ABSTRACT

VANGALA, RAVIKANTH. Design of a Dynamic Quality Control System for Textile Processes. (Under the direction of Dr. Moon W Suh).

An attempt has been made to apply the structural equations published during the last 60 years for designing a *dynamic quality control system* for dry and wet textile processes that are either continuous or contiguous and are serially connected with time lags.

This new system provides process averages and control limits that are relative to the conditions of the prior processes. According to the new system the changes observed in the prior process will update the process averages and control limits of the current process using the structural relationship between the two stages. By obtaining more accurate control limits, the root causes of the out of control situations will be determined precisely, and unnecessary corrective actions that are detrimental to quality monitoring improvement be minimized.

The major research task was to identify all published papers and sort out clearly defined input and output parameters that are essential in determining the structural relationships between the various process stages that are serially connected.

The next challenge was to align and consolidate the multiple equations to a single set at each stage in such a way that a dynamic system can be developed by combining all process steps in sequence, linking all input and outputs parameters. In the j^{th} process, the output Y_j is expressed as a function of Y_{j-1} of the previous process and 'm' new input factors $\underline{z}_j$ ($\underline{z}_{j1}, \underline{z}_{j2}, \ldots, \underline{z}_{jm}$);

In any given two contiguous processes, the input ($\underline{z}$) and output (Y) relationships are more than one in most cases. Using FAMSE technique, the multiple structural equations are to be consolidated into a single structural equation. Using Variance Tolerancing and Channeling technique the output variances are computed and thus the dynamic process averages and their relative dynamic control limits are calculated.

Design of a Dynamic Quality Control System for Textile Processes

by
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DEDICATION

This work is dedicated to My Mentor Dr. Moon W. Suh, Family and Friends.

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BIOGRAPHY

Ravikanth Vangala was born on March 5th, 1984 in Hyderabad, India. He received a Bachelor of Technology in Textile Technology from University College of Technology, Osmania University in 2006. After completion of his under graduation in 2006, he came to the United States to pursue higher studies. He is currently pursuing a Master of Science in Textile Technology Management at North Carolina State University.

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Chapter 1

Introduction

Development of textile science and engineering during the last 100 years has been truly remarkable based on the published research reports and claims. However, as Prof. John W. S. Hearle (UMIST) once said in his farewell seminar at NC State University in 1999, it is quite troublesome to find that only a small fraction of what has been discovered and reported by himself and others is being applied in textile manufacturing operations today [1]. In particular, the structural models and prediction equations published to date are seldom used in quality and process control practices in the US or elsewhere. A large number of scientific and engineering equations remain unused in practice, whether understood or not. Also, it is often startling to discover that textile-manufacturing operations throughout the world seldom make use of the vast amount of advanced technical information accumulated during the last 50 years for their quality-control and improvement efforts.

Observing this as a failure, Suh [2] considered some modes of failure mechanisms at work, and has shown new directions for the future. Predicting quality characteristics of textile structures from the input variables has been the target of many research attempts in the past. These prediction equations proposed by most of the researchers work on the basis of

statistical approaches using regression and correlation analyses in place of finding the true underlying structural relationships. The estimated coefficients thus found from specific populations and operating conditions are often highly volatile and unstable. Furthermore, proving a statistically significant relationship does not necessarily guarantee the existence of a true cause-effect relationship.

Over the years, textile producers and manufacturers have made huge investments in the quality control department but are unfortunately it neither reduced costs nor increased benefits to its maximum potential. This is mainly due to the use of control systems that are static and inflexible for accommodating the complex, dynamic and interactive nature of textile production environment. Frequent false alarms and unwarranted process calibrations based on the "single stage control algorithms", often built in the manufacturing equipment, have resulted in loss of production time, materials and consequently profit [3].

Therefore, in this research we have designed a new quality control system which is dynamic and one of most attractive alternatives to the current practices in dry and wet textile processes. It is accomplished by combining the known structural models linking the process input to the output variables through time-dependent statistical models similar to EWMA and on-line computer simulations. The discrete textile processes are linked through the structural equations via variance channeling as already demonstrated by Suh and Koo [4, 5].

Chapter 2

Review of Literature

One of the oldest industries, which fulfill the basic needs of mankind, is the '*Textile Industry*'. It is believed that the first traces of textiles (scraps of linen cloth) were found in the Egyptian caves around 500 BC [6].

Quality and its management always have been important in human life since ancient civilizations and their standardization policies can be regarded as the first step towards quality. The earliest quality engineer was probably the first HomoSapien who smoothened the wheel or sharpened a tool to free it from blemishes thereby improving its rolling ability or increasing its cutting power respectively. In ancient Rome, a uniform measurement system was introduced for manufacturing bricks and pipes; and regulations were in force for the construction of buildings. The Chinese Song Dynasty (10th century BC) had specifications on the quality factors such as shape, size, and length etc., of products in handicrafts. Socrates, Sun-Tzu and Aesop are among those few prominent people who emphasized the importance of quality management. Significant discussions about quality of goods were also initiated by Plato, Aristotle, and other Greek philosophers [7].

In the textile industry, the concept of quality control always has its own importance, centralizing and standardizing textile production occurred as early as the *Zhou Dynasty* (11^{th} to 8^{th} Centuries BC, China). This dynasty had very explicit stipulations and standards for silk and cotton fabrics and textile producers who didn't meet these exacting standards were penalized and punished. The quality standards were so highly observed that even a decree was passed which 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.*" They even incorporated separate warp and weft standards for silk in the north and south because of differing weather and humidity [8]. In the West, an early regulation for quality assurance in the textile trade dates back to the 14^{th} century. In Germany a special practice called '*Tuchshau*' (Showing of Cloth) was followed, where a panel of expert inspectors along with an equal number of city council members supervised the entire manufacturing process starting at the loom. No piece of cloth could be sold unless it was produced under this supervision [9].

The concept of '*Quality*' has been a topic of intense interest today. '*Quality*' has been the buzz word among managers and executives in contemporary organizations and Feigenbaum [10] once said: "*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 [11], executives ranked the improvements of service and product as the most critical challenge facing U.S. business.

A search for the definition of '*Quality*' has yielded inconsistent results [7]: "*Value (Feigenbaum, 1951; Abbott, 1955), Conformance to Specifications (Levitt, 1972; Gilmore, 1974), Fitness for Use (Juran, 1974), Conformance to Requirements (Crosby, 1979), Meeting*

and/or Exceeding Customers Expectations (Gronroos, 1983; Parasuraman, Zeithaml & Berry, 1985) and Loss Avoidance (Taguchi, cited in Ross, 1989)."

According to Kadolph [12], some view 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 which pass are sold at normal prices while unacceptable products are sold as seconds at a lower price. But to guarantee 100% quality through examination is quite impossible for any manufacturing industry and especially in textile industry, the inherent variations coming from various stages during processing make it further difficult to guarantee quality at all levels and stages. Hence, manufacturers prefer controlling the system that produces the product to control of products.

Whether the companies are involved in producing materials or finished products, they are involved directly with the customer. According to Atilgan [13], 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. Hence, there is a need for better quality and higher productivity.

2.1 Statistical Process Control (SPC) and Statistical Quality Control (SQC)

Shewhart and Dodge were the principal architects of the science of statistical quality control. These two most influential people during the mid-twenties 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 [7]. 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, Kaoru Ishikawa [14], a well-known Japanese quality philosopher speculated that the Second World War was won by quality control and by utilization of statistical methods.

Shewhart [14], considered as the father of Statistical Process Control (SPC) and inventor of control chart technique, believed that any industrial process could be brought into statistical control by defining the limits of random variation for any aspect of a worker's task. The modern quality movement is said to have started on May 16, 1924, when he 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 wherein he defined the control chart as: "*A decision-making device that gives the user information about the quality of product resulting from a manufacturing process.*"

A control chart is 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 only 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/ 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.

In the case of Shewhart Control Chart procedure [15], the parameters of interest are the average and standard deviation and the upper and lower control limits are symmetrical about the average. If M is a control statistic (say), its mean will be μ_M and standard deviation σ_M. Then the Central Line (CL), the Upper Control Limit (UCL) and the Lower Control Limit (LCL) are calculated as follows:

$$UCL = \mu_M + k\sigma_M$$

$$CL = \mu_M$$

$$LCL = \mu_M - k\sigma_M$$

where k is the distance of the control limits from the central line, expressed in standard deviation units.

The center line represents the mean quality parameter and the upper and lower control limits represent the boundaries between variabilities due to chance or random causes and variabilities due to assignable causes. Points falling outside the control limits are considered to be "o*ut-of-control*".

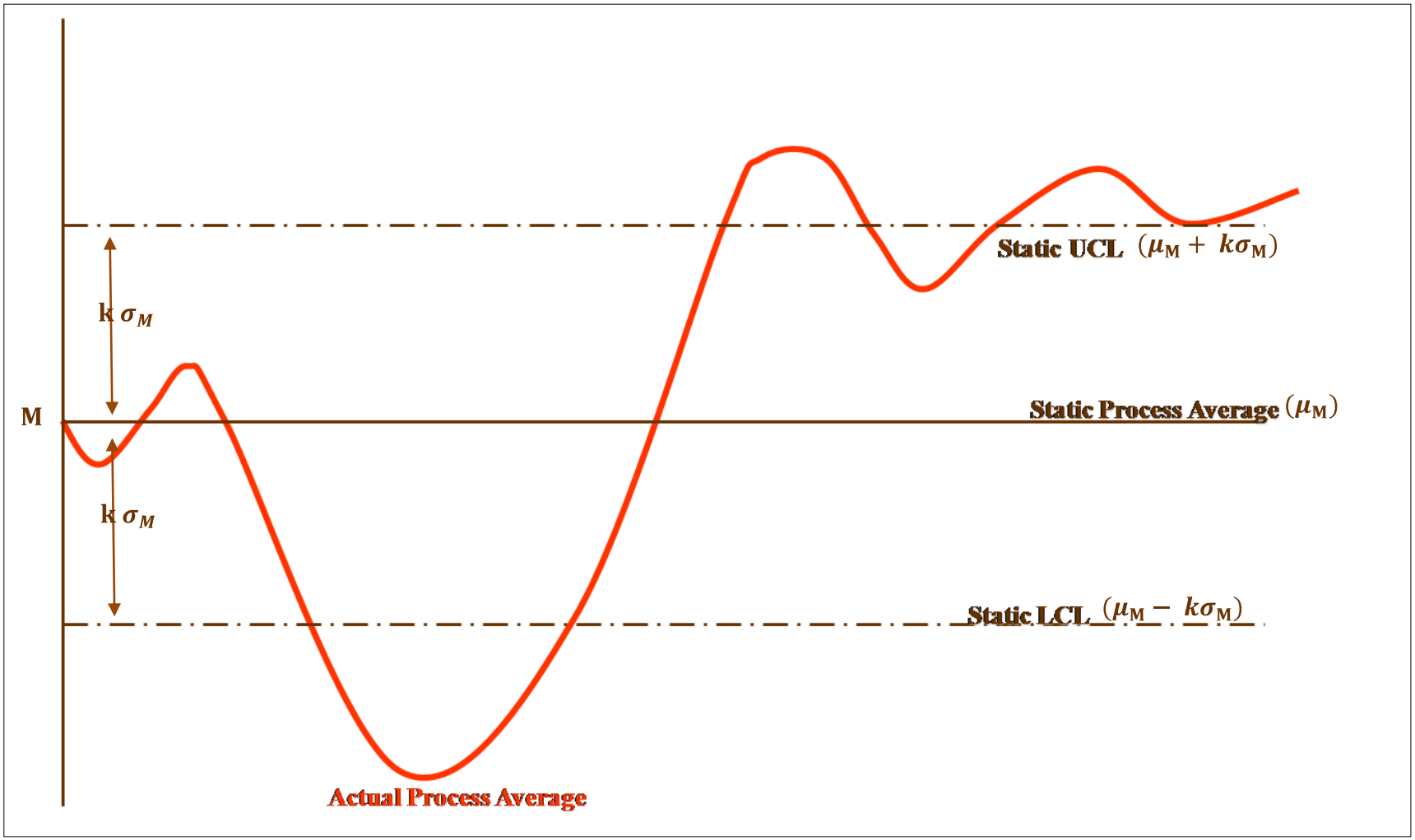


Figure 1: Schematic Diagram of the concept for Shewhart Control Charts for any Continuous Manufacturing Process

Of late, there have been many articles written on the subject of SPC/SQC as a new technique for transforming management. Although these researchers claim novelty in their concepts and techniques, these are not new. Deming [16] advocated fourteen key principles of management for transforming business effectiveness over forty years ago and 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 him, '*statistical thinking is critical to improvement of a system'.* His so-called 14 principles have been the impetus for the widespread use of data and statistical methods in process industry today.

Deming [14] identified several different charts for use in achieving statistical control of a process and most manufacturing companies implement Deming's SPC/SQC via use of the control chart. The most frequently used charts 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

SPC/SQC assumes that every process has variation and control charts help us to identify, analyze and control those variations in each process. As mentioned earlier, 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 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 program utilizes 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 control charts should continue to be used to monitor the process so that aberrations can be quickly identified and resolved maintaining a steady state or controlled process.

In any production process, there exists certain amount of inherent or natural variability depending upon the number of process and input variables. The variability in quality that occurs in an actual production process should be either '*error*' or '*natural/inherent variability*'. Sources of variability which are identifiable and preventable are called as '*assignable causes*' or '*special causes*' of variation. Common examples of such causes are improper functioning of machines, employing wrong methods, faulty raw material etc. Generally, these '*assignable causes*' are considered to lie outside the process and contribute significantly to the total variation of the process performance. Although, the variation in such cases is usually unpredictable, it can be very much explainable after the causes have been observed.

In most cases, there are always some common factors which are inherently designed in the process and they affect the process producing roughly the same amount of variation at

each interval of time. These variations are thus very much predictable and are labeled as '*noise*' because there is no real change in process performance. Sometimes, '*noise*' cannot be traced to a specific factor/cause, and it is therefore, either uncontrollable or unexplainable although very much predictable. The amount of variation from the target in the process thus depends on the strength of the noise and has a huge impact on the controllable process factors/ parameters. Variation is created by both common causes (which contribute to controlled variation) and assignable causes (which contribute to uncontrolled variation). The term controlled variation as explained by Shewhart [17] as follows: "*A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future, where prediction within limits means that we can state, at least approximately, the probability that the observed phenomenon will fall within given limits.*"

Improvement in quality can be achieved by reducing the variability in processes and products and as variability can be defined/ understood only in statistical terms, the use of statistical methods becomes very important to reduce the variability in quality and/or to improve the process efficiency. 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. Depending on the type and nature of variations, the application of statistics and development of tools to predict the presence of causes of variation on statistical grounds are characterized. In any production process SPC includes many statistical tools which can only detect and warn the presence of special causes of variability but to actually eliminate the causes of variability and to correct

the process variability engineering functions have to be used. If the only variability present is due to common causes and all special causes are absent, the production process is said to be in a state of statistical control. Using the probability laws which govern the stable state of control, special cases can be detected such as the special or assignable causes increasing the variability beyond the level permitted by the common or chance causes.

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 etc. 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 ($\bar{X}$) 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 the inevitable common cause 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.

Hence, it is necessary for the technical person to be familiar with the statistical techniques and also for the statistician to have some knowledge of the production processes.

2.2 Statistical Process Control (SPC)/ Statistical Quality Control (SQC) in Textile Manufacturing Industry

According to Johnson [18], much progress has been made in the application of SPC in Textiles over the past twenty years. 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 Team Approach to Quality Improvement.

According to Bona, textile quality control often involves keeping output of individual processes in control though the use of Shewhart Control Charts [19] and 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 in America. American textile companies are more than ever faced with the challenge to produce better quality products, faster and at reduced costs. 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.

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 society even though they are contiguous in nature.

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 [20]. As this process was tedious, time consuming and laborious, a set of inspection procedures and product specification rules were developed and today these

rules are referred to as acceptance sampling. In simple terms, they represent a set of communication tools between the user and the producer.

The second generation of quality assurance development in textile manufacturing started with the advent of Statistical Process Control (SPC) Techniques. Online quality control systems have been traditionally used to describe the statistical process control concepts such as control charts, cause and effect diagrams, process capability studies etc., and this development led to the successful minimization in rejections. The main objective of the SPC programs was to keep the variability of a process or product within the customer specification limits.

In recent years, different sectors in textile industry started implementing SPC as the technology 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. The first step in the setting up of a quality control system in textile manufacturing is the determination of where the major variations are occurring and of what characteristics should be controlled.

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. Almost from the beginning, the control charts were warmly received in the textile field. The superintendents and over-seers closely observe the trends several times a week and interpret the data. The weekly reports are made for each item, giving the percent of "Good", "Warning

Region" and "Out of Control" points so that the over-all quality records of a department can be compared from week to week [21].

The knowledge of quality control chart methods facilitates the planning of the comparison. The control chart techniques emphasize about the principles to follow in sampling i.e., the use of frequent small samples instead of infrequent large ones, rational subgroups and grouping of data on the basis of production. As mentioned earlier, the variations are labeled as 'noise' and the noise factors in textile manufacturing can be broadly divided into two categories: External and Internal. External noise includes the factors which are not a part of processing but still affect the process such as temperature, humidity, dust etc. Internal noise includes mainly product and manufacturing factors such as draft variations, twist variations, short fiber content etc.

The development of testing and test methods is the basis of much of the applied textile research [22] for the creation of a means of simulation under controlled conditions on what happens to a material during processing. The profit in the application of this technique lies in increasing the personal efficiency of the researcher and also is fundamental to the advancement of knowledge of that particular material. Although, the use of quality control chart techniques in applied textile research cannot take the place of creative imagination, ingenuity and technical skill, it can increase a research worker's efficiency and effectiveness by providing self criticism of his own work and by providing principles and a course of action in the often recurring problems of comparison of materials and machines. Thus, in applied textile research, the control chart method makes a valuable contribution.

In the recent past, revolutionary developments have been made in textile technology which led to wide scale industrial applications of textile products. These applications call for a new approach to quality based on design aspects but it is believed that implementing the design aspects in quality programs is more expensive than monitoring and re-adjusting the process as variation of assignable causes occurs [23].

2.2.1 SPC in Yarn Manufacturing

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 and allows the operator to better yet would be a move toward determining key processing factors that affect the key internal and external customer requirements of the outgoing product and then controlling and optimizing these factors.

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 autolevelers 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.

2.2.2 SPC in Dyeing and Finishing

The process of dyeing a textile fabric has historically been one of the most monitored and controlled processes in the 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.

Dyeing Processes

Process parameters such as temperature, pH, rate of temperature rise and cooling, etc. for the dyeing process have been widely known, documented and monitored for many years. Different levels of control equipment for dyeing have been readily available for the past 25-30 years. However, as is in the case in spun yarn manufacturing, controllers for dyeing have historically used 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, etc.)
- Use statistically calculated control limits for key process parameters

- Use spectrophotometers to establish dye formulas, determines color additions, and evaluate the final shade, or color of the fabric.

The processing technique whether employed in the laboratory or in the plant are subjected to a greater extent to 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 very essential to improve the accuracy by means of statistics.

Dyeing is considered as one of the most critical, complex and costly operations. In dyeing there are many sources of product variation which can be attributed to many factors including:

- Material Variations
- Variations in Chemicals
- Variations in preparation of the substrate for dyeing
- Procedural Variations

The above factors leading to variation in dyeing can generally be classified into two classes: 1) Process Variations and 2) Raw Material Variations. Raw material monitoring is very essential to accomplish process optimization. If raw materials vary, then process optimizations are nothing more than adjustments to a fluctuating input, and the result is continual change with little improvement.

The current dye process controls are essentially automated versions of centuries-old open-loop manual methods. Lot-to-lot shade variations, which are common in modern textile

production, are the direct result of the inherent limitations of open loop control systems when applied to the dynamic process of dyeing.

Gilchrist *et al*. [24] developed a mathematical model to predict the uneven levelness in a dyed yarn package and used the model and in-line measurements of the dye liquor concentration and liquor temperature feedback control to achieve and maintain a set rate of dye exhaustion in a pilot scale dyeing machine. The mathematical model uses a mass-balance approach to calculate the dye present in the yarn package and in the liquor and differential equations to describe the rate of dye adsorption. They defined the quality of the final dyeing in terms of uneven levelness in color are measured by the dye deposition error across the package. This simply the difference in the amount of dye deposited on the inside and outside of the package and is related to the visual color difference. This simplified structural model of the dyeing process is used to predict the uneven levelness at any time during dyeing cycle based on the measured rate of exhaustion, liquor flow rate, total liquor volume, etc.

$$\frac{\partial M(r,t)}{\partial t} = \frac{\epsilon}{(1-\epsilon)} \times \omega(t)K'(t)C(t) \times \exp\left\{-\frac{V_s}{F} \times K'(t)[\omega(t)-1]\left[\frac{(r^2-A^2)}{(B^2-A^2)}\right]\right\} \quad \text{------ (1)}$$

where A = internal radius of package, B = external radius of package, r = radius of interest, V = total dye bath volume, V_s = dye liquor entrained in package, t = time, M (r,t) = amount of dye on fiber at radius r, time t, K (t) = rate constant of dyeing, F = flow rate, C (t) = dye bath concentration at time t, K' (t) = overall rate constant of dyebath, ω (t) = ratio of rate constants = $\frac{K(t)}{K'(t)}$, and Є = porosity of yarn = $1 - \left(\frac{\text{Vol.of yarn}}{\text{Vol of package}}\right)$

The relative incremental deposition error was given by

$$Z_{rel}(t) = Z(t) \times \frac{V_s}{D_t} \times \frac{(1-\epsilon)}{\epsilon} \quad \text{---------- (2)}$$

where D_t – Total amount of dye to be adsorbed by the fiber, Z(t) – Incremental deposition error

A significant application of the prediction method [25] was made in the determination of limits of accuracy in the control of the dyeing process. To produce a right-first-time product, process control is essential for dyeing. Any failure to control the dyeing operation may be disastrous for the resulting dyeing quality. In a dyeing process, the limit of each step in the process is reflected in the results of final dyeing. The limit of accuracy is the definition of a process limit such that the accumulative effect of each variable gives an end product within the tolerance level. Hence, the dyer has to know the tolerance levels for specific variables of specific recipes.

To determine the total color sensitivity (ΔE) of a dye recipe, based on the recipe color sensitivity (S) and the changes in lightness, chroma and hue (ΔL, ΔC and ΔE respectively)

$$\Delta E = \sqrt{\left\{\left(\frac{\sum \Delta L_i}{2S_L}\right)^2 + \left(\frac{\sum \Delta C_i}{S_C}\right)^2 + \left(\frac{\sum \Delta H_i}{S_H}\right)^2\right\}} \quad \text{---------- (3)}$$

where, $L_i = \frac{\Delta L_i}{\Delta i}$; $C_i = \frac{\Delta C_i}{\Delta i}$; $H_i = \frac{\Delta H_i}{\Delta i}$; L_i, C_i, and H_i indicate respectively, the change caused by a unit percentage change of a parameter for lightness, chroma and hue and Δi is the change of a parameter i (i.e., concentration c, temperature T, time t, and liquor ratio r respectively);

Finishing Processes

The finishing of a textile fabric is often broken down into chemical finishing and mechanical finishing. Chemical finishing involves the application of materials such as permanent press resins, softeners, water repellents and flame retardant finishes. Mechanical

finishing is often defined as any operation that physically manipulates the fabric with mechanical devices to improve the fabric appearance or performance. Process control parameters for both chemical and mechanical finishing are known, but the evaluation methods used for both areas tend to be very subjective. For most finishing processes, a key measurement is the way the fabric feels. This is called the hand of the fabric and is measured by having people touch the fabric and giving it some type of subjective description. This is why the finishing processes are often described as "*an art rather than a science*."

In the Textile Finishing Industry, not only are efficient technical plants required but also an extensive flow of information between suppliers and customers is required to achieve better reproducibility of manufacturing processes and thus a better uniform product quality. Accuracy in this case means that the production process takes place within narrower limits and that it is capable of adhering to these limits with a high degree of probability.

2.3 Feedback and Feedforward Control Systems in Continuous Manufacturing Industries

As mentioned earlier, the consistency of the product quality has become a major deciding factor in the highly competitive industrial markets. Regardless of the changes of the environment, the duty of engineers is to ensure that the controlled product quality lies within the specification limits. This has led to an intensive research in the field of monitoring and assessment of the control-loop performance in continuous manufacturing industries including the textile manufacturing industry during the last decade.

Several methodologies for the estimation of the performance bound in terms of output variance have been established for the feedforward/feedback systems in the recent past in

continuous manufacturing industries such as the textile industry. Desborough and Harris in 1993 [26], used analysis of variance table to investigate the variance contributions due to disturbances and controllers for a feedback/feedforward system. In the year 2000, Huang *et al*. [27] extended the Minimum Variance Control (MVC) methods to feedback/ feedforward systems and based on linear time invariant assessment techniques, the time varying minimum variance benchmark in feedback and feedforward control systems was developed by Olaleye *et al.* [28] in 2004. Several other researchers like Petersson *et al*. [29], Stanfelj *et al*. [30], Sternad and Soderstrom [31] also tried to extend the MVC theory to define feedforward/ feedback performance. However, feedback control is not a new concept. Its first use was documented when James Watt used a fly-ball governor to control the speed of his steam engine [32]. The technique developed slowly at first and has evolved from the use of pneumatic and electrical devices to a wide range of intelligent digital devices from various vendors which are all integrated to provide real-time control actions in response to variations in the process.

Feedforward control [33] allows the control scheme to compensate for variation by making adjustments to related variables in the process loop. The main advantage using a feedback control system is that it can be utilized even when the source of variation is unknown or its magnitude is unknown. Also, specific control actions are automatically executed via feedback control as it utilizes the deviation from the target to calculate the necessary compensatory changes required to achieve normal processing. In order to eliminate the effect of process disturbances, to stabilize the process and to keep the process within the

desired specification levels, the control system makes every effort to automatically compensate via feedforward, feedback or a mixture of feedback and feedforward control.

A feedforward 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. This system is often used in a combined feedforward/ feedback control system. Depending on the controlled output, the feedback-only effect or the feedforward-only effect contribute to the output variance of the feedback/ feedforward system. The feedback loop variance can be expressed as the sum of the feedback invariant term and the feedback-dependent term. Generally, it is difficult for operators who supervise the process to determine which parts of the system are defective. Hence, a diagnostic tool is required to assist the operators in keeping the system at the normal operation and in finding out the possible faults. The measured output consists of the disturbance effect from unmeasured disturbance in the feedback loop and from measured disturbance in the feedforward loop. Any fault in the control elements will violate the output response. The diagnosis is to analyze the measured output data and to find out the fault causes when the process faults come from the control elements.

2.4 Reasons for failure of quality control systems in textile manufacturing in the past

Textile quality control often involves keeping output of individual processes in control though the use of Shewhart control charts [19]. As mentioned earlier, although textile producers have invested in quality control systems through Shewhart control methods, manufacturers have yet to experience a significant cost reduction or increased benefits. This

is mainly due to the use of control systems that are static and inflexible for accommodating the complex, dynamic and interactive nature of textile production environment. Frequent false alarms and unwarranted process calibrations based on the "single stage control algorithms", often built in the manufacturing equipment, have resulted in loss of production time, materials and consequently profit. In case of an out-of-control situation, the backtracking of the problem source naturally begins with the last machine where the problem is caught [2, 19]. This is known as feedback control, which often accompanies instability with a tendency for over-control or unwarranted calibration.

In addition, a feedback control in textiles often leads to disappointing guesswork rather than an effective corrective action due to 1-to-N nature of manufacturing processes [34]. Thus, use of a static target reference in a continuous, dynamic textile process causes frequent false alarms when the changes in process averages originate from the prior process stages. To remedy this difficulty, a dynamic EWMA control chart procedure [35, 36] can be employed. However, this procedure was somewhat effective only for short-run process control situations as it forces us to examine only the current process average against the target with no reference to the biases generated by the prior processes [37] indefinitely. This undoubtedly is a terribly inefficient control process completely void of structural relationships already known for the causes and effects.

According to Suh [2], the large textile science and engineering knowledge base has not been much utilized for textile production and quality control for reasons that can be amply justified. He further emphasized the need and importance for new quality control

systems while describing the main reasons for failure of the past textile research in quality control and improvement as follows:

Forward Prediction Equations: Predicting yarn and fabric properties based on fiber and processing characteristics is a typical example of forward prediction equations. This knowledge base, while critical for general optimization, has not been utilized primarily for three reasons:

- the prediction equations are not applicable for specific choices of raw materials, machinery, and processing conditions, thus accompanying large amounts of bias and errors
- the forward-prediction equations are useless in tracing back the responsible factors and processing conditions that produced the specific 'out-of-control' situations on a daily basis
- the predictions usually link no more than two stages, with no capability to go back beyond the immediate past step

The fact that forward-prediction equations are inadequate for a backward projection leads textile quality control to disappointing guess work rather than effective corrective action. In summary, forward prediction equations are both incomplete and disjoint for making a truly satisfactory forward prediction, while the ultimate equation, even if it is found, cannot move backward to a set of unique prior-process conditions which produced the specific outcome.

Deterministic Modeling: Multi-factor, multi-variate models based on deterministic, non-stochastic models have long been used to illustrate the 'average' phenomena based on

the input or predictor variables. Depending on the functional forms, the variances and/or coefficients of variation (CV) of the output factors are often found to be much greater than those of individual factors. As the complexity of the functional form and the number of predictor variables increase, the precision of the factor to be predicted becomes extremely low. When this reality is added to the introduction of the 'process variance', it is not surprising at all that the multitudes of forward-prediction equations are seldom used in quality-control and quality-improvement practice in textile manufacturing.

Sample Sizes and Sampling Practices: In manufacturing quality control, the purpose of the sampling is often to detect the out-of-control situations in the process averages that change with time. Sampling intervals and sampling frequencies are as important as the sample sizes and the sampling fraction. Based on these, the random-sampling and testing practice which prevails now is grossly inadequate and superfluous. None of the sampling/ testing methods for raw materials, intermediate fiber assemblies, yarns and fabrics have been time-aligned or location-specific to provide a meaningful analysis. When random samples are taken at infinitely small fractions and analyzed for statistical correlations only, the likelihood of either confirming an existing correlation or pinning down the root causes of the observed deviations becomes extremely low.

A significant correlation confirmed by a set of actual data is as likely to be from spurious data as from a true cause-effect relationship. In addition, the sample sizes and sampling fractions for today's off-line textile quality-control practice are adequate perhaps only for establishing the long-term process averages but totally inadequate for searching for the causes of specific out-of-control situations.

An example may be drawn from the testing of cotton bales by using an HVI (High Volume Instrument). Although each and every bale is tested for uniform laydown and blending purposes in the USA today, 2000 cotton fibers may not adequately represent the entire bale of a single test beard consisting of roughly 500 lb or 272,000 g. If every fiber is assumed to be 1 in. (2.54cm) long and to have a fineness of 4 micronaire units (i.e. a linear density of 0.157 tex), a bale of cotton contains 56.7 billion of fibers, or enough to go around the earth 36 times when the circumference of the equator is estimated at 40000 km. In terms of the sampling fraction, the HVI testing is equivalent to testing one out of every 28.35 million fibers. Whereas the testing of yarn and fabric properties is somewhat better than this, there exists little chance of isolating an out-of-control situation based on this type of current sampling and testing practice.

Regression and Correlation Analysis: A significant deterrent to the advancement of textile research has been the use of regression and correlation analysis instead of finding the true structural relationships. The estimated coefficients found from specific populations and operating conditions are often highly volatile and unstable. Furthermore, the existence of a statistically significant correlation coefficient does not guarantee the existence of a true cause-effect relationship. More importantly, any effort to apply regression models for optimization is bound to fail under a high degree of multi-collinearity among the predictor variables. Correlation analyses are also made by collapsing the time and location-specific quality measurements, thus making it most difficult to trace the quality traits. In spite of these obvious deficiencies, the use and abuse of statistical methods of ill-designed experiments continue as stopgap measures.

Chapter 3

Objectives

1. To develop general theories and design an effective dynamic process and quality control system which would be applicable to textile manufacturing processes, especially for staple spinning processes as a model case.
2. Survey and analyze the structural/functional relationships in the production and control of ring-spun yarns and consolidate them to form a final set of equations for the design of a Dynamic Quality Control System for a few control factors.
3. Develop a concept for an algorithm (FAMSE) aimed at streamlining a set of multiple structural/functional equations that may be similar to each other, redundant, incompatible or contradictory to each other.
4. Apply the variance tolerancing method developed by Suh *et al*. [4, 5] to the variance of an output function based on the variances of the input and output parameters selected for the spinning processes in order to establish the dynamic control limits in continuous time domain.
5. And finally, to establish the "dynamic process average" and the "dynamic control limits" at each process stage based on the functional/structural relationships between the variables involved in the previous and present spinning process stages to develop a "Dynamic Control Chart."

Chapter 4

Concept of a Dynamic Process Control System

In recent years, it is becoming more important than ever to provide an effective system of controlling the quality of production as the trend in the textile industry towards shorter processing sequences, higher productivity and more automation is accompanied by the removal of many quality safeguards which increases the risk of producing an unacceptable product. 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 substantially. According to Suh [38], 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 to such a situation is to widen the control limits for all of the subsequent stages. By continuing the practice, however, all control limits become so wide to make the so-called statistical limits useless.

As mentioned earlier, a new dynamic quality control system is one of the most attractive alternatives to the current practices in dry and wet textile processes. A Dynamic Control System can be defined [39] as a continuously-acting control system which responds to normal and abnormal system conditions or events so as to enhance the system stability by acting upon one or more system quantities as determined by measurement of one or more system parameters.

It is accomplished by combining the known structural models linking the process input to the output variables through time-dependent statistical models similar to EWMA and on-line computer simulations [35]. The discrete textile processes are linked through the structural equations via variance channeling as already demonstrated by Suh and Koo [4, 5].

The concept of a "dynamic control chart" procedure incorporates the following:

- Additive effects of the system biases
- Magnification of biases on subsequent process stages through "structural or functional relationships"
- Additive random errors
- Feedback control mechanisms for excessive biases and errors

In the continuous process type of manufacturing, such as ring spinning, 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, as shown in Figure 5. Generally the input error σ_0^2 comes from raw materials, preconditioning, etc. During processing, slight differences in

speeds, humidity, actual drafts, and mechanical imperfections of equipment add variation. In the case of ring spinning, variation is usually composed of several distinct sources such as the variation inherited from the previous process, within-spindle and between spindle variations, within frame and between frame variations etc.

Each (*i*) of the k stages is assumed to generate certain amount of bias (B_i) and random error (σ_i^2) inherently. The input bias B_0 may or may not be zero as the raw material that enters into processing is not perfectly uniform. At k^{th} stage, the total bias (B_T) must be separated from the random component σ_T^2, the total error variance. This is the only way the k^{th} stage control limits can be examined independently of the expected total bias.

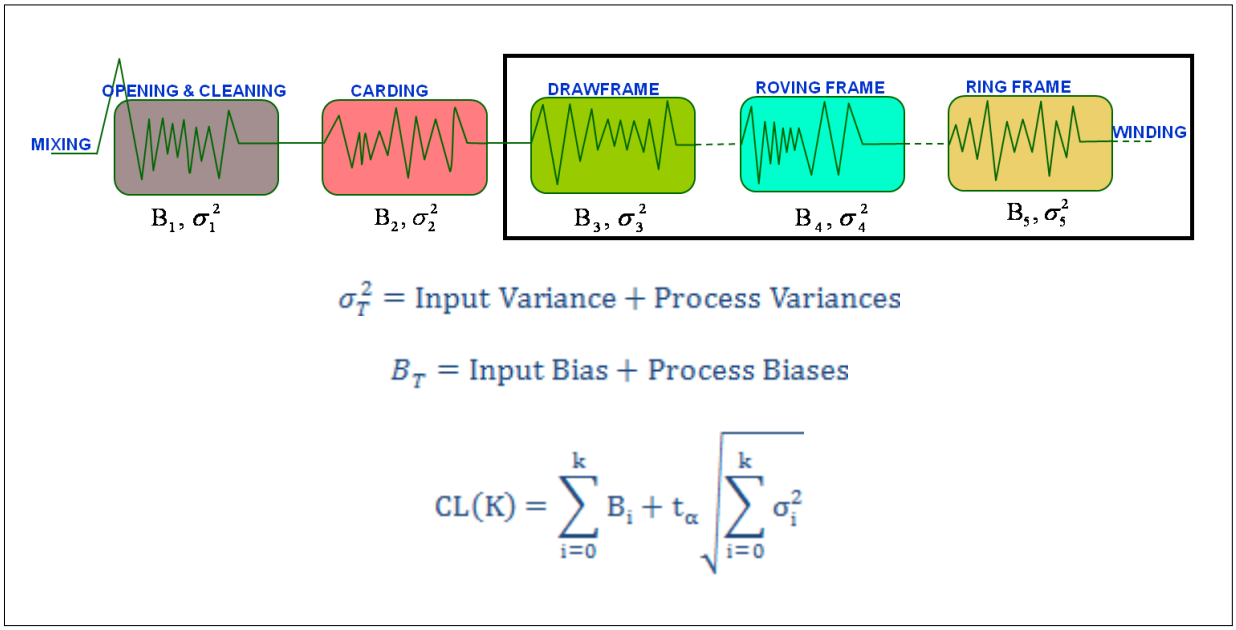


Figure 2: Conceptual Frame for Dynamic Control Limits from Mixing/Blending to Ring-frame via the Structural Relationships Developed.

The two key points to be considered for the construction of a dynamic control chart are:

- Estimation of the biases based on the "structural relationships"
- Estimation of the process variance at each stage and the total upto a given stage to provide "dynamic control limits."

The traditional static process average and the corresponding control limits are now coupled with the dynamic process average and its control limits which reflect the biases of the previous stages. The decision scheme is as shown in the Figure 3. One important point is that the out-of-control situation based on the static limits has to be "swallowed" even if it is neither desirable nor acceptable. The only remedy would be to correct the previous stage processes through the known structural relationships via feedback algorithms.

The graphics can be modified in various ways in order to make the dynamic control most practical and easy to understand. The importance is to understand and quantify the inter-dependence of all the processes in advance in order to make the process control system more responsive to the ever-changing conditions of the process.

When the present process stage performs as designed, then no control action would be warranted regardless of the decision obtainable from the static control limits. When certain specification limits must be met closely, the target process average may have to be compromised if the total process bias exceeds an upper limit. When the static process average and the corresponding control limits are coupled with dynamic process average and its control limits three different cases of *out of control* situations arise which are shown in Figure 3. This provides an option for choosing an optimal control. The three different cases are:

Case A: The actual process average is found to be out of control with respect to the static control limits. This case is where no corrective actions may be justified even when the process average exceeds the static control limits.

Case B: The actual process average is found to be out of control with respect to the dynamic control limits. This case is considered to be the case where a corrective action in the particular stage can be justified independently of the biases generated prior to that stage.

Case C (A&B): The actual process average is found to be out of control with respect to the both the static and dynamic control limits. This is the situation where a corrective action is fully justified based on both the static and dynamic limits. This is the most serious case since the process as well as the product specifications may not be most in the absence of a corrective action.

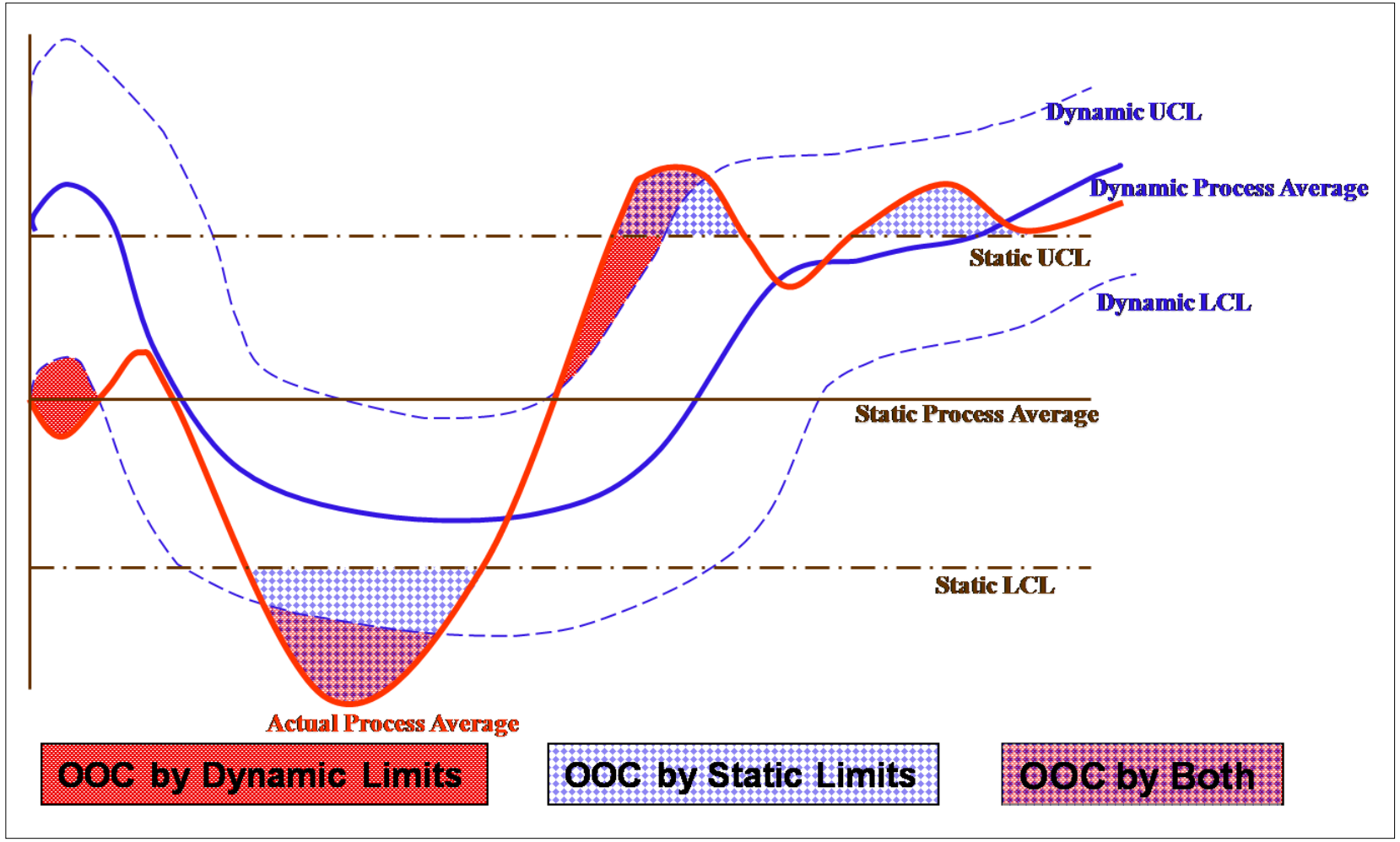


Figure 3: Schematic Diagram of a Dynamic Control Chart

4.1 Importance of Structural and Functional Relationships for Dynamic Process Control Systems

It is important to discuss why we would need the structural equations for the construction of a control chart. Generally, the structural equations form the link between any two stages of a continuous/contiguous manufacturing and processing industry. For example, the case of ring spinning which involves several stages like mixing, carding, drawing etc in sequence during the processing of a yarn. These stages are interlinked with each other as the output delivered material from present processing stage would be the input feed material for the next sequential processing stage. The fiber properties thus can be studied and traced with the use of the existing structural and functional relationships from the literature. Also, the structural and functional relationships in the literature explain the relationship between the input and output process variables in a better and efficient way. A structural and function relationship uncovers particular structural parameters which govern economic behavior. As the structural equations generally are based on a specific theoretical model they provide the most direct way of testing a particular theory. The key strategy in the construction of a dynamic control chart is to estimate the output process averages and variances as functions of the input process averages and also the variances originating from the prior process stage. Hence, in order to estimate the process averages and variances of the final structural equation which is developed linking the various structural equations from different processing stages the variance tolerancing and channeling technique developed by Suh and Koo [4, 5] is employed (example in the Chapter 5). Based on the dynamic process average and the *"toleranced"* variances, we can establish the Dynamic Control Limits. These limits can be

on-line or *off-line* depending on the processes involved and the need. The *Out-of–Control* decisions can be made using both the static limits and the dynamic limits.

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 affect 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 regression equations proposed generally are merely a concept for the search process rather than a specific analysis method. Also, structural/ functional relationships and equations lead to an efficient optimization of analysis with less experimentation and data whereas the regression models are less stable and need more data and experimentation to draw any conclusions. The need to assume a functional form for the relationship between an output and selected inputs, and potential ambiguities in the interpretations are the key potential drawbacks of regression analysis. The "models" so-called, are not truly models in the sense that they are often population dependent, remote form physical modeling, not suitable for repeated predictions and most of the times are based on invalid assumptions. The traditional regression analyses assume that there are 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. Thus, we can say that the traditional regression analysis has many drawbacks when compared to the structural and functional relationships.

4.2 Method for the Use of Multiple Structural Equations

Almost in each and every continuous manufacturing process, we find many structural equations for various intermittent stages in processing in the literature which exist in different forms with varied number of input and output parameters. As each research finding from each researcher around the globe yields new and mostly a different structural equation sometimes we may even find hundreds of equations on the same processing stage or sometimes we may find hardly any structural equation on a particular processing stage. Also, sometimes we may face a situation wherein we come across the same equation written in different forms by various researchers. Sometimes, it even depends on the environment and the place the research is being carried. From a researcher with high mathematical skills it is obvious to expect a complex mathematical structural equation involving many processing parameters that affect the process at that stage. Hence, it becomes a very tough task to pick the right and the best fit equation among those as each one has its own merits and de-merits.

In order to find the right structural equations and to consolidate equations into one final equation when there is more than one structural equation at each stage of spinning, we have developed a novel concept called the *Fusion Algorithm for Multiple Structural Equations* (FAMSE) Technique which is used to consolidate the multiple structural equations of any form.

4.2.1 Fusion Algorithm for Multiple Structural Equations (FAMSE)

This approach/technique is used to consolidate the multiple structural equations obtained by various researchers. As discussed earlier, we have multiple structural equations

for every processing stage for most of the manufacturing process. Especially in the case of ring spinning process at every stage of processing we find many structural equations in the literature which can be used to determine the variation in mass, irregularity, strength, uniformity etc. It is a tough task to pick the right and the best fitting equation among those as each one has its own merits and de-merits. Sometimes the same equations are written in different forms by different researchers or they have to be slightly modified so as to make it into a feasible one. As mentioned above, we even find contradictory statements or equations by researchers and when we have to pick the one that fits the best, we cannot decide or choose one among those depending on their proofs or explanations. Also the number the input factors vary for almost each and every structural equation.

In order to consolidate *N* multiple structural equations, that may exist between the input and output variables, where the output Y_j at j^{th} process stage is expressed as a function of Y_{j-1} of the previous process and '*m*' new input factors z_j $(z_{j1}, z_{j2}, \ldots, z_{jm})$, the new algorithm (FAMSE) being developed obtains one structural equation from the '*N*' original sets. Thus, when we find 'N' structural equations with certain number of factors, each structural equation is re-written in Polynomial form. These polynomial functions with same input terms are consolidated into one equation which is of the form

$$[\mathrm{Y}]_{\mathrm{N}\times 1} = [\mathrm{A}]_{\mathrm{N}\times \mathrm{k}}\,[\mathrm{X}]_{\mathrm{k}\times 1}\ ,$$

where $$\left[A\right]_{N\times k} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & .... & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 0 & .... & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 & .... & 0 \\ . & . & . & . & . & .... & . \\ . & . & . & . & . & .... & . \\ a_{N1} & a_{N2} & a_{N3} & a_{N4} & a_{N5} & .... & a_{Nk} \end{bmatrix}$$

Hence in order to consolidate multiple structural equations and to determine the best fit equation a new algorithm is developed called the 'FAMSE Technique'. After the 'N' structural equations are re-written in suitable polynomial form they are consolidated in various ways/methods such as by equating, by mere sub-merging, by simplifying them into congruent forms and solving them using various simultaneous equations solving techniques and using mathematical computational tools/software such as MAPLE, MATLAB, TK SOLVER!, etc.

4.2.2 Components of FAMSE

There are two significant components in designing the fusion algorithm.

1. **Factor Decision:** Number of factors to be considered is an important aspect in the design of the algorithm as most of the polynomial functions/structural equations exist in varied forms with different number of input and output factors. For example, in order to identify the best fit polynomial functions/structural equations in the spinning process the key fiber properties which influence the processing are to be considered and among those key properties certain number of input factors are decided based upon the level of significance of those factors. We considered the example of Mass Variance and Strength as input factors for the spinning process to carry out the literature survey and based on these factors the established structural equations and relationships were identified.

2. **Consolidation:** As mentioned earlier there would be a situation wherein many polynomial functions with same/similar number of input terms would be identified and they have to be consolidated into one equation. This can be achieved in various ways. For example: By equating/ By mere submerging/ By simplifying into congruent forms/solving using mathematical computational tools such as Maple, Matlab, TK Solver!

4.2.3 Various Stages in FAMSE

1. **Redundancy Check**

   The first step in FAMSE is to check if more than one equation with identical X-variables are redundant even with different coefficients for X's when there exist internal functional relationship(s) among X's.

   As a simple example:

   $$Y = 2X_1 + 3X_2 + 3X_3 \quad \text{---------- (4)}$$
   $$Y = 2X_1 + X_2 + 9X_3 \quad \text{---------- (5)}$$
   $$\text{with } X_2 = 3X_3$$

   Now, when $3X_3$ is substituted in the place of X_2 equations (4) and (5) turn out to be the same. Hence, they can be considered as redundant equations and one of them can be eliminated.

2. **Congruency Check**

   The second step is to check the compatibility of equations. In the case of more than one equation, this step is carried out to check if the equations are congruent and hence the number of equations can be reduced by simplifications such as averaging or

substitutions, etc. As an example for congruency check, a couple of equations which were surveyed from the literature for the mass variance at mixing stage in spinning process are considered. (A detailed explanation has been given in the next chapter (section 5.3) about the identification of these equations.)

$$\sigma^2_{WLD} = (V.W.H.d)^2 \quad \text{---------- (6)}$$

$$\sigma^2_{total} = \frac{(L-1)n}{(Ln-1)}\ \sigma^2_{BLD} + \frac{(n-1)}{(Ln-1)}\ \sum_1^L \sigma^2_{WLD} \quad \text{---------- (7)}$$

$$\sigma^2_{total} = \frac{(L-1)n}{(Ln-1)}\ \sigma^2_{BLD} + \frac{(n-1)}{(Ln-1)}\ (V.W.H.d)^2 \quad \text{---------- (8)}$$

The equations (6) and (7) above are congruent and when a term in Equation (7) is substituted with Equation (6), we get Equation (8). Thus, two equations are consolidated into a single equation

3. Fusion Modeling

When the "cleaned up" equations are in various functional forms, they have to be "fused" into similar type of structural equations using known algorithms such as Taylor's series expansion and Maclaurin's series expansion.

Consider the following case where the function with the term (x^2e^{-2x}) has to be computed.

$$Y = x^2e^{-2x} + K_1 + K_2 + K_3$$

where K_1, K_2, K_3 are arbitrary constants.

Using Taylors Series expansion, the above equation is expanded into a suitable linear form as follows:

Expansion of (x^2e^{-2x}) using Taylors Series $\sum_{n=0}^{\infty}\frac{(x-a)^n}{n!}f^n(a)$ around "a",

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

$$= a^2e^{-2a} + \frac{(x-a)}{1!}(2ae^{-2a} - 2a^2e^{-2a})$$

$$+ \frac{(x-a)^2}{2!}(2e^{-2a} - 8ae^{-2a} + 4a^2e^{-2a}) + \dots$$

$$= a^2e^{-2a} + 2(x-a)(ae^{-2a} - a^2e^{-2a})$$

$$+ (x-a)^2(e^{-2a} - 4ae^{-2a} + 2a^2e^{-2a}) + \dots \quad \text{---------- (9)}$$

4. Simulation

In order to solve simultaneous equations, various mathematical computational tools such as Matlab or Maple or TK Solver! etc can be used. These computational tools use simulation techniques to solve the simultaneous equations.

For Example: Consider

$$Y = x_1 + x_2 + x_1^2 + x_2^2 \quad \text{---------- (10)}$$

$$Y = x_1 + x_2^2 + x_1^2 x_2^2 \quad \text{---------- (11)}$$

$$Y = x_1 + x_2 + x_1^2 + x_2^2 + 2x_1x_2 \quad \text{---------- (12)}$$

4.3 Variance Tolerancing and Variance Channeling

4.3.1 Concept of Variance Tolerancing in Ring Spinning

Suh [2] pointed out in his paper that in textile manufacturing, large variations in process and product characteristics are often 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. He also suggests that 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.

Suh and Koo [4, 5] pointed out that much textile research in the past has been devoted to '*forward prediction and characterization'* of physical properties such as strength, evenness, uniformity etc through various modeling approaches. These models have long been using forward prediction equations to estimate the average pattern of output characteristics from available averages of input characteristics. However, the prediction as well as the accuracy of characteristics to be predicted becomes extremely low as the complexity of the functional form and the number of predictor variables increases. This is due to the non-uniform and confounding response pattern of the output variable over the entire ranges of the predictor variables that are often highly correlated among them. When this reality is added to the large variance introduced at each process stage (process-induced variance), it is not surprising at all that the forward prediction equations are neither precise nor accurate enough to control or improve the qualities in textile manufacturing.

In developing a forward prediction equation, difficulties are often due to the '*trivial many'* components that inhibit formulation of an exact functional relationship. In estimating the variance of a response variable with high precision, therefore, only the *'vital few'* must be chosen for variance tolerancing. This may be accomplished in two steps:

- filtering only the intrinsic components for variance tolerancing,

- finding a geometric, probabilistic, or structural model that is capable of estimating the variance of a product characteristic defined by its intrinsic components.

The definition of an intrinsic component is the component which is measurable or countable and is measurable or countable and is structurally imbedded for explaining the variance of *Y*. The intrinsic component can be an input material characteristic, a geometric or structural factor. They can be filtered by using such as Pareto analysis of variance components. For tensile strength of a yarn, fiber length, strength, fineness and yarn twist can be the intrinsic components and in the case of tensile strength of a fabric, yarn tensile properties and the density of weave can be the intrinsic components.

Conventional *statistical tolerancing* methods while effective in many well-defined processes are inadequate in many ways for textile products and processes. The control and improvement strategies for textile process qualities will have to come from better analyses of variance on the input and output variables imbedded in simplified and verifiable structural relationships.

Statistical Tolerancing techniques can be used to determine the probability distributions of output characteristics from a set of input component variances when the structural cause and effect relationship is known functionally. This technique, however, is not easily applicable to textile products and processes, where reliable functional forms of the structural relationships are either not known at all or only partially understood.

Variance Tolerancing uses geometric and probabilistic models to depict characteristics of textile products and facilitates decomposing of the output product

characteristic into relevant sub-components. Then a set of variance ranges are set up for the sub-components. Applying these, out-of-control situation in the output characteristic signifies that there exists a set of input variances which were significantly deviating from the norms established. By examining the ranges for the input sub-components one at a time, it is possible to comb out the responsible factors and/or processing conditions that produced the specific out-of-control situation. 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.

Suh and Koo [4, 5] developed a novel concept for separating and estimating random errors associated with raw materials and yarn structures from process-induced errors based on structural relationships governing the strength of a spun yarn. The process average at a given process stage is assumed to be the output generated by a structural equation linking that to the input process average of the previous process. Simultaneously, a set of dynamic control limits is obtained by *tolerancing* or channeling the variance of the input variable to the variance of the output variable through an applicable functional/structural relationship.

If B_k is the bias introduced at the K^{th} stage, it will be added to the sum of all biases generated from the previous processes to make up the observed process average, and the process variance σ_k^2 originating at the K^{th} stage would be added to the total variance channeled down from the $(K-1)^{th}$ process through the structural/functional relationship. Thus,

the control limits at the K^{th} stage are generated from the sum of the biases and the total expected variance.

Figure 4 [40] below, explains the above concept using an example of density profiles of a sliver and the resulting roving and yarn in three successive processing stages. We can observe 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 the new dynamic process control system can be used.

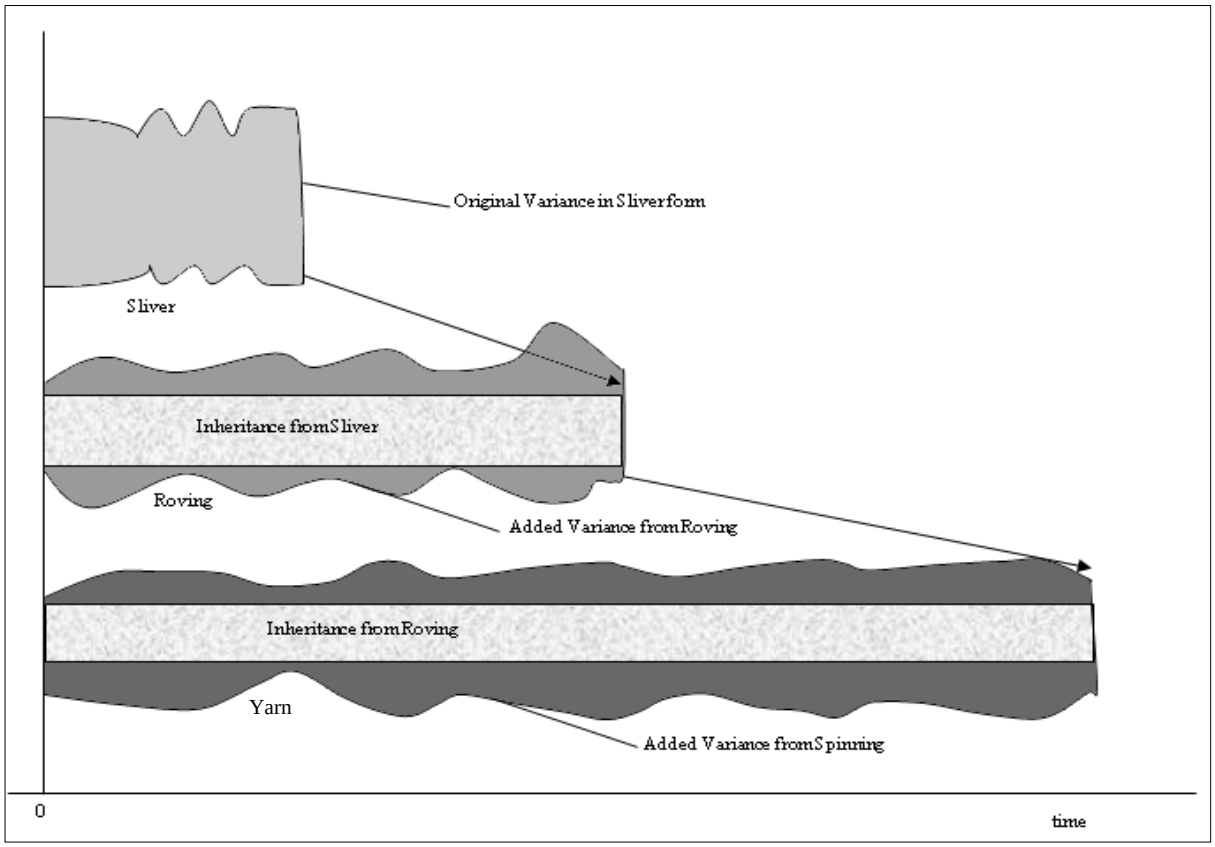


Figure 4: Schematic Diagram of Inheritance of Variance from Previous Process Stages

4.3.2 Methods of Achieving Variance Tolerancing

As mentioned earlier, Suh and Koo [4, 5] developed a novel method for achieving the variance tolerancing and decomposition applicable to fiber and yarn. They illustrated the process by the specific structure of the response variable *Y* as follows:

Let a textile product characteristic, *Y*, be

$$Y = g\,(X_1 \ldots X_m \backslash \underline{h}),\ m \leq n, \text{ ---------- (13)}$$

where g is a geometrical, probabilistic and structural model, $x_1, \ldots, x_m$ are the intrinsic components and $\underline{h}$ a set of intercepts which may equal to zero. Since the intercepts are not necessary for predicting Var (*Y*), Equation (13) can be written as

$$Y^* = g^*\,(X_{1\ldots}\, X_m),\ m \leq n.$$

where *Y** is a simplified form of *Y* and g* a modified function of g reflecting only the effects of Var (X_i) without regard to E (X_i), $i = 1, 2, .., m$.

The geometrical, probabilistic and structural models are often structure specific in that they may take account of the number of structural elements or units which contribute to textile product characteristics. The number of structural units contributing to a given characteristic of a textile product is usually determined by the geometrical structure of the product. In addition, the intensity of aggregating the structural units to forma textile structure is to be called '*degree of constraints'*.

As the degree of structural constraints becomes larger, the estimated variance of the textile product characteristic becomes smaller. Thus, the structural constraints act as variance inhibitors in textile products. The variance of a textile product can be estimated using the

Equation (13). The estimated variances are compared to variances calculated based on the actual data in order to verify the theoretical estimates.

Based on the variance tolerancing through a geometrical, probabilistic and structural model with intrinsic components, the variance of a textile product characteristic can be estimated in terms of the statistical distributions of the intrinsic components. This can facilitate the optimal selection of input materials, process conditions and prediction/ optimization of textile product characteristics without having to rely heavily on the existing structural relationships that are often inadequate for a variance tolerancing. If each of X_1 is associated with independent errors or variances, the classical statistical tolerancing formula by Tukey [41] can be applied to the Equation (13) to give

$$Var\ (Y) = \sum \left(\frac{\partial f}{\partial X_i}\right)_0^2 Var(X_i) = \sum f_i^2\, Var(X_i) \text{ ---------- (14)}$$

The Equation (14) is used to predict the variance of response Y in terms of the variances of the intrinsic components within their tolerance ranges. The variance, of a textile product characteristic can be estimated from input variances of intrinsic components through variance tolerancing based on geometrical probability and structural model. The total variance of the textile product can be decomposed into the variance tolerance from intrinsic components and those from each process.

When the product characteristic is found to be out-of-control, there should be a set of out-of-norm prior process conditions or raw material properties which gave rise to the specific outcome. In order to detect the responsible sources, each variance component of the process and raw material is examined to see if it were within acceptable limits. For example,

let the variance of the product characteristic *Y* be σ_y^2 when *Y* is found to be out-of-control. If the variance estimated from raw materials is within the set limits, the input material can be eliminated from the list of suspicious factors. Through a sequential elimination of the innocent factors and processes, it is possible to narrow down the list to one or two factors or processes. In order to complete the task, however, it is necessary to pinpoint the time and location as well as the mechanism, structural relationship through which the situation was realized. The time is added as a new dimension based on a continuous monitoring and measurement scheme.

4.4 Advantages obtained using Dynamic Quality Control Systems

The new Dynamic Quality Control System developed, replaces the traditional static process average and the static stationary control limits by a dynamic process average and the associated dynamic control limits. This system will provide process averages and control limits that reflect what happened in the prior process stages. Also, this dynamic control system is thus designed in such a way that it prevents unnecessary corrective actions, minimizes the impact when the out-of-control situation causes an irreversible damage and provides a useful control system for searching the root causes of the out-of-control situations.

Here are a few advantages of the dynamic control chart over the traditional static control chart (Shewhart Control Chart):

- As mentioned earlier, the control limits at any given stage in the static mode are fixed and non-reactive to the dynamic changes of the previous stages. Also, biases and errors are introduced at each and every processing stage in a continuous

process widening the control limits to such an extent where they have now become almost useless in reducing the variance of the process. Hence, the dynamic quality control system is designed in such a way that the control limits obtained are more accurate than the ordinary static control limits.

- Using the forward-prediction equations, the root causes of the 'out-of-control' situations cannot be determined precisely as the back tracking of the responsible factors and processing conditions which produced the specific 'out-of-control' situation often leads to a disappointing guess work rather than an effective solution. But using structural equations which connect the interlinking stages in a continuous process help us in determining the accurate root causes of the 'out-of-control' situations. Hence, the dynamic quality control system determines the actual and accurate root causes of the out of control situations on a daily basis.
- The use of a static target reference in a continuous, dynamic textile process causes frequent false alarms when the changes in process averages originate from the prior process stages. In order to minimize the unnecessary corrective actions (false positives) use of dynamic and flexible control limits is mandatory. Also, to minimize the loss of production time, materials and profit, the dynamic quality control chart is a best fit.
- Using the concept of variance channeling demonstrated by Suh and Koo [4, 5], the discrete textile processes are linked through the structural equations. Thus, in the dynamic control chart constructed the dynamic control limits take into consideration the summation of all biases and variances coming from the previous

process stages and the biases and variances at the present stage. Hence, by computing the dynamic process averages and associated dynamic control limits, the dynamic quality control system designed generates an optimal control strategy at each process stage.

Chapter 5

Development of Dynamic Control Chart & Variance Tolerancing - Application in Ring Spinning Process

A conceptual/theoretical frame for a dynamic quality/process control system is being developed. The key strategy is to estimate the output process averages and variances as functions of the input process averages and also the variances originating from the prior process stage.

The simplest definition of spinning according to Marsh [42] 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 (Figure 5).

Table 1: Key fiber parameters which influence the processes in Figure 2.

Process	Input Parameters	Process Parameters	Output Parameters
Mixing	1. Fiber fineness variation 2. Fiber length 3. Strength 4. Maturity 5. Trash Content 6. Color	1. Bale Arrangement 2. Bale Variation 3. Mixing Method	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. Tuft size 2. Roller speeds 3. M/c stoppage time 4. Type of feed 5. Grid settings 6. Type of opening device	1. Material quantity variation 2. Quantity of material
Carding	1. Impurities 2. Neps 3. Fiber length distribution 4. Fiber orientation	1. Cylinder speed 2. Settings between doffer, licker in, flat tops 3. Speeds of various rotating parts 4. Type of feeding	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. Draft Ratio 2. Pressure exerted by top roller 3. Hardness of top roller 4. Distribution of draft between the various drafting stages 5. Roller settings 6. Type of drafting 7. Type of autolevelers 8. Frictional force	1. Linear density of the strand 2. Fiber orientation 3. Waste % 4. Drafting waves

Table 1: Key fiber parameters which influence the processes in Figure 2 (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. Feed hank & delivery hank 2. Bobbin movement speed 3. Flyer angular speed 4. Spinning triangle length 5. Centrifugal tension formation 6. Drafting system settings 7. Roller speeds and settings	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. Draft distribution 2. Ring and Traveler speed properties 3. Spinning speed 4. Twist 5. Lift of the machine 6. Load mechanism 7. Spacing between the ring and the traveler	1. Yarn characteristics – count, twist, strength, hairiness etc 2. Uniformities 3. Amount of yarn delivered 4. Number of stoppages

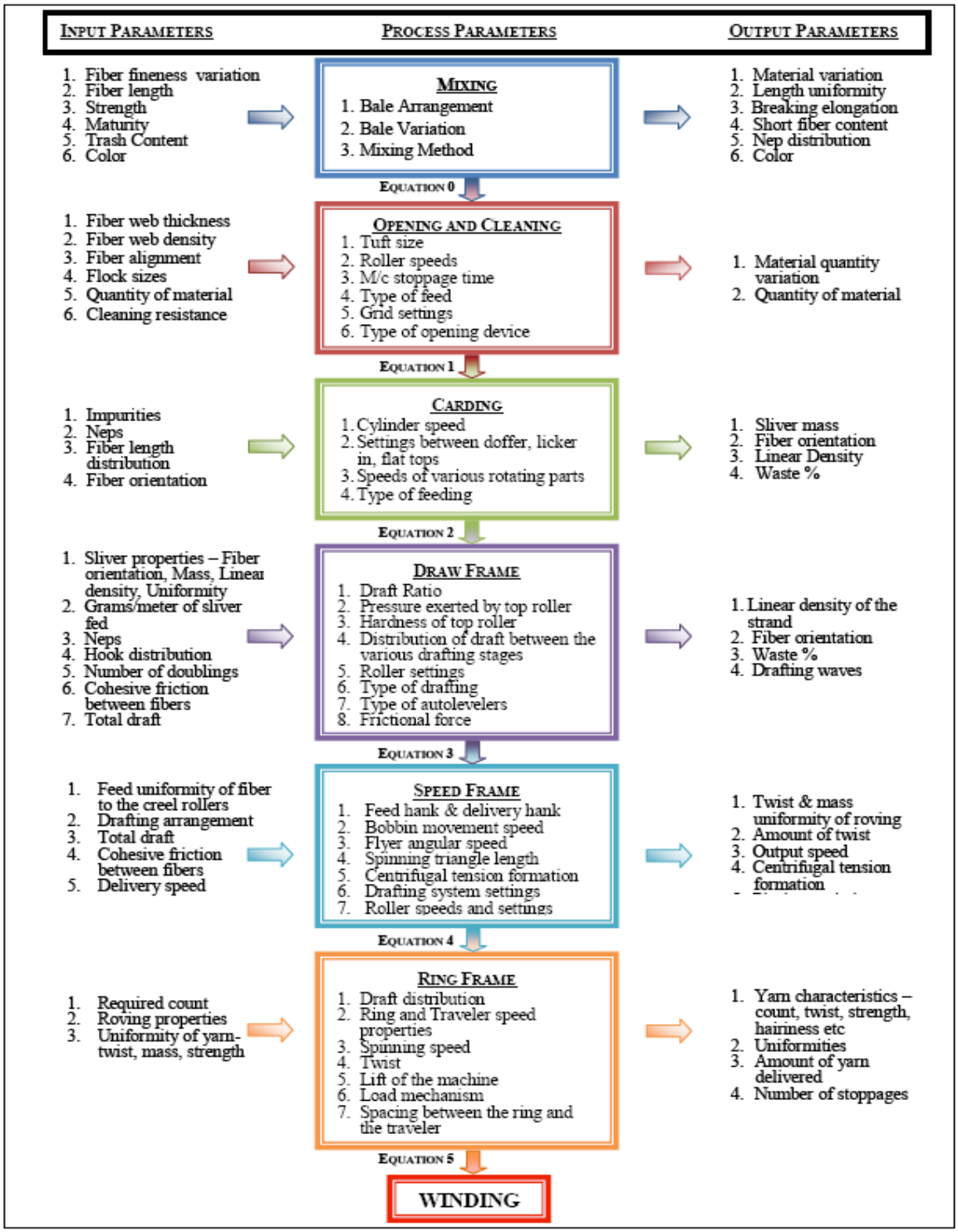


Figure 5: Framework for Structural and Functional Relationships among Key Spinning Processes

5.1 Approach for Designing a Dynamic Control Chart

All scientific publications and reports available to date have been sorted out to establish the connectivity as a *contiguous system* within a framework of *"disjoint real-time"* domain as a requirement for *"variance tolerancing and channeling."* This approach consisted of the following phases:

a) The initial task was to identify and sort out the clearly defined input and output parameters that are essential for controlling process performance and product qualities from the published papers.

b) The next step was to identify the structural equations/ relationships between the input and output variables between two contiguous process stages. In some cases, there were more than one structural equation and/or relationship between two contiguous process stages which were often incongruent and/ or incompatible to each other.

c) In such-a-case, the multiple equations were consolidated or aligned into a single equation through a special algorithm called "FAMSE" at each stage in such a way that a dynamic system can be developed by combining all the process steps in sequence, linking all input and output parameters.

d) Once the final structural equation/ relationship was developed (from the multiple structural equations obtained from different researchers) into one manageable equation, *Variance Tolerancing and Channeling* were achieved by computing the variance of the output function based on the variances of the input parameters.

e) The final structural equation facilitated computation of the variances and biases of all previous process stages, and gave rise to a "DYNAMIC" process average.

f) Based on the dynamic process average and the *"toleranced"* variances, *Dynamic Control Limits* were obtained. These limits could be obtained *on-line* or *off-line* depending on the processes involved and the need. The *Out-of–Control* decisions can be made by using both the static limits and the dynamic limits.

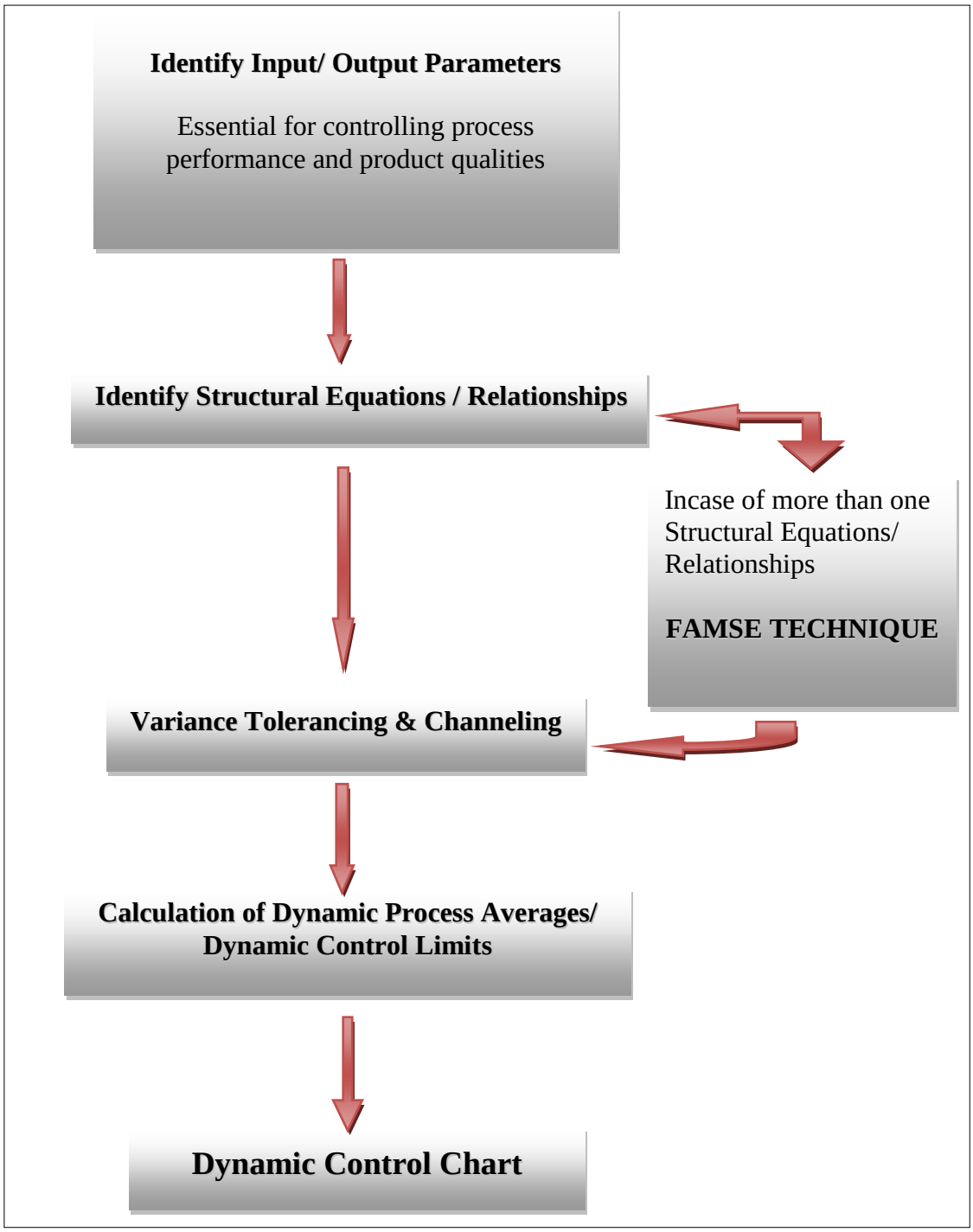


Figure 6: Flow Sheet for Design a Dynamic Control Chart

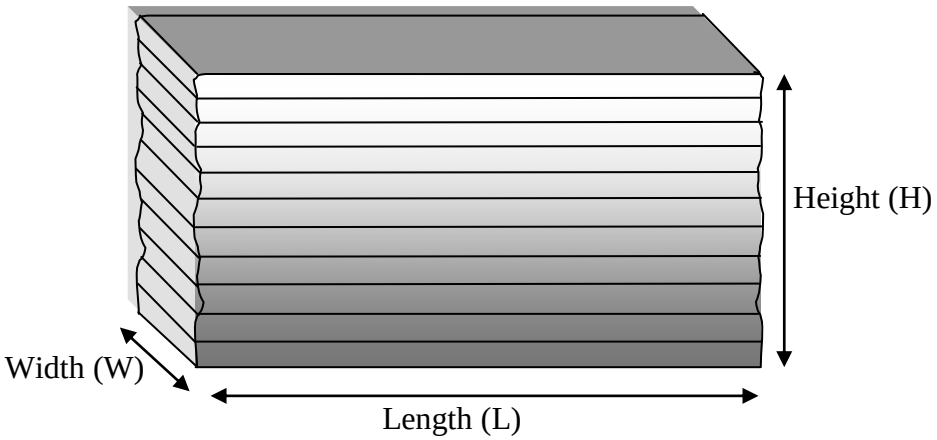
5.2 Identification of Structural Equations in Spinning Using Various Key Influencing Factors

Various equations are identified at different stages of spinning process using mass uniformity and yarn strength as key factors from the literature. As mentioned in the earlier sections, some of these equations were similar and some were even contradictory as each researcher has a different approach. Hence, we identified '*clean*' and '*manageable*' structural equations which were developed into a single structural equation.

5.2.1 Identification of Structural Equations in Spinning for Mass Uniformity

Stage I: Examples for Mass Variance Equations at Opening and Mixing

Equation 1: In the Opening and Mixing stage, the inherent variations are modified and redistributed for the amount of cotton picked up by the picking machine along the width during the mixing stage. Now let us consider that the bale is divided into 'N' parts along its width and the length and height of bales remain constant while the density (ρ) varies. When the picking machine picks up certain mass of fibers from each of these parts, the mass will be redistributed.



$$\text{Mass } (M_i) = \text{ Volume } (V_i) \times \text{Density } (\rho_i) \quad \text{---------- (15)}$$

$$\text{where Volume}(V_i) = \text{ Length}(L) \times \text{Width}(W_i) \times \text{Height}(H)$$

El Mogahzy *et al.* [43] 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. But the key factor is the fiber property used in the picking scheme.

Two components of variability can be considered for any cotton fiber characteristic: within-laydown variability, between-laydown variability.

Now the sum of Mass all the individual 'N' parts will give us the total Mass of the bale and Mass Variance Within the bale can thus be calculated from the obtained 'N' masses. By summing up these within bale mass variances for 'n' bales we calculate the Total Within-Bale Mass Variance.

The Total Within-laydown Mass Variance = $\sigma^2_{WLD} = \frac{(n-1)N}{(nN-1)} \sigma^2_{BB} + \frac{(N-1)}{(nN-1)} \sum_1^L \sigma^2_{WB}$ ------ (16)

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.

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

$$\sigma^2_{total} = \frac{(L-1)n}{(Ln-1)} \sigma^2_{BLD} + \frac{(n-1)}{(Ln-1)} \sum_1^L \sigma^2_{WLD} \text{ ---------- (17)}$$

where σ^2_{BLD} = Total Mass Variance Between bales in a laydown

and σ^2_{WLD} = Total Mass Variance Within bales in a laydown

Equation 2: Let 'M' be the mass of fibers being collected from each bale by the mixing frame, 'W' the total width of the bale, 'H' the height /depth of each bale, 'L' the length of each bale, 'd' the density of the bale and 't' the collection time unit.

Then we can calculate the amount of mass M being collected by the mixing frame in time t seconds as

$$M = L \cdot W \cdot H \cdot d \cdot t \text{ ---------- (18)}$$

Now by differentiating Equation (18) with respect to time t we get the variation in feed (input) i.e.,

σ_{feed} = Change in mass with respect to time

= dM / dt

$\sigma_{feed} = W.d$ ---------- (19)

Equation 3: Sevost'yanov [44] considered a model of mixing bed formed in a machine chamber of length L. If at a given instant the pinned lattice combs through the mixing bed at a section MN at the distance *x* from the front edge of the bed, the newly formed blend-flow will contain various sections (1, 2, 3 …) of the flow of components. If section BC of the continuous component flow is unfolded, the number of fibers in a section MN of the mixing bed or the weight of a very short length Δl of the bed at section MN is determined form the following equation:

$$f(l,x) = y(l) + y(l_1) + y(l_2) + y(l_3) + \cdots \text{ ---------- (20)}$$

$$l_1 = l - 2x; l_2 = l - 2L; l_3 = l - 2L - 2x;$$

where $y(l)$, $y(l_1)$, $y(l_2)$, $y(l_3)$ ..., are the number of fibers in sections 1, 2, 3…, of the component flow or the weight of a very short length Δl of the flow at these sections.

The Coefficient of Variation (the mass irregularity), $C_f^2(x)$ of the number of fibers in the sections of the component mixing bed is given by:

$$C_f^2(x) = C_y^2 \left\{ \frac{1}{2d} + \frac{e^{-2\alpha x}}{2d} + \frac{1}{d^2} \sum_{n=1}^{d/2} \left(\frac{d}{2} - n\right) \left[e^{-2\alpha(nL+x)} + e^{-2\alpha(nL-x)} + 2e^{-2\alpha nL} \right] \right\} \text{---(21)}$$

where'd' is the number of layers in the bed, 'C_y' is the irregularity of the flow of components admitted to the mixing machine, '*x*' is the distance MN from the front edge, 'L' is the chamber length.

The irregularity of the distribution of the fibers of the different components over the sections of the mixing bed is given as:

$$C^2 = \frac{1}{m} \sum_{i=1}^{m} C_{fi} \text{ ------ (22)}$$

where 'm' is the number of components in the mixture.

Stage II: Examples for Mass Variance Equation at Carding

Equation 1: Buturovich [45] 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 .

Then, the variation in web (output) is given as:

$$\sigma_{web} = \int_0^t K(t)X_p\,(t-\delta)d\delta \quad \text{------ (23)}$$

where, $X_\pi = \frac{Y_\pi}{q_\pi}$, $X_p = \frac{Y_p}{q_p}$, and $K(t) = \frac{e^{-t/c}}{c}$

Stage III: Examples for Mass Variance Equations at Drawing

Equation 1: Let 'V' be the irregularity CV, 'n' the number of doublings, 'V_0' the mass irregularity of the input, 'A' and 'B' the coefficients where '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, 'N_0' the hank of input, 'z' the draft ratio and 'V_α' be the additional irregularity arising from roving tension at roving frames.

Then, according to the Law of Drafting [46],

$$V^2 = \frac{1}{n}\left[V_0^2 + AN_0\,(z-1) + BN_0(z-1)^2z\right] + V_\alpha^2 \quad \text{--------- (24)}$$

where, $A = \varphi\frac{10^4}{N_f}$ and $B = \gamma^2\varphi\frac{10^4}{N_f}(1+3c_f^2)\beta$

Equation 2: Sittut *et al*. [47] expressed the variation of the irregularity from drafting as follows:

$$C^2 = C_0^2 + A_1(B_1-1) + A_2(B_2-1) \quad \text{---------- (25)}$$

where C^2 and C_0^2 are the squared values of the coefficients of variations in cross-section of the ingoing and delivered sliver, B_1 and B_2 are the drafts in the front and back zones, and A_1 and A_2 are the coefficients which are independent of the draft.

Equation 3: In this paper Murauskaite [48] used a statistical method for the mathematical description of the object on the basis of experimental results. The drafting system of a

drawframe represents a mathematical probability model, a model in which the parameters and structure of the ingoing product vary in accordance with a random law while the disturbances governing the performance of the drafting system are also random.

When given characteristics at the input and output of a system during a protracted period of time are determined, the function linking these characteristics under steady state operating conditions of the object can be called the static characteristic. i.e.,

$$y = f(x_1, x_2, \ldots, x_n)$$

The method used for the determination of the static characteristics of a dynamic system in this paper is Brandton Method [49] – Method of approximation of the functions of several variables by successive elimination.

The influence and significance of variable parameters of the ingoing product and of the operating parameters of the drafting gear are brought to light by means of a variance analysis.

In the present case the required function is assumed to be a derivative of the functions of the individual factors or characteristics, i.e.,

$$\sigma_{out} = \bar{\sigma}_{out} f_1(E-1) f_2(R) f_3(\sigma_{in}) \quad \text{---------- (26)}$$

where 'σ_{out}' is the estimated variance of the thickness regularity of the sliver delivered by the drafting system, '$\bar{\sigma}_{out}$' is the mean value of this valuation, 'E' is the draft, 'R' is the setting, 'σ_{in}' is the estimated variance of the thickness regularity of the slivers fed into the drafting system.

Stage IV: Examples for Mass Variance Equation at Roving

Equation 1: The relative variance (V_α^2) added by drafting at the roving frame [50] is given as

$$V_\alpha^2 = \frac{AN_0}{n}\left(\frac{S-\bar{L}}{\bar{L}}\right)(z-1) + d \quad \text{---------- (27)}$$

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.

Stage V: Examples for Mass Variance Equations at Spinning

Equation 1: Substituting the value of V_α^2 obtained at roving frame in the variance equation at Drawing (Equation 24), we get

$$V^2 = \frac{1}{n}\left\{ V_0^2 + A\,N_0\,(z-1)\left[\frac{S}{\bar{L}}\right] + BN_0(z-1)^2 z + nd\right\} \text{---------- (28)}$$

Equation 2: There are several equations for the Theoretical Coefficient of Variation, those formulated by Spencer-Smith and Todd, Martindale, Picard, Vanden Abeele, Beniopadhi and Sulser. M. Zilachi and Vanden Abeele.

But Privalov *et al*. [51] derived a new equation for the *Theoretical Variation Irregularity*, CB (0) which is more suitable for practical purpose which is given as:

$$CB^2(0) = \frac{\bar{a}_i}{T_\eta}\left(\frac{\bar{a}_g}{\bar{a}_l} + \frac{\bar{l}_g}{\bar{a}_l}\right)\left(1 - \frac{T_\eta}{T_{\eta max}}\right) \quad \text{---------- (29)}$$

where '$\bar{a}_i$' is the mean fiber fineness $\left(a = \frac{g}{l}\right)$ weighted for the fiber length, '$\bar{a}_2$' is the mean fiber fineness weighted for the fiber weight, $\left(\frac{\bar{a}_g}{\bar{a}_l} = 1 + C_{\bar{a}}^2\right)$, '$C_{\bar{a}}$' is the coefficient of fineness variation between fibers, '$\bar{l}_g$' is Picard's mean index of

irregularity weighted for the fiber weight, 'T_η' is the mean yarn weight, '$T_{\eta max}$' is the maximum yarn weight, '$1 - \frac{T_\eta}{T_{\eta max}} = p$'is the Vandeen Abeele Coefficient, '$\frac{T_\eta}{\bar{a}_i} = \bar{\eta}$' is the average number of fibers in the yarn cross-section.

The probability model of ideal yarn can be defined only by two conditions; the fiber distribution in the yarn does not depend on their length distribution. The fiber distribution along the yarn is governed by Poisson's Law, i.e., the probability of a given yarn cross-section being intersected by n fibers is given by the following expression:

$$P(n) = \frac{(k\bar{l})^n}{n!} e^{-k\bar{l}} \text{ ---------- (30)}$$

The final form of the equation of the theoretical coefficient of variation of the yarn of length 'b' is given as:

$$CB^2(b) = \frac{\bar{a}_i}{\tau_n} \times \frac{1}{L} \times \frac{1}{\eta}\left(\frac{1+\cos\bar{\beta}_o}{2\cos\bar{\beta}_o}\right)(1 + \bar{C}_i^2 + C_{\bar{a}}^2 + C_{\bar{l}}^2)\left(1 - \frac{T_\eta}{T_{\eta\,max}}\right)\left(1 - \frac{b}{3\bar{l}}\right) \text{ ----- (31)}$$

5.2.2 Identification of Structural Equations in Spinning for Yarn Strength

Equation 1: Suh [52] considered the yarn strength in terms of fiber properties such as fiber strength, fiber length and micronaire value at the end of spinning process.

$$Y = k\left(\frac{L \times U}{M^2}\right) \text{ ---------- (32)}$$

where, Y – Yarn Strength, L – HVI length of fiber, U – HVI Uniformity ratio, M^2 – HVI Micronaire Value, k – Proportionality Constant.

Yarn Strength is proportional to Length and Uniformity of fiber and is inversely proportional to Square of its Micronaire value.

Equation 2: According to Sullivan [53], the yarn under consideration is an extended bundle of fibers, which are aligned parallel to the lengthwise axis of the bundle. He considered the strength of the yarn to be contributed by each fiber of cross section in an amount equal to that necessary to cause the particular fiber to break or slip. Thus, he gave the following equations for the strength of yarn when there is a break/ no break in fibers.

Strength of the yarn when no fibers may break (F_1) = $\frac{fnL}{4}$

where f – frictional force per unit length of fiber, n – number of fibers per cross section, L – length of fibers

Strength of the yarn when some fibers may break (F_2) = $nJ\left(1 - \frac{J}{fL}\right)$

where J – Breaking strength of a fiber,

According to him, frictional force (f) depends on the forces which press the fibers together and on the coefficient of friction, consider p to be the average pressure exerted upon a fiber by adjacent fibers.

Hence $f = \mu p y$,

where μ- coefficient of friction, y – the perimeter of the fiber cross section taken normal to the fiber axis.

But $y = \alpha \delta S$,

where α - fiber cross sectional area, δ - fiber density, S - surface per unit mass of the fiber.

And hence frictional force becomes $f = \mu \alpha \delta S p$

Thus, for a yarn in which fibers may not break, yarn strength

$$F_1 = \frac{n\,\mu\,\alpha\,\delta\,S\,p\,L}{4} \quad \text{---------- (33)}$$

and for a yarn in which fibers may break, yarn strength

$$F_2 = nJ\left(1 - \frac{J}{\mu\,L\,\alpha\,\delta\,S\,p}\right) \quad \text{---------- (34)}$$

If M = mass per unit length of a yarn, λ = Strength of a fiber in strength units per mass per unit length of fiber,

$$F_1 = \frac{M\,\mu\,S\,p\,L}{4} \quad \text{---------- (35)}$$

$$F_2 = M\lambda\left(1 - \frac{\lambda}{L\,\mu\,S\,p}\right) \quad \text{---------- (36)}$$

If the bundle of fibers contains twist then the total strength of a twisted yarn is given by

$$F = \frac{1}{2\pi\,\tau^2}(p^* - p_0) \quad \text{---------- (37)}$$

where p* - pressure at yarn center, p_0 - pressure at yarn radius, τ - number of turns of twist per unit length and $p^* = p^0\left[\frac{4\pi\tau^2 M}{\delta'} + 1\right]^{\frac{\delta' L \mu S}{s}}$ where δ' - density of the yarn.

Equation 3: The variation in the strength of roving at roving frame [54] can be represented empirically by the equation:

$$V^2 = \frac{aC+b}{p}(D - 1.2) + \frac{V_s^2}{p} + d \quad \text{---------- (38)}$$

where C – Hank number (or) Count, p – Number of ends, D – Draft Ratio,

V_s^2 - Variation in strength of sliver from drawframe, a, b, d – Constants.

Since a, b, d are relatively smaller in value, Equation (38) can be re-written as:

$$V^2 = \frac{\alpha_1 C}{p}(D - 1.2) + \frac{V_s^2}{p} \text{ ---------- (39)}$$

where α_1 - Irregularity co-efficient, which decreases with hank number 'C'.

Variation in strength of yarn at ring frame can be represented empirically by the equation:

$$V^2 = 0.73\left\{\frac{\alpha_2 C}{p}(D - 1.43) + \frac{V_r^2}{p}\right\} \text{ ---------- (40)}$$

where α_2 - Irregularity co-efficient, C – Hank number (or) Count, p – Number of ends, D – Draft Ratio, V_s^2 - Variation in strength of roving from roving frame

Substituting Equation 39 in Equation 40, we get:

$$V^2 = 0.73\left\{\frac{\alpha_2 C}{p}(D - 1.43) + \frac{\frac{\alpha_1 C}{p}(D - 1.2) + \frac{V_s^2}{p}}{p}\right\}$$

$$V^2 = 0.73\left\{\frac{\alpha_2 C}{p}(D - 1.43) + \frac{\alpha_1 C(D-1.2)+V_s^2}{p^2}\right\} \text{ ---------- (41)}$$

5.3 Development of Structural Equations/Relationships Based on Key Influencing Factors in Spinning

The dynamic process control system for staple yarn spinning process is developed by treating opening & mixing, carding, drawing, roving and spinning as continuous but disjoint processes. Since every previous process affects the following processes certain functional relationships were surveyed, classified, analyzed and evaluated for their applicability from the vast amount of published work and literature. The measured fiber properties such as strength, length, short fiber content, length uniformity, micronaire and color as well as the

intermediate measurements of mass, mass uniformity at different processing stages provided the necessary input process averages and variances of the subsequent processes.

Our initial goal was to take a well-known property of a fiber assembly such as mass, mass uniformity, or strength, and tracking their changes through the established relationships between various stages of yarn production. The relationships, however, were often not in the functional forms which we could easily transfer to the discrete stages of continues yarn production. Therefore, we mapped these equations into most compatible, congruent forms between the process stages. During mapping as expected, due to the complexity and unrealistic nature of some of these assumptions, we often had to abandon few equations in order to obtain '*clean*' and '*manageable*' structural equations.

5.3.1 Development of Structural Equations considering Mass Uniformity in Spinning as an Influencing Factor

We considered the mass variation in the early stages of spinning. After the structural equations for the mass variations were found/ developed from literature, the expected levels of mass variances and their variances are to be computed. As the different stages in the spinning process are linked to each other they are treated as contiguous chain of process, the output mass variation becomes the input of the subsequent stage.

A process chain is thus formed by tying the various processes involved in the spinning process. The output mass variance from mixing and blending is now the input mass variance at the Carding stage. Hence, the output variance biases will be a cumulative of input biases /variances generated at the Carding stage and also the biases carried over from the previous process stage i.e., Mixing and Blending.

Substituting the values of Xπ, K (t) and X_p in Equation (23), we obtain,

$$\sigma_{web} = \left[\frac{(e^{-t/c}\, VHWdt)(t-0) - \left(e^{-\frac{t}{c}}\, VHWd\right)\left(\frac{t^2}{2} - 0\right)}{c}\right]$$

By letting L = W·H·d,

$$\sigma_{web} = \frac{L}{2c}\left(Ve^{-t/c}\, t^2\right) \text{ ---------- (42)}$$

The coefficient of variation, denoted as V (%) based on Equation (42), is given by

$$V(\%) = \frac{\sigma_{web}}{\bar{X}}$$

where, mean $\bar{X}$ = V ·W ·H ·d ·t

$$V = \frac{\frac{L}{2c}\, V\, e^{-t/c}\, t^2}{V\, W\, H\, d\, t}$$

Substituting the value of L from above we get,

$$V = \frac{t}{2c}\, e^{-t/c} \quad \text{---------- (43)}$$

Now, this output mass variance will be added to the input mass variances generated at the drawing stage. Substituting the value of V_{output} from above in the Equation (24) at drawing, we obtain the following:

$$V^2 = \frac{1}{n}\left[\frac{t^2 e^{-2t/c}}{4c^2} + AN_0(z-1) + BN_0(z-1)^2 z\right] + V_\alpha^2$$

Finally, the output mass variance obtained at the spinning stage is a cumulative of mass variances from the previous process stages and the present stage.

$$V^2 = \frac{1}{n}\left[\frac{t^2 e^{-2t/c}}{4c^2} + AN_0(z-1)\left(\frac{S}{L}\right) + BN_0(z-1)^2 z\right] + nd \text{ ------- (44)}$$

These consist of the structural equations necessary for obtaining the expected process averages and the basic equations for performing the variance tolerancing.

5.4 Variance Tolerancing in Ring Spinning - Application Examples

5.4.1 Variance Tolerancing for Variation in Mass Uniformity of Spun Yarns

The output mass variation is being determined at every stage of the spinning process in terms of the input mass variation. Here, the "input and output variances" constitute the factors linking the structural equations. For the roving process, the variance tolerancing and channeling are accomplished by estimating the variance of the "output mass variance" as a function of the input variances from the previous processes as follows:

The coefficient of variation at a roving frame can be expressed by Equation (44) as

$$V^2 = \frac{1}{n}\left[V_i^2 + AN_0(z-1)\left(\frac{S}{\bar{L}}\right) + BN_0(z-1)^2 z + nd\right]$$

where V_o^2 is the output variance and $V_i^2 = \frac{t^2 e^{-2t/c}}{4c^2}$ the input variance.

For variance tolerancing, we need to compute the variance of V_o^2, that is, we must calculate

$$Var[V_o^2] = \frac{1}{n^2} Var[V_i^2] \text{ (since the other terms are constants)}$$

By letting, t/c= x,

$$Var[V_o^2] = \frac{1}{n^2} Var[x^2 e^{-2x} + P_2 + P_3 + P_4]$$

$$= \frac{1}{n^2} Var(x^2 e^{-2x}) + \text{Constant.}$$

Here, $Var(x^2 e^{-2x})$ can be expanded by using a Taylor's series $\sum_{n=0}^{\infty} \frac{(x-a)^n}{n!} f^n(a)$ with a = μ:

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

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

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

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

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

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

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

Equation (45) 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.

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

$$+ [\sigma^2(6\mu^2 - 16\mu^3 + 8\mu^4)] - [\sigma(2\mu^2 - 8\mu^3 + 4\mu^4)] \text{ --- (45)}$$

5.4.2 Variance Tolerancing for Variation in Strength of Spun Yarns

Similarly variance tolerancing and channeling are accomplished by estimating the variance of the output variance of the "strength variance of yarn" (Equation (32)) as a function of means of fiber length μ_L, fiber uniformity μ_U, fiber micronaire value μ_M and their respective variances σ_L, σ_U and σ_M.

$$V(Y) = \frac{1}{\mu_M^8}\left[\sigma_L^2\left(\mu_M^4\,\mu_u^2 + 20\sigma_M^2\,\mu_u^2 + \sigma_u^2\,\mu_M^4 + 20\,\sigma_M^2\,\sigma_u^2\right)\right]$$

$$+\left[\sigma_u^2\left(\mu_L^2\,\mu_M^2 + 12\,\mu_L^2\,\mu_M^2\,\sigma_M^2 + 36\,\sigma_M^2\,\mu_L^2 - 36\,\sigma_M^4\right)\right]$$

$$+\left[\sigma_M^2\left(8\,\mu_L^2\,\mu_M^2\,\mu_u^2 - 36\mu_u^2\right)\right] \quad \text{---------- (46)}$$

5.5 Design of a Dynamic Control Chart in Spinning

For any textile manufacturer, the aim in spinning would be to produce a yarn of specified count and quality at lowest price. One of the prime functions of a dynamic quality control chart in spinning is the control of count and its variability. The quality of the raw material i.e., fibers should be sufficient to ensure that it performs well in subsequent processes and that the final end product i.e., yarn is acceptable. This quality of yarn is determined by its uniformity, tensile strength, elongation, etc., and the relative importance of these factors depends on subsequent processes such as weaving, knitting etc and the final product. Over-all control at spinning consists of maintaining the average count as specified, ensuring that the count variation is satisfactory and minimizing thin spots, thick spots and neps. The dynamic control chart 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 helps in producing better quality goods.

5.6 Design of Dynamic Control Charts in Other Textile Manufacturing Processes

This dynamic control chart can be applied in other continuous manufacturing processes in textiles such as finishing. During the finishing operation, the fabric from the

loom or knitting machine is subjected to a series of chemical and physical processes designed to give it the properties needed for a particular end use. The fabric must be so finished that it meets the subjective standards related to drape (softness, firmness, lusture, cover, solidity of shade), the objective properties (such as matching and uniformity of shade, weight per unit area, fabric construction, width, length, tensile strength, color fastness and dimensional stability) and any special property required of the fabric end use (flammability, shower-proofing, air permeability etc.). Quality has to be maintained during the entire processing while the costs have to be kept down.

Quality control at the finishing stage involves a number of different functions such as:

- Control of raw materials
- Selection of the finishing sequence and control of process parameters
- Control of fabric specifications
- Inspection of fabrics

As this is a continuous sequence of processes, the application of dynamic quality control chart would result in minimization of false positives and the unnecessary corrective actions, the root cause of ‘out-of-control’ situations can be traced, and also optimal control strategy at each stage is generated.

Chapter 6

Summary and Conclusions

a) A conceptual framework has been designed to construct a *Dynamic Quality Control System for Textile Processes* by which 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.

b) Well-known properties of cotton fiber assemblies such as mass uniformity and strength are traced along the spinning process through the structural relationships surveyed and established at various stages of yarn production. The relationships were often not in simple functional forms that we could easily transfer to the discrete stages of continues yarn production. Therefore, we mapped these equations into most compatible, congruent forms between the process stages. Due to the complexity and unrealistic nature of some of these assumptions, we often had to abandon the aspiration of obtaining a "clean" and manageable structural equation.

c) Structural equations were developed for the different process variations observable in the early stages of staple yarn spinning for the mass variation of the fiber assemblies. The expected levels of mass variance and their variances (i.e., the variances of the mass non-uniformities) were computed for opening/blending, carding, drawing and roving processes. Similarly, the expected value of yarn strength and its variance were computed as a function of cotton fiber characteristics measurable at any stage of the spinning process.

d) Concept was developed for creating a *"Fusion Algorithm for Multiple Structural Equations (FAMSE)"* in order to consolidate a set of disjoint, incongruent and often non-compatible multiple equations into one functional form linking the input and output of any two contiguous processes. The algorithms will be used for performing variance tolerancing and formulation of dynamic control limits.

e) Variance tolerancing was computed between the mass variations between carding/drawing and roving and strength variations of yarn. While the algebraic expressions appear to be complex, the process is shown to be straightforward, thus enabling us to generate a set of dynamic control limits at the end of roving.

Chapter 7

Future Work

As a sequel to this work, the same concept should be applied to all wet textile processes where time is a much important and dominant factor. The on-line real-time dynamic control system is indeed more readily acceptable to any continuous dyeing or finishing process by considering 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. 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.

In addition, the concept developed in the work may be computer programmed for selected processes and for yarn strength control. For such an application, however, the data acquisition system, measurement methods and instrumentation much work in synchronization. Nevertheless, the concept developed here should be tried at a selected process quite easily with more time and industry participation.

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