{\sigma_M^2}{\mu_M^3}$$

$$E\left(\frac{R}{M}\right) = \mu_R\left\{\frac{1}{\mu_M} + \frac{\sigma_M^2}{\mu_M^3}\right\} \text{------------- (29)}$$

$$E\left(\frac{1}{M^2}\right) = E\left\{\frac{1}{M^2} + \left(-\frac{2}{M^3}\right)\frac{(x-M)}{1} + \left(\frac{6}{M^4}\right)\frac{(x-M)^2}{2*1} + \ldots\right\}$$

$$= E\left(\frac{1}{M^2}\right) + E\left[\left(-\frac{2}{M^3}\right)\frac{(x-M)}{1}\right] + E\left[\left(\frac{6}{M^4}\right)\frac{(x-M)^2}{2*1}\right]$$

$$= \frac{1}{\mu_M^2} + \frac{3\,\sigma_M^2}{\mu_M^4}$$

$$E\left(\frac{R^2}{M^2}\right) = (\sigma_R^2 + \mu_R^2)\left(\frac{1}{\mu_M^2} + \frac{3\,\sigma_M^2}{\mu_M^4}\right)$$

$$V(Y) = k'^2\left\{E\left(\frac{R^2}{M^2}\right) - \left(E\left(\frac{R}{M}\right)\right)^2\right\}$$

$$= k'^2\left\{\left(\frac{\sigma_R^2}{\mu_M^2} + \frac{3\sigma_M^2\sigma_R^2}{\mu_M^2} + \frac{\mu_R^2}{\mu_M^2} + \frac{3\sigma_M^2\mu_R^2}{\mu_M^2}\right) - \left(\mu_R\left(\frac{1}{\mu_M} + \frac{\sigma_M^2}{\mu_M^3}\right)\right)^2\right\}$$

$$= k'^2\left\{\left(\frac{\sigma_R^2}{\mu_M^2} + \frac{3\sigma_M^2\sigma_R^2}{\mu_M^2} + \frac{\mu_R^2}{\mu_M^2} + \frac{3\sigma_M^2\mu_R^2}{\mu_M^2}\right) - \left(\mu_R^2\left(\frac{1}{\mu_M^2} + \frac{\sigma_M^4}{\mu_M^6} + 2\,\frac{\sigma_M^2}{\mu_M^4}\right)\right)\right\}$$

$$= k'^2 \left\{ \left(\frac{\sigma_R^2}{\mu_M^2} + \frac{3\sigma_M^2\sigma_R^2}{\mu_M^2} + \frac{\mu_R^2}{\mu_M^2} + \frac{3\sigma_M^2\mu_R^2}{\mu_M^2} \right) - \left(\frac{\mu_R^2}{\mu_M^2} + \frac{\mu_R^2\sigma_M^4}{\mu_M^6} + 2\,\frac{\mu_R^2\sigma_M^2}{\mu_M^4} \right) \right\}$$

$$= k'^2 \left\{ \frac{\sigma_R^2}{\mu_M^2} + \frac{\sigma_M^2}{\mu_M^2} \left(3\sigma_R^2 + 3\mu_R^2 - \frac{\sigma_M^2\mu_R^2}{\mu_M^4} - \frac{2\mu_R^2}{\mu_M^2} \right) \right\}$$

$$V(Y) = k'^2 \left\{ \frac{\sigma_R^2}{\mu_M^2} + \frac{\sigma_M^2}{\mu_M^2} \left(3\sigma_R^2 + 3\mu_R^2 - \frac{\sigma_M^2\mu_R^2}{\mu_M^4} - \frac{2\mu_R^2}{\mu_M^2} \right) \right\} \text{ ------------- (30)}$$

$$\Longrightarrow \sigma_Y = k \sqrt{ \left\{ \frac{\sigma_R^2}{\mu_M^2} + \frac{\sigma_M^2}{\mu_M^2} \left(3\sigma_R^2 + 3\mu_R^2 - \frac{\sigma_M^2\mu_R^2}{\mu_M^4} - \frac{2\mu_R^2}{\mu_M^2} \right) \right\} }$$

From above, it can be observed that any variation in the input parameter means and variances has a significant impact on the output variance of amount of dye absorbed. Using the dynamic means and standard deviation from above, dynamic control limits can be obtained as follows:

$$Dynamic\ CL = \mu_{Y(\mu_x,\sigma_x)} \pm 3\, \sigma_{Y(\mu_x,\sigma_x)}$$

Thus, the dynamic control system reveals the exact state of the dyebath, providing a real opportunity for the dyer to adjust variables during the exhaustion process to achieve the correct outcome. Also, this novel system creates profiles for real-time variations in both input factors and output material, thus providing the dyer with an ability to determine and analyze the root-cause for variations occurred when matching the shade to its master. This system not only provides the dyer with an ability to predict and control dyeing process output with great precision based on real-time monitoring of key input parameters and using structural equations, but also helps in minimizing run times by reducing or eliminating unnecessary stoppage time in exhaustion/fixation/washing.

Chapter 5

Concept Validation and Graphical Illustration

Validation of a concept (existing or newly developed) is a process of ensuring that it is a true representation of the theoretical framework incorporated in its design. It helps to understand whether the newly developed system operates as per design, effectively and efficiently. Moreover, it enables decision-making based on solid evidence, strengthening the case to conclude that the newly developed model is actually valid. It also provides an opportunity to identify areas for improvement. Hence, it is one of the most important steps in verification of a new concept, model or system.

In order to validate the Dynamic Quality Control System (DQCS), continuous dyeing process is used as a case study and time dependent data of key input parameters is simulated such that it reflects the true variations in input parameters and accurately predicts the amount of dye absorbed onto the material. As described in figure 7 below, the novel DQCS conceptual framework is explained through application examples, which are validated through data simulation technique. Also, the DQCS conceptual framework is explained through the use of a graphical simulation a technique, which is explained in Section 5.2.

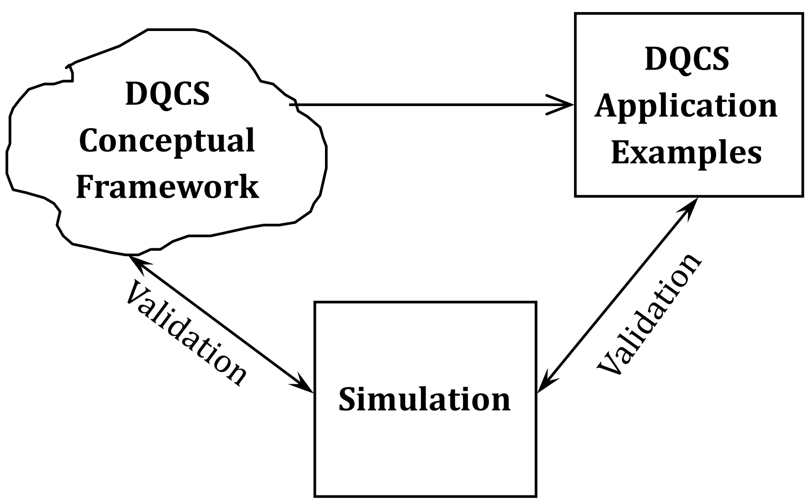

Figure 7: Validation steps for Dynamic Control Chart Concept

5.1 Concept Validation using Data Simulation

In order to validate the DQCS concept, the *mean* and *standard deviation* values of continuous dyeing process output variable (*amount of dye absorbed onto fabric*) obtained through mathematical calculation (as explained in Section 3.4.1) is compared with the values obtained through simulation using Microsoft Excel program. The data simulated is random in nature and follows the hypothesis that every continuous processing sequence has certain amount of bias inherited in it. Variance components are generated around 'zero' mean and standard deviation calculated based on the tolerance allowed for each input factor. For example, for input factor – rate of dyeing, a 10% amount of variation (CV%) and for parameter - mass of fabric, a 5% amount of variation is considered. This implies that variance components are generated around the parameter means with 17.60 $dm^3 min^{-1}$ and 6.90 gsm standard deviations respectively. These variance components are added to the randomly generated input parameter values. Now, output parameter (*amount of dye absorbed onto fabric*) values are calculated using the structural equation that exhibits the relationship between input parameters (*rate of dyeing* and *mass of fabric*) and output parameter. These output values are a true representation of continuous dyeing process variables. This approach provides a valuable insight on the accuracy of mathematical calculations and theoretical assumptions made in designing the system.

Although, real-time data obtained from actual dye-processing houses would have been ideal to compare and contrast the output obtained through mathematical calculations and real-world, due to time and resource constraints, only simulated data is being used for this purpose. There will several limitations even if the data would have been obtained from actual dye-houses as the inconsistency in operations and procedures followed in dye-houses across the globe. So, this approach may be the only feasible approach (if not the ideal one). The results obtained clearly show that there is output means and standard deviations obtained through mathematical calculations and simulations are positively correlated.

Table 5. Comparing Theoretical and Simulated Means and Standard Deviations

Theoretical	Mean	80.29	**Simulated**	Mean	78.58
	SD	27.50		SD	27.00

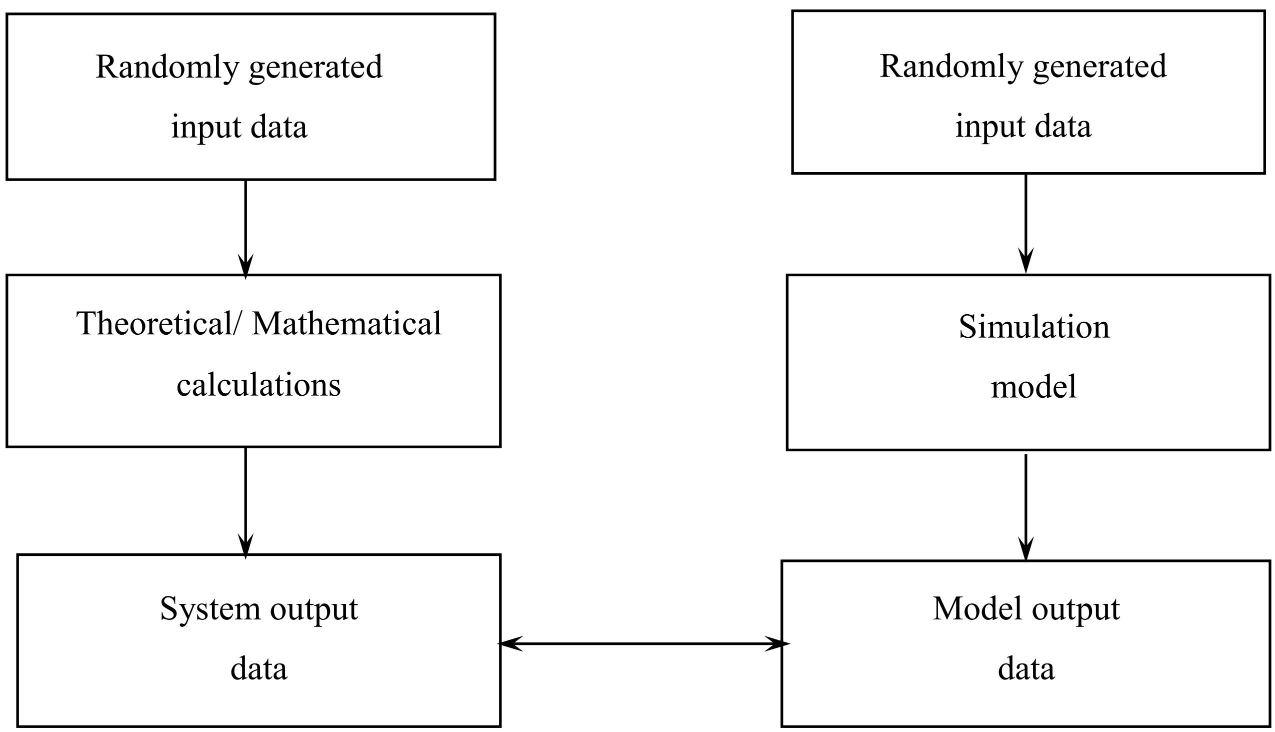

Figure 8. Framework for Concept Validation

Time	Fabric Speed	Dye bath flow rate (w/bias)	10% Error component	Actual Dye bath flow rate (w/variance)	Avg. Dye bath flow rate	Mass of fabric (w/bias)
hr	$m\ min^{-1}$	$dm^3\ min^{-1}$	(Variance)			$g\ m^{-1}$
	V	R		R'	R"	M
0.1	5	81	10.54610147	91.54610147	93.48	130
0.2	5	82	-14.86619122	67.13380878	93.48	132
0.3	6	83	-2.92241366	80.07758634	93.48	134
0.4	6	84	12.32496196	96.32496196	93.48	135
0.5	7	84	28.33470635	112.3347064	93.48	136
0.6	9	86	25.28523123	111.2852312	93.48	137
0.7	10	87	19.94864976	106.9486498	93.48	140
0.8	11	89	30.36768977	119.3676898	93.48	140
0.9	12	94	-19.69452684	74.30547316	93.48	141
1	14	94	-19.69452684	74.30547316	93.48	142
1.1	16	97	-10.03785561	86.96214439	93.48	143
1.2	16	98	6.98838049	104.9883805	93.48	144
1.3	18	98	-2.002254738	95.99774526	93.48	145
1.4	18	99	26.30172294	125.3017229	93.48	145
1.5	21	99	21.98163318	120.9816332	93.48	146
1.6	22	102	-23.25224781	78.74775219	93.48	147
1.7	23	102	3.938905367	105.9389054	93.48	148
1.8	23	102	-20.96514147	81.03485853	93.48	148
1.9	23	102	3.68478244	105.6847824	93.48	149
2	24	103	29.60532099	132.605321	93.48	149

Figure 9a. Simulation of Input data using Microsoft Excel software

5% Error component	Actual Mass of fabric (w/variance)	Avg. Mass of fabric (w/bias)	Amount of Dye adsorbed onto material (Y)						
(Variance)	g/m	g/m	g/gm of fabric						
	M'	M"	Y = k' (R/M)		Y' = k' (R'/M')			Variance	
4.813600422	134.8136004	146.90	0.03595	35.95366	0.03918	5.00000	36.86	0.00323	-30.95366
0.962720084	132.9627201	146.90	0.03585	35.84605	0.02913	29.13485	36.86	-0.00671	-6.71120
1.971283982	135.9712840	146.90	0.03574	35.74166	0.03398	33.98327	36.86	-0.00176	-1.75839
-4.538537541	130.4614625	146.90	0.03590	35.90434	0.04260	42.60475	36.86	0.00670	6.70041
-4.26347466	131.7365253	146.90	0.03564	35.64034	0.04920	49.20499	36.86	0.01356	13.56466
6.372290083	143.3722901	146.90	0.03622	36.22258	0.04479	44.78925	36.86	0.00857	8.56667
-10.68160856	129.3183914	146.90	0.03586	35.85854	0.04772	47.72176	36.86	0.01186	11.86322
6.097227201	146.0972272	146.90	0.03668	36.68288	0.04715	47.14615	36.86	0.01046	10.46327
7.289166354	148.2891664	146.90	0.03847	38.46894	0.02891	28.91431	36.86	-0.00955	-9.55463
4.905288049	146.9052880	146.90	0.03820	38.19803	0.02919	29.18669	36.86	-0.00901	-9.01134
-9.948107539	133.0518925	146.90	0.03914	39.14147	0.03771	37.71470	36.86	-0.00143	-1.42677
-1.696221101	142.3037789	146.90	0.03927	39.27037	0.04257	42.57221	36.86	0.00330	3.30184
8.389417879	153.3894179	146.90	0.03900	38.99954	0.03611	36.11329	36.86	-0.00289	-2.88625
6.739040591	151.7390406	146.90	0.03940	39.39750	0.04765	47.64981	36.86	0.00825	8.25231
-2.613097372	143.3869026	146.90	0.03913	39.12765	0.04869	48.68682	36.86	0.00956	9.55917
10.58992093	157.5899209	146.90	0.04004	40.03910	0.02883	28.83442	36.86	-0.01120	-11.20468
8.572793133	156.5727931	146.90	0.03977	39.76856	0.03904	39.04277	36.86	-0.00073	-0.72579
-9.764732285	138.2352677	146.90	0.03977	39.76856	0.03383	33.82630	36.86	-0.00594	-5.94227
10.31485805	159.3148580	146.90	0.03950	39.50166	0.03828	38.27874	36.86	-0.00122	-1.22292
-2.796472626	146.2035274	146.90	0.03989	39.88893	0.05234	52.33648	36.86	0.01245	12.44755
0.77934483	150.7793448	146.90	0.04039	40.39238	0.03644	36.43936	36.86	-0.00395	-3.95302
6.188914829	157.1889148	146.90	0.04051	40.50703	0.02982	29.81663	36.86	-0.01069	-10.69039

Figure 9b. Simulation of Output data using Microsoft Excel software

5.2 Graphical Representation of Dynamic Quality Control System

Computer simulations have become an indispensable tool in modern scientific investigations to promote understanding of probabilistic problems. According to Ören (2011) "*Computer simulation is the process of designing a model of a real system, implementing the model as a computer program, and conducting experiments with the model for the purpose of understanding the behavior of the system, or evaluating strategies for the operation of the system"*. To present the novel concept of Dynamic Quality Control, graphical illustrations have been used that can bring out the essence of this idea succinctly. A HTML5 program has been written in the Application Programming Interface (API) Highcharts. Highcharts is a charting library offering intuitive, interactive charts for dynamic illustration purposes. Highcharts is an ideal tool for anyone to create graphics without having to actually learn JavaScript like a seasoned developer.

One of the main objectives of developing this dynamic graphical representation (simulation) is to be able to provide an actual and simplistic representation of the concept of Dynamic Quality Control System to even those people who are not familiar with Concept of Control Charts. As discussed in the section above, the theoretical assumptions made in design and development of this system have been tested quantitatively. As mentioned above, HTML5 language was used to write program to compare the effect of variance components in input parameters on output parameter. The HTML5 program/code has been listed as Appendix 1 and 2. As it can be observed below, the Figure 11 clearly shows the impact of variance components in input parameters on output variable.

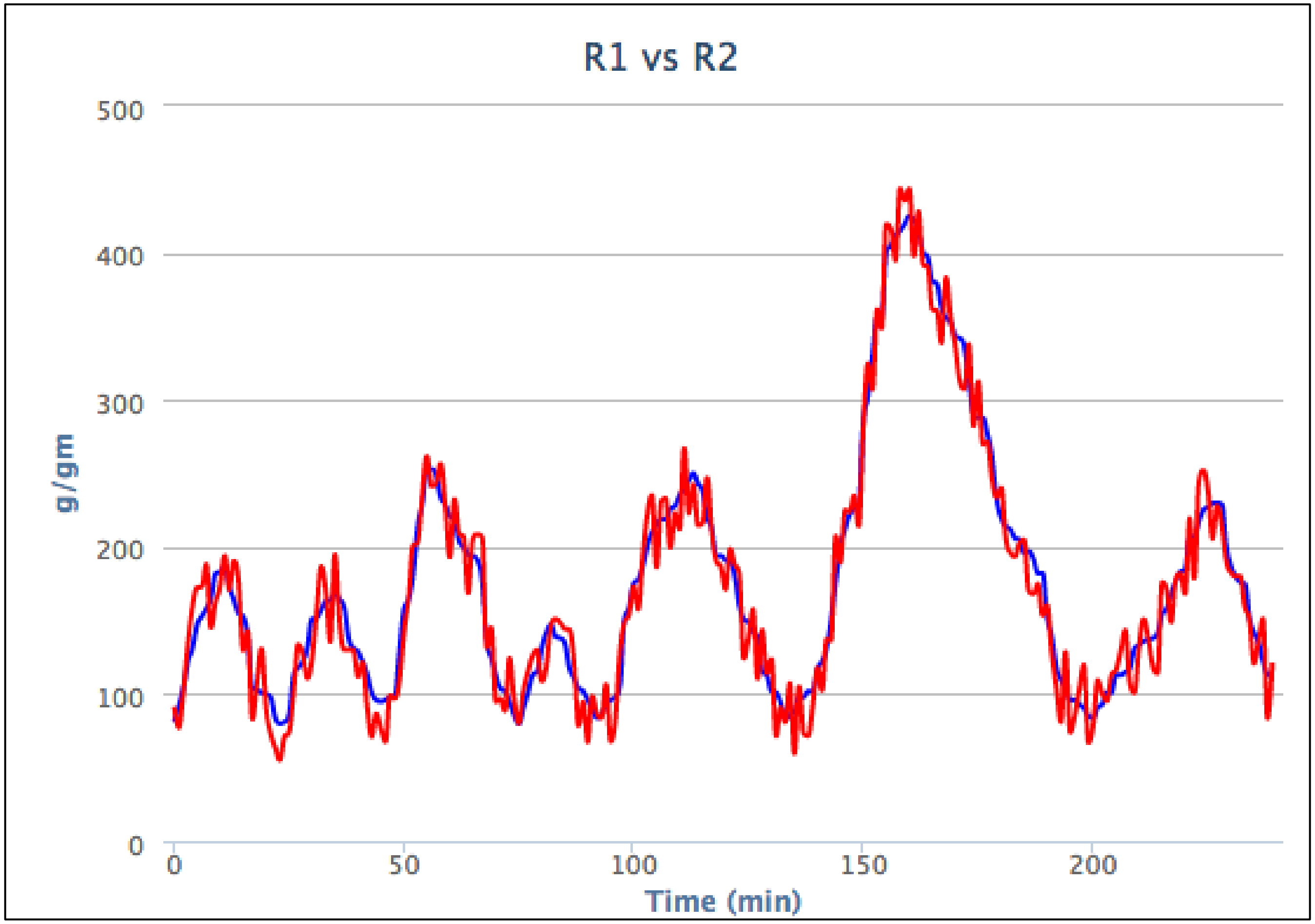

Figure 10a. Comparison of input parameter Rate of Dyeing (R) with and without variance components

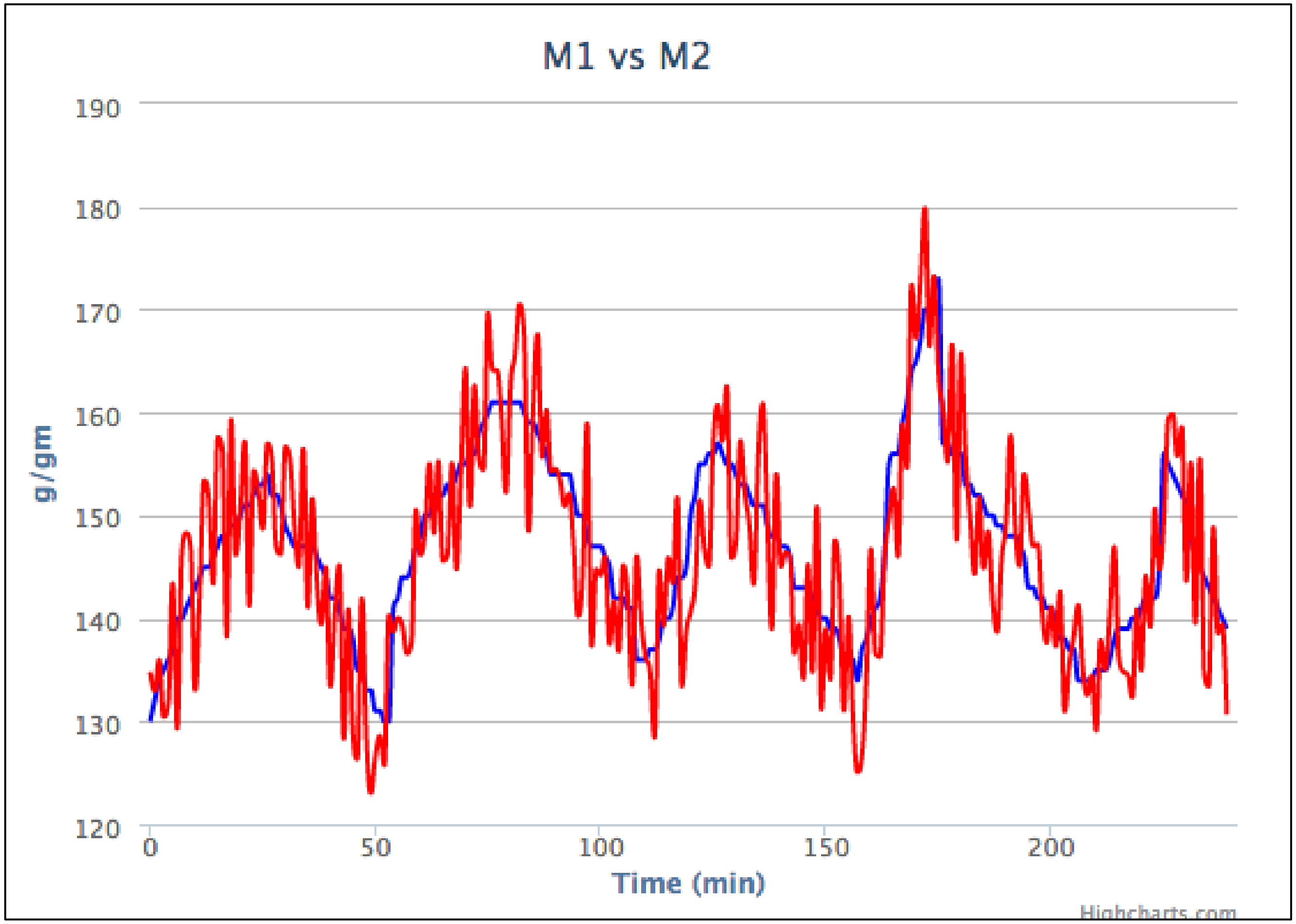

Figure 10b. Comparison of input parameter Mass of fabric (M) with and without variance components

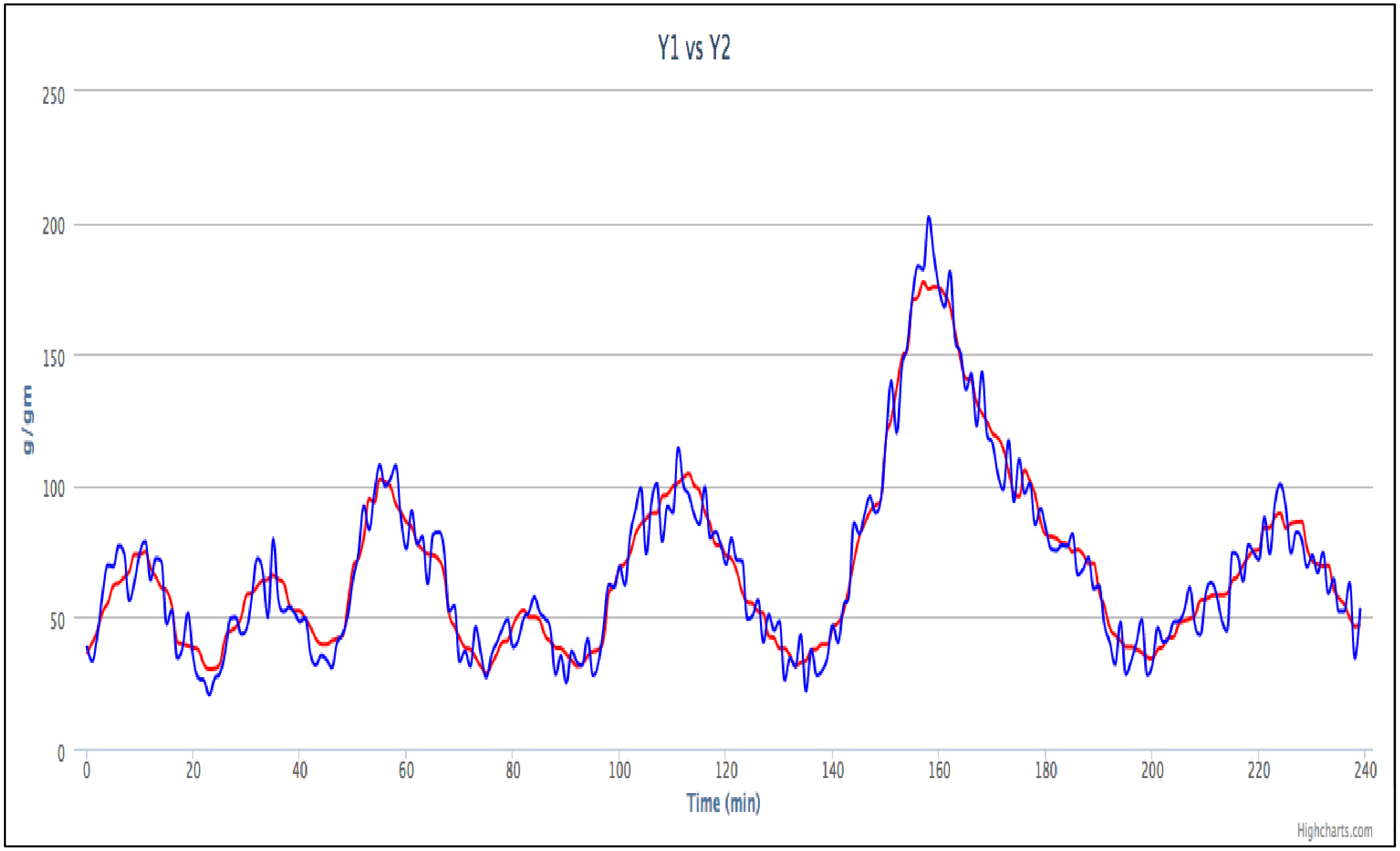

Figure 11. Output parameter (amount of dye absorbed) based on input parameters R & M

This second program was written to represent the concept of Dynamic Quality Control System dynamically. Using the simulated data discussed earlier, a conventional static control chart and a dynamic control chart are plotted and compared against each other. The plots identify the time periods when the output parameter is out of control. This plot also highlights those areas that are out-of-control *w.r.t* both static and dynamic control limits (as discussed in section 3.5). Thus, the dynamic control chart effectively explains the concept of Dynamic Quality Control and highlights the need for development of a newer and enhanced control chart method.

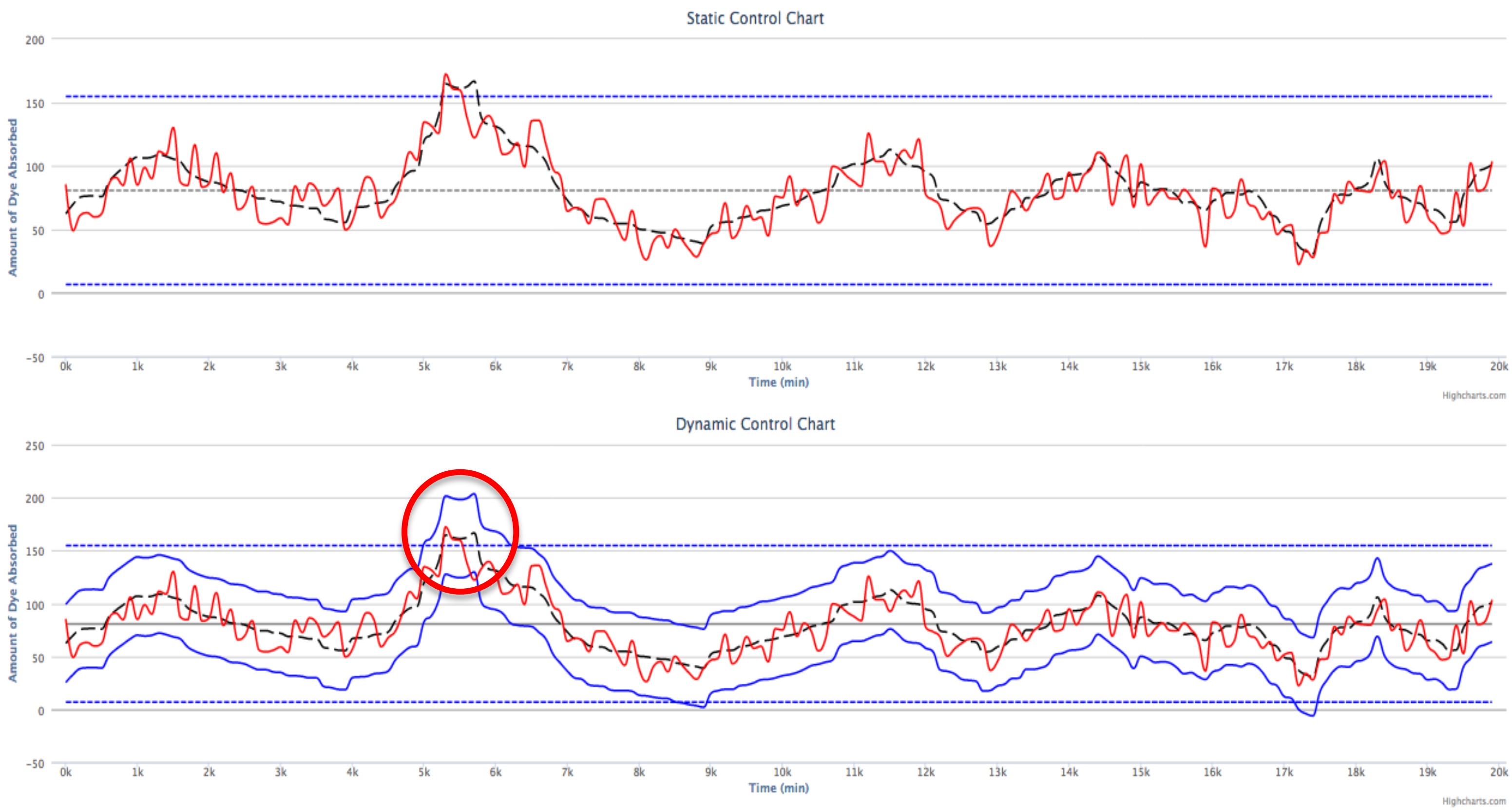

Figure 12. Shewhart Control Chart vs. Dynamic Control Chart

Chapter 6

Major Results & Future Work

Key Accomplishments:

I. **Successfully developed a general working model of a dynamic process control system:** A conceptual framework has been designed and developed to construct a *Dynamic Quality Control System* for any continuous manufacturing processes. In this novel system, the expected process average and expected process variance at the end of each process stage can be expressed as functions of the means and variances of the previous processes in order to establish a set of dynamic control limits that are responsive to the process errors (biases) of the previous processes.

II. **Successfully applied Dynamic Process/Quality Control System in Ring Spinning and Continuous Dyeing processes:** The dynamic process control system has been applied in staple yarn spinning and continuous dyeing process. Process parameters that have significant influence of the process were studied and an extensive literature review was carried out to scout desirable structural equations that form a true relationship between those input and output variables.

III. **Successfully applied *Variance Tolerancing* Schemes to obtain "Dynamic Control Limits":** Variance tolerancing was achieved through structural/functional relationships using Taylor's series expansion. Traditional static process averages and the corresponding control limits and dynamic process averages and corresponding control limits were calculated. The output variance was computed as a function of input means and standard deviations.

IV. **Successfully validated the concept of Dynamic Process/Quality Control:** Using simulated data, the novel concept of dynamic control was verified and validated. Theoretically/mathematically calculated dynamic means and variances were compared against the simulated values and the significant correlation was observed.

V. **Successfully developed a software program for graphical illustration:** A software program was developed for Dynamic Quality Control System that includes dynamic process averages, their matching dynamic control limits and the graphical representation of dynamic control charts for selected processes based on simulated data.

Contribution to the Industry

By monitoring quality using this novel technique of Dynamic Quality Control System, textile producers and manufacturers (both domestic and international) will be able to:

- generate optimal control strategy at each process stage through more accurate control limits
- minimize/eliminate the unnecessary corrective actions (false positives) by determining the actual root-causes of out-of-control situations
- minimize the impact when the out-of-control causes an irreversible damage
- reduce quality costs by minimizing loss of production time and materials
- increase their competitive position in the globe by producing high quality textile products at lowest price

Limitations of this study

The findings of this study contribute significantly to the literature of development of quality and process control of continuous/contiguous manufacturing systems. However, this study has several limitations. The structural equations used in developing a framework of quality/process control systems are often unreliable. Realistically, there are too many equations available in the literature for the same parameters. Moreover, the significance of parameters to a particular processing sequence is very hard to determine as there may be various researchers across the globe who would compliment or contradict the theory proposed. Hence, the validity of the structural equations used was not examined in this research.

Moreover, compounding of structural equations is often quite challenging for more than 2 stage processes. This is a complex topic area, as it requires advance mathematical computational softwares. Although, this research work does not provide any frameworks to solve multiple structural equations, this research team has been successful in providing linkage between stages of processing using structural equations. Ongoing research related to the scouting out the most important parameters in a given manufacturing sequence such as textile complex is required understand and address the needs of a complex and dynamic nature of processing.

Future Work

As a sequel to this work, the concept can be extended using structural equations based on other key processing parameters in textile processes (spinning, dyeing, finishing etc). The on-line real-time dynamic control system will be more readily acceptable to any continuous process by considering if all relevant input and output factors and variables, including the basis weight, mass uniformity, uniformity of physical properties, dimensional properties, speeds of fabric and dye flows, moisture contents, liquor ratio, dye concentration, dye injection rate, fabric speed, bath temperature, etc were considered. While the relationships among these variables have been studied in the past, the process averages have seldom been linked in terms of structural relationships. Therefore, establishing a set of dynamic control limits for an on-line, real-time system would be a significant challenge. Also, it can be verified using actual industrial data.

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Suh, M.W., Koo H.J. & Woo J.L. (2001). Variance tolerancing and decomposition in short staple spinning processes, Part II - Simulation and application to ring carded, ring combed and o-e spun yarns. *Textile Res. J. Vol.*71(2), 105-111.

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APPENDICES

Appendix A

Y$_1$ $\left(\boldsymbol{f}(\boldsymbol{M_1}, \boldsymbol{R_1}) - \textbf{without variance component}\right)$ vs. Y$_2$$\left(\boldsymbol{f}(\boldsymbol{M_2}, \boldsymbol{R_2}) - \textbf{without variance component}\right)$

```
<!DOCTYPE HTML>
<html>
    <head>
        <meta http-equiv="Content-Type" content="text/html; charset=utf-8">
        <title>Highcharts Example</title>
        <script type="text/javascript"
src="http://ajax.googleapis.com/ajax/libs/jquery/1.8.2/jquery.min.js"></script>
        <script type="text/javascript">
$(function () {
    $(document).ready(function() {
        Highcharts.setOptions({
            global: {
                useUTC: false
            }
        });
        var myChart;
        myChart = new Highcharts.Chart({
            chart: {
                renderTo: 'R1 vs R2',
                type: 'spline',
```

```
marginRight: 50,
events: {
  load: function() {
    i=0;
    var R1 =
[81,92,101,103,104,104,122,131,139,147,153,153,155,158,157,155,153,142,137,133,131,13
1,128,124,124,122,118,113,113,109,107,102,101,100,98,98,86,84,81,80,95,96,96,98,99,101,
113,122,127,129,157,164,181,214,229,229,234,240,200,195,194,191,178,177,176,175,168,1
58,137,125,113,104,102,95,94,94,89,88,88,87,81,80,78,76,75,70,68,65,63,60,80,84,86,86,90,
90,93,96,96,98,101,102,104,106,111,113,115,118,131,135,138,139,142,147,151,158,153,147
,144,144,142,139,115,113,110,102,101,99,84,85,91,93,101,101,113,113,115,118,131,133,13
6,137,138,141,154,148,140,132,122,106,122,118,113,113,110,104,96,96,93,90,101,105,112,
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14,112,106,105,96,97,92,82,82,110,122,135,139,142];
    var R2 =
[108.06,66.71,75.46,87.37,87.35,77.95,127.97,130.87,126.42,153.48,123.39,150.33,129.46,1
60.41,161.96,180.29,152.11,126.37,167.37,122.71,128.08,157.05,124.32,140.39,101.00,105.
86,136.42,87.46,96.35,81.43,90.86,95.52,113.58,105.72,122.27,115.66,94.00,98.61,109.84,6
5.90,83.44,101.72,123.57,114.39,81.85,90.96,99.40,121.11,155.34,139.04,177.20,162.09,170
.45,236.24,234.72,218.71,237.18,211.16,223.00,191.57,197.94,170.29,159.07,183.23,149.70,
205.11,194.81,181.76,158.47,152.32,106.01,124.71,94.76,92.08,114.97,113.69,96.75,82.54,6
5.76,97.29,58.51,49.63,66.18,81.46,65.72,80.80,70.92,52.17,45.59,56.32,76.06,76.00,115.61,
76.22,81.49,118.84,80.67,81.64,79.86,108.04,102.40,128.30,101.08,110.96,99.69,93.31,89.7
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5,94.40,59.63,110.02,128.76,101.71,112.33,144.78,126.40,119.84,95.07,103.94,80.86,81.89,
93.87,35.68,59.43,49.82,93.89,87.13,125.02,110.71,128.51,148.20,117.96,122.39,138.00,151
.93,111.23,118.70,96.88,99.77,128.76,85.45,80.10,66.46,70.18,109.06,81.41,148.30,116.32,1
22.10,148.99];
            var series1=this.series[0];
            var series2=this.series[1];
            setInterval(function() {
              series1.addPoint (data[i], true,true);
              series2.addPoint (data[i], true,true);
              i++;
              if(i==199)
              i=0;
            }, 1000);
          }
        }
      },
      title: {
        text: 'Rate of Dyeing'
      },
      xAxis: {
      title: {
      text: 'Time (min)'
      },
```

```
startOnTick : false
},
yAxis: {
   title: {
      text: 'dm^3 min^-1'
   },
   plotLines: [{
      value: 0,
      width: 1,
      color: '#808080'
   }]
},
tooltip: {
   formatter: function() {
         return '<b>'+ this.series.name +'</b><br/>'+
         Highcharts.numberFormat(this.y, 2);
   }
},
legend: {
   enabled: false
},
  plotOptions: {
   spline: {
```

```
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        states: {
            hover: {
                lineWidth: 3
            }
        },
        marker: {
            enabled: false
        },
    },
     series: {
    animation: {
        duration: 25000
    }
}
},
exporting: {
    enabled: false
},
series: [{
    name: 'R1',
    type: 'spline',
   color: 'blue',
```

```
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90,93,96,96,98,101,102,104,106,111,113,115,118,131,135,138,139,142,147,151,158,153,147
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115,120,125,122,114,100,97,81,79,63,56,53,93,102,116,121,120,128,128,137,161,133,120,1
14,112,106,105,96,97,92,82,82,110,122,135,139,142]
         },
        {
            name: 'R2',
           type: 'spline',
           color: 'red',
            data:
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93.87,35.68,59.43,49.82,93.89,87.13,125.02,110.71,128.51,148.20,117.96,122.39,138.00,151
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22.10,148.99]
            } ,
            ]
        });
    });
});
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    $(document).ready(function() {
        Highcharts.setOptions({
            global: {
                useUTC: false
            }
        });
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            chart: {
                renderTo: 'M1 vs M2',
```

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65,167,170,170,172,173,157,157,156,156,156,153,153,152,152,151,150,150,149,149,148,14
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34.05,133.29,132.53,146.62,132.21,135.29,135.10,138.10,134.22,134.22,132.66,139.91,132.
94,131.66,123.13,135.59,137.15,145.98,136.89,172.08,172.59,167.49,137.33,154.07,155.95,
143.33,155.18,150.86,151.34,143.33,155.46,162.71,166.23,164.55,185.61,145.13,168.27,155
.94,153.57,149.05,159.74,157.82,150.25,153.85,189.34,163.22,181.22,184.29,161.34,169.95,
152.86,160.02,144.57,164.27,157.54,163.07,176.49,161.91,173.25,139.97,136.89,177.37,141
.89,136.49,139.45,146.50,136.29,134.73,168.81,134.93,137.58,132.46,143.87,146.99,132.86,
```

```
135.50,147.07,132.49,168.59,135.29,149.11,147.42,138.21,160.27,156.98,165.99,179.01,155
.70,163.15,183.05,164.59,159.74,156.38,164.75,158.11,163.15,159.15,143.73,161.51,154.78,
153.26,177.86,178.37,136.25,170.25,170.27,169.56,145.82,165.49,171.08,167.29,137.58,145
.71,148.95,161.74,163.27,144.07,137.62,139.66,136.18,141.39,145.59,164.05,133.69,161.97,
171.86,175.35,161.79,179.76,177.98,163.62,162.86,174.99,158.33,175.35,158.77,175.71,178
.19,199.30,182.03,160.30,156.66,146.69,182.30,146.93,153.66,147.26,146.05,149.02,147.42,
174.78,153.50,152.66,140.49,148.42,141.57,144.42,137.65,154.11,144.98,144.94,147.23,143
.82];
            var series1=this.series[0];
            var series2=this.series[1];
            setInterval(function() {
              series1.addPoint (data[i], true,true);
              series2.addPoint (data[i], true,true);
              i++;
              if(i==199)
              i=0;
            }, 1000);
          }
        }
      },
      title: {
        text: 'Mass of Fabric'
      },
      xAxis: {
      title: {
```

```
text: 'Time (min)'
},
startOnTick : false
},
yAxis: {
   title: {
      text: 'gsm'
   },
   plotLines: [{
      value: 0,
      width: 1,
      color: '#808080'
   }]
},
tooltip: {
   formatter: function() {
         return '<b>'+ this.series.name +'</b><br/>'+
         Highcharts.numberFormat(this.y, 2);
   }
},
legend: {
   enabled: false
},
```

```
  plotOptions: {
   spline: {
       lineWidth: 2,
       states: {
           hover: {
               lineWidth: 3
           }
       },
       marker: {
           enabled: false
       },
   },
    series: {
   animation: {
       duration: 25000
   }
}
},
exporting: {
   enabled: false
},
series: [{
   name: 'M1',
```

```
            type: 'spline',
           color: 'blue',
            data:
[130,132,134,135,136,137,140,140,141,142,143,144,145,145,146,147,148,148,149,149,150,
151,151,152,153,153,154,152,152,151,149,148,147,147,147,147,147,146,145,144,142,142,1
41,139,139,138,135,135,133,133,131,131,130,130,141,142,144,144,145,147,148,150,150,15
2,152,152,153,153,154,155,155,156,156,158,159,160,161,161,161,161,161,161,161,160,159,
159,158,157,156,154,154,154,154,154,152,150,150,148,147,147,147,146,145,142,142,142,1
41,141,136,136,136,137,137,138,140,140,141,144,144,145,150,152,155,155,156,156,157,15
6,155,155,154,153,153,152,151,151,151,149,148,148,147,147,146,143,143,143,143,142,141,
140,140,139,139,138,136,136,136,134,137,138,140,141,142,146,155,156,156,159,161,164,1
65,167,170,170,172,173,157,157,156,156,156,153,153,152,152,151,150,150,149,149,148,14
8,148,147,146,143,143,142,142,141]
        },
        {
            name: 'M2',
           type: 'spline',
           color: 'red',
            data:
[126.34,135.78,123.61,138.54,146.03,125.05,149.55,144.02,149.11,144.94,145.10,152.23,14
3.74,143.86,148.58,138.53,174.56,149.14,143.53,147.02,148.50,142.53,156.71,148.70,153.5
4,151.74,163.07,156.86,177.03,145.41,154.23,177.35,135.05,145.26,141.65,141.53,136.97,1
34.05,133.29,132.53,146.62,132.21,135.29,135.10,138.10,134.22,134.22,132.66,139.91,132.
94,131.66,123.13,135.59,137.15,145.98,136.89,172.08,172.59,167.49,137.33,154.07,155.95,
143.33,155.18,150.86,151.34,143.33,155.46,162.71,166.23,164.55,185.61,145.13,168.27,155
.94,153.57,149.05,159.74,157.82,150.25,153.85,189.34,163.22,181.22,184.29,161.34,169.95,
```

```
152.86,160.02,144.57,164.27,157.54,163.07,176.49,161.91,173.25,139.97,136.89,177.37,141
.89,136.49,139.45,146.50,136.29,134.73,168.81,134.93,137.58,132.46,143.87,146.99,132.86,
135.50,147.07,132.49,168.59,135.29,149.11,147.42,138.21,160.27,156.98,165.99,179.01,155
.70,163.15,183.05,164.59,159.74,156.38,164.75,158.11,163.15,159.15,143.73,161.51,154.78,
153.26,177.86,178.37,136.25,170.25,170.27,169.56,145.82,165.49,171.08,167.29,137.58,145
.71,148.95,161.74,163.27,144.07,137.62,139.66,136.18,141.39,145.59,164.05,133.69,161.97,
171.86,175.35,161.79,179.76,177.98,163.62,162.86,174.99,158.33,175.35,158.77,175.71,178
.19,199.30,182.03,160.30,156.66,146.69,182.30,146.93,153.66,147.26,146.05,149.02,147.42,
174.78,153.50,152.66,140.49,148.42,141.57,144.42,137.65,154.11,144.98,144.94,147.23,143
.82]
           } ,
            ]
        });
    });
});
  </script>
        <script type="text/javascript">
$(function () {
    $(document).ready(function() {
        Highcharts.setOptions({
            global: {
                useUTC: false
            }
        });
        var myChart;
```

```
myChart = new Highcharts.Chart({
  chart: {
    renderTo: 'Y1 vs Y2',
    type: 'spline',
    marginRight: 50,
    events: {
      load: function() {
        i=0;
        var Y1 =
[62.31,69.70,75.37,76.30,76.47,75.91,87.14,93.57,98.58,103.52,106.99,106.25,106.90,108.9
7,107.53,105.44,103.38,95.95,91.95,89.26,87.33,86.75,84.77,81.58,81.05,79.74,76.62,74.34,
74.34,72.19,71.81,68.92,68.71,68.03,66.67,66.67,58.50,57.53,55.86,55.56,66.90,67.61,68.09,
70.50,71.22,73.19,83.70,90.37,95.49,96.99,119.85,125.19,139.23,164.62,162.41,161.27,162.
50,166.67,137.93,132.65,131.08,127.33,118.67,116.45,115.79,115.13,109.80,103.27,88.96,8
0.65,72.90,66.67,65.38,60.13,59.12,58.75,55.28,54.66,54.66,54.04,50.31,49.69,48.45,47.50,4
7.17,44.03,43.04,41.40,40.38,38.96,51.95,54.55,55.84,55.84,59.21,60.00,62.00,64.86,65.31,6
6.67,68.71,69.86,71.72,74.65,78.17,79.58,81.56,83.69,96.32,99.26,101.47,101.46,103.65,106
.52,107.86,112.86,108.51,102.08,100.00,99.31,94.67,91.45,74.19,72.90,70.51,65.38,64.33,63
.46,54.19,54.84,59.09,60.78,66.01,66.45,74.83,74.83,76.16,79.19,88.51,89.86,92.52,93.20,94
.52,98.60,107.69,103.50,97.90,92.96,86.52,75.71,87.14,84.89,81.29,81.88,80.88,76.47,70.59,
71.64,67.88,65.22,72.14,74.47,78.87,78.77,77.42,80.13,78.21,71.70,62.11,59.15,49.09,47.31,
37.06,32.94,30.81,53.76,64.97,73.89,77.56,76.92,82.05,83.66,89.54,105.92,87.50,79.47,76.0
0,74.67,71.14,70.47,64.86,65.54,62.16,55.78,56.16,76.92,85.31,95.07,97.89,100.71];
        var Y2
=[85.54,49.13,61.05,63.06,59.82,62.34,85.57,90.87,84.78,105.89,85.04,98.75,90.07,111.51,1
```

```
09.00,130.14,87.14,84.73,116.60,83.46,86.25,110.18,79.33,94.41,65.78,69.77,83.66,55.76,54
.43,56.00,58.92,53.86,84.10,72.78,86.31,81.72,68.63,73.56,82.41,49.72,56.91,76.94,91.34,84
.67,59.27,67.77,74.06,91.30,111.03,104.59,134.59,131.64,125.72,172.25,160.78,159.76,137.
83,122.35,133.14,139.50,128.48,109.20,110.98,118.07,99.23,135.53,135.92,116.92,97.40,91.
63,64.43,67.19,65.29,54.72,73.73,74.03,64.91,51.67,41.67,64.75,38.03,26.21,40.55,44.95,35.
66,50.08,41.73,34.13,28.49,38.95,46.30,48.24,70.89,43.18,50.33,68.60,57.64,59.64,45.03,76.
14,75.02,92.00,68.99,81.41,73.99,55.27,66.49,99.72,97.46,91.80,87.57,83.87,125.71,103.67,
103.71,92.59,105.67,112.48,106.21,121.19,77.42,73.41,68.13,50.28,57.18,62.44,66.35,66.87,
63.00,36.89,45.29,62.44,80.21,74.24,64.92,73.98,80.45,93.99,74.01,75.49,94.87,80.10,92.32,
97.62,110.57,106.40,69.28,93.26,108.35,67.78,101.44,69.26,76.14,81.52,74.67,74.19,81.41,7
5.36,64.84,36.35,82.29,79.50,59.18,64.06,89.49,70.31,67.33,58.10,63.82,46.21,51.72,53.53,2
2.47,33.82,27.96,47.11,47.87,77.99,70.67,87.61,81.30,80.28,79.65,93.72,104.02,74.64,80.52,
55.43,65.00,84.34,60.82,53.97,46.94,48.60,79.23,52.83,102.29,80.25,82.93,103.59];
            var series1=this.series[0];
            var series2=this.series[1];
            setInterval(function() {
               series1.addPoint (data[i], true,true);
               series2.addPoint (data[i], true,true);
               i++;
               if(i==199)
               i=0;
            }, 1000);
         }
      }
   },
```

```
title: {
            text: 'Amount of Dye absorbed onto material'
        },
        xAxis: {
        title: {
        text: 'Time (min)'
        },
        startOnTick : false
        },
        yAxis: {
           title: {
               text: 'gm/gmm-2'
           },
           plotLines: [{
               value: 0,
               width: 1,
               color: '#808080'
           }]
        },
        tooltip: {
           formatter: function() {
```

```
return '<b>'+ this.series.name +'</b><br/>'+
            Highcharts.numberFormat(this.y, 2);
        }
    },
    legend: {
        enabled: false
    },
      plotOptions: {
        spline: {
            lineWidth: 2,
            states: {
                hover: {
                    lineWidth: 3
                }
            },
            marker: {
                enabled: false
            },
        },
         series: {
        animation: {
            duration: 35000
        }
```

```
        }
        },
        exporting: {
            enabled: false
        },
        series: [{
            name: 'Y1',
            type: 'spline',
           color: 'blue',
            data:
[62.31,69.70,75.37,76.30,76.47,75.91,87.14,93.57,98.58,103.52,106.99,106.25,106.90,108.9
7,107.53,105.44,103.38,95.95,91.95,89.26,87.33,86.75,84.77,81.58,81.05,79.74,76.62,74.34,
74.34,72.19,71.81,68.92,68.71,68.03,66.67,66.67,58.50,57.53,55.86,55.56,66.90,67.61,68.09,
70.50,71.22,73.19,83.70,90.37,95.49,96.99,119.85,125.19,139.23,164.62,162.41,161.27,162.
50,166.67,137.93,132.65,131.08,127.33,118.67,116.45,115.79,115.13,109.80,103.27,88.96,8
0.65,72.90,66.67,65.38,60.13,59.12,58.75,55.28,54.66,54.66,54.04,50.31,49.69,48.45,47.50,4
7.17,44.03,43.04,41.40,40.38,38.96,51.95,54.55,55.84,55.84,59.21,60.00,62.00,64.86,65.31,6
6.67,68.71,69.86,71.72,74.65,78.17,79.58,81.56,83.69,96.32,99.26,101.47,101.46,103.65,106
.52,107.86,112.86,108.51,102.08,100.00,99.31,94.67,91.45,74.19,72.90,70.51,65.38,64.33,63
.46,54.19,54.84,59.09,60.78,66.01,66.45,74.83,74.83,76.16,79.19,88.51,89.86,92.52,93.20,94
.52,98.60,107.69,103.50,97.90,92.96,86.52,75.71,87.14,84.89,81.29,81.88,80.88,76.47,70.59,
71.64,67.88,65.22,72.14,74.47,78.87,78.77,77.42,80.13,78.21,71.70,62.11,59.15,49.09,47.31,
37.06,32.94,30.81,53.76,64.97,73.89,77.56,76.92,82.05,83.66,89.54,105.92,87.50,79.47,76.0
0,74.67,71.14,70.47,64.86,65.54,62.16,55.78,56.16,76.92,85.31,95.07,97.89,100.71]
        },
       {
```

```
            name: 'Y2',
           type: 'spline',
           color: 'red',
            data:
[85.54,49.13,61.05,63.06,59.82,62.34,85.57,90.87,84.78,105.89,85.04,98.75,90.07,111.51,10
9.00,130.14,87.14,84.73,116.60,83.46,86.25,110.18,79.33,94.41,65.78,69.77,83.66,55.76,54.
43,56.00,58.92,53.86,84.10,72.78,86.31,81.72,68.63,73.56,82.41,49.72,56.91,76.94,91.34,84.
67,59.27,67.77,74.06,91.30,111.03,104.59,134.59,131.64,125.72,172.25,160.78,159.76,137.8
3,122.35,133.14,139.50,128.48,109.20,110.98,118.07,99.23,135.53,135.92,116.92,97.40,91.6
3,64.43,67.19,65.29,54.72,73.73,74.03,64.91,51.67,41.67,64.75,38.03,26.21,40.55,44.95,35.6
6,50.08,41.73,34.13,28.49,38.95,46.30,48.24,70.89,43.18,50.33,68.60,57.64,59.64,45.03,76.1
4,75.02,92.00,68.99,81.41,73.99,55.27,66.49,99.72,97.46,91.80,87.57,83.87,125.71,103.67,1
03.71,92.59,105.67,112.48,106.21,121.19,77.42,73.41,68.13,50.28,57.18,62.44,66.35,66.87,6
3.00,36.89,45.29,62.44,80.21,74.24,64.92,73.98,80.45,93.99,74.01,75.49,94.87,80.10,92.32,9
7.62,110.57,106.40,69.28,93.26,108.35,67.78,101.44,69.26,76.14,81.52,74.67,74.19,81.41,75
.36,64.84,36.35,82.29,79.50,59.18,64.06,89.49,70.31,67.33,58.10,63.82,46.21,51.72,53.53,22
.47,33.82,27.96,47.11,47.87,77.99,70.67,87.61,81.30,80.28,79.65,93.72,104.02,74.64,80.52,5
5.43,65.00,84.34,60.82,53.97,46.94,48.60,79.23,52.83,102.29,80.25,82.93,103.59]
        } ,
         ]
      });
   });
});


      </script>
      <style>
```

```
            .myContainer1 {
    display: inline-block;
    height: 550px;
    width: 550px;
}
        .myContainer2 {
    display: inline-block;
    height: 550px;
    width: 550px;
}
        </style>
    </head>
    <body>
<script src="http://code.highcharts.com/highcharts.js"></script>
<script src="http://code.highcharts.com/modules/exporting.js"></script>
     <div id="R1 vs R2" class = "myContainer1" style="min-width: 400px; height: 400px;
margin: 0 "> </div>
     <div id="M1 vs M2" class = "myContainer1" style="min-width: 400px; height: 400px;
margin: 0 "> </div>
     <div id="Y1 vs Y2" style="min-width: 400px; height: 400px; margin: 0 auto"> </div>
    </body>
</html>
```

Appendix B

Static Control Chart vs. Dynamic Control Chart

```
<!DOCTYPE HTML>
<html>
    <head>
        <meta http-equiv="Content-Type" content="text/html; charset=utf-8">
        <title>Highcharts Example</title>
        <script type="text/javascript"
src="http://ajax.googleapis.com/ajax/libs/jquery/1.8.2/jquery.min.js"></script>
         <script type="text/javascript">
$(function () {
    $(document).ready(function() {
        Highcharts.setOptions({
            global: {
                useUTC: false
            }
        });
        var myChart;
        myChart = new Highcharts.Chart({
            chart: {
                renderTo: 'Static Control Chart',
                type: 'spline',
                marginRight: 10,
```

```
    events: {
       load: function() {
            i=0;
            var series1 = this.series[0];
            var series2 = this.series[1];
           setInterval(function() {
                series1.addPoint(data[i], true, true);
                series2.addPoint(data[i], true, true);
                i++;
                if(i==199)
                i=0;
            }, 1000);
        }
    }
},
title: {
    text: 'Static Control Chart'
 },
xAxis: {
    title: {
    text: 'Time (min)'
 },
endOnTick: false
```

```
},
yAxis: {
   title: {
      text: 'Amount of Dye Absorbed'
   },
   plotLines: [{
      value: 0,
      width: 1,
      color: '#808080'
   }]
},
tooltip: {
   formatter: function() {
         return '<b>'+ this.series.name +'</b><br/>'+
         Highcharts.numberFormat(this.y, 2);
   }
},
legend: {
   enabled: false
},
plotOptions: {
   spline: {
      lineWidth: 2,
```

```
        states: {
          hover: {
            lineWidth: 3
          }
        },
        marker: {
          enabled: false
        },
        pointInterval : 100
      },
       series: {
      animation: {
        duration: 35000
      }
    }
    },
    exporting: {
      enabled: false
    },
    series: [
  {
      name: 'S-CL',
     type: 'spline',
```

```
            color: 'grey',
            dashStyle: 'ShortDash',
              data :
[80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
4,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.74,80.7
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   });
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        });
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            chart: {
                renderTo: 'Dynamic Control Chart',
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                   load: function() {
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                       setInterval(function() {
                           series1.addPoint(data[i], true, true);
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                i++;
                if(i==199)
                i=0;
            }, 1000);
        }
    }
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type: 'spline',

color: 'black',

dashStyle: 'LongDash',

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name: 'Actual Process Average',

type: 'spline',

color: 'red',

data :
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