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Dynamic Textile Process and Quality Control Systems

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Project Goals

A conceptual/theoretical framework called *"Dynamic Textile Process and Quality Control System* (DTPQCS)" is being developed for dry and wet textile processes that 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 via structural relationships that connect the factors in a given process stage to that of the next stage. By obtaining more accurate control limits, the root causes of the out of control situations will be determined precisely, and unnecessary corrective actions (false positives) that are detrimental to quality monitoring and improvement will be minimized.

The initial task was to research and identify all published papers and sort out clearly defined input and output parameters that are essential for controlling process performance and product qualities. Then the challenge was to align and consolidate the 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. An approach (FAMSE) under development attempts to consolidate the multiple structural equations obtained by different researchers into one manageable equation. 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 $\underline{z}_j$ $(\underline{z}_{j1}, \underline{z}_{j2}, \ldots, \underline{z}_{jm})$;

$$Y_j = f_j(Y_{j-1}, z_j), \quad j = 1, 2, 3, \ldots, k$$

In any given two contiguous processes, the input ($\underline{z}$) and output (Y) relationships are more than one in most cases. With 'P' structural equations with certain number of factors, each structural equation may be rewritten as a polynomial function for finite solutions or an iterative solution.

Introduction and Technical Approach

Development of textile science and engineering during the last 100 years has been truly remarkable based on the published research reports and claims. The literature and structural equations found to date are indeed quite impressive in their scope and application potentials. However, the structural models and prediction equations known to date are seldom used in quality and process control practices in the US or elsewhere. Why?

Textile quality control often involves keeping output of individual processes in control through the use of Shewhart control charts [2]. 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 [1, 3]. 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 [4]. 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 [5, 6] 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 [2] indefinitely. This undoubtedly is a terribly inefficient control process completely void of structural relationships already known for the causes and effects.

Therefore a *dynamic quality control system* for dry and wet textile processes is being developed as an entirely new attempt to apply the known structural equations published during the last 60 years. The task was to align and consolidate the 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. This task is quite challenging but most rewarding.

By obtaining more accurate control limits, the root causes of the out of control situations will be determined precisely and unnecessary corrective actions (false positives) that are detrimental to quality monitoring and improvement will be minimized. The conventional quality/process management based on Shewhart control scheme and the so-called "feed-back" and "feed-forward" control system has had only limited success in textile manufacturing in the past. These "failure mechanisms" have been outlined by Suh [1]. The key missing links are the structural relationships that connect the factors in a given process stage to that of the next stage. These stages may be linked through the structural equations via variance channeling as already demonstrated by Suh and Koo [13, 14]. Without implementing these relationships, the stand-alone Shewhart control systems become totally useless when the input factors have been perfectly in control and match the process averages established. Otherwise, the "in-control" or "out-of-control" decisions become either false positives or false negatives.

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 stages as shown in Figure 1. Upon identification of the most relevant structural models, the upper and lower control limits at any given process stage will be computed by incorporating the "process variance" generated from the current stage through the known functional or structural relationships. The process average of the current process will also be computed based on the functional relationships that reflect the "biases" or the amounts of the out-of-control generated from the previous process stages, if any. Here, the bias B_k is introduced at the K^{th} stage along with new process variance σ_k^2 to generate the control limits as sum of the biases and the process variances. In addition, the process variance would be the sum of the variances inherited from the prior processes through the structural or functional relationships and the new variances introduced at that particular stage.

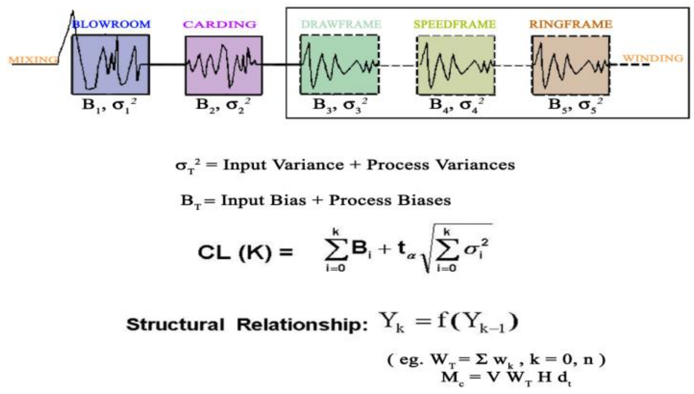


Figure 1. Conceptual frame for dynamic control limits from mixing/blending to ring frame via the structural relationships developed

In Figure 2, some of the structural and functional relationships between yarn spinning processes are shown. The inputs and outputs of each spinning process are given on the left and right side of the process parameters, respectively. The process parameters along with the input parameters produce an output, which in fact becomes the input parameters of the following process.

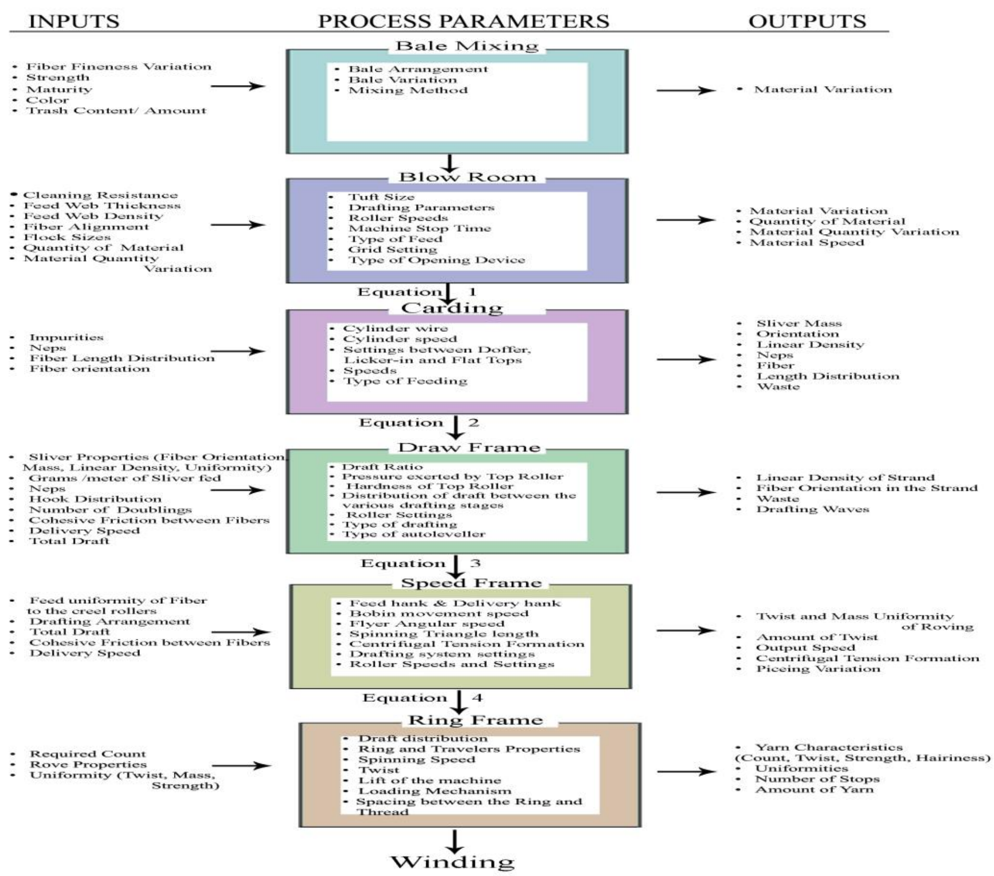
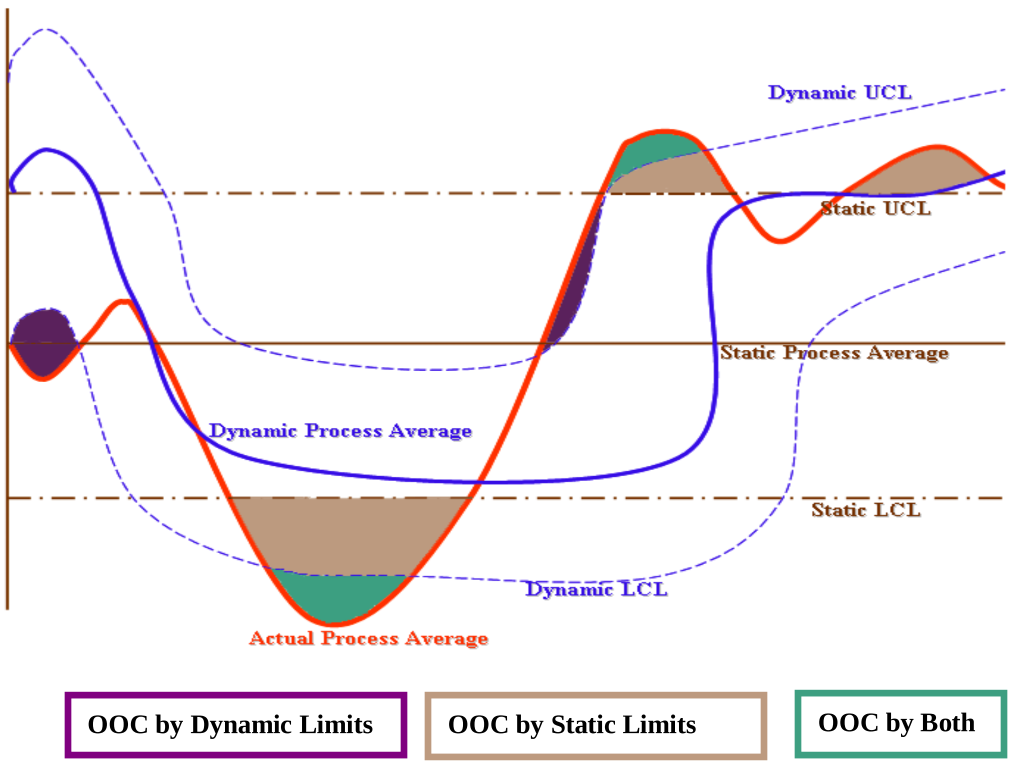


Figure 2. Framework for structural and functional relationships among key spinning processes

Principles of Dynamic Control Chart



The traditional static process averages and its control limits are coupled with dynamic process average and its control limits which reflect the biases of the previous process stages. This decision scheme is shown in the figure above [7].
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 is to correct the previous stage processes through the known structural relationships.
To make the process control system more responsive to the ever changing conditions of the processes it is important to understand and quantify the inter-dependence of all processes.

Work in Progress

We have been developing the conceptual and theoretical framework for the DTPQCS in the traditional staple yarn production process. The scientific papers published in several key journals have been searched and the relevant information extracted from many published papers. Many of the published papers are often found to be seemingly important but incongruent to each other in forming a seamless input/output structure. A major challenge, as expected, would be to sort out only the essential information and combine them into a usable form of structural equation for each and every stage. Some of the work being done is as follows:

I. Development of Structural Equation

An off-line dynamic control system for staple yarn spinning process was developed by treating blending, carding, drawing, roving and spinning as continuous but disjoint processes. Since every previous process affects the following processes [13,14,15] 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. Eventually, the output averages and their variances will be computed in time domain and compared against the actual values for optimal control. The data obtained would be handled as a continuous process although they are analyzed off line.

Our initial approach was to take a well-known property of a fiber bundle such as mass, uniformity or strength and tracing its progress through the established relationships between various stages of yarn production. The relationships were often not in the 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. During this mapping, we kept in mind the assumptions that are made during the derivation of each relationship. As expected, due to the complexity and unrealistic nature of some of these assumptions, we often had to abandon the aspiration of obtaining a "clean" structural equation. Here are two examples of structural equations developed from the literature.

Example 1: ***Mass Variation in Spinning***

We considered the mass variation in the early stages of spinning. Structural equations for the mass variations were developed. The expected levels of mass variances and their variances were computed. The output mass variation becomes the input of the subsequent stage.

a) Mass Variation in Opening and Mixing

Let *'M'* be the mass of fibers being collected from each bale by the mixing frame, *'V'* the speed at which the mixing frame collects the mass *M*, *'W'* the total width of the bales, *'H'* the height /depth 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

$$M = V \cdot W \cdot H \cdot d \cdot t \quad \text{------------ (1)}$$

Now by differentiating Equation (1) with respect to time *t* we get the deviation in feed (input) i.e.,

$$\sigma_{feed} = \text{Change in mass with respect to time}$$

$$= dM / dt$$

$$\sigma_{feed} = V \cdot W \cdot H \cdot d \qquad \text{---------- (2)}$$

b) Mass Variation in Carding

Let 'X_π' be the deviation in web (output), 'X_p' the deviation 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 deviations in 'q_π' and 'Y_p' the instantaneous deviation in q_p.

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

The deviation in web (output) is given [9, 10] by equation, below

$$\sigma_{\text{web}} = \int_0^t K(t) X_p(t-\delta)\, d\delta \text{ ------ (3)}$$

Substituting the values of X_{Π}, $K(t)$ and X_p in Equation (3), we obtain,

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

By letting $L = W{\cdot}H{\cdot}d$,

$$\sigma_{\text{web}} = \frac{L}{2c}\,(V\, e^{-t/c}\ t^2) \text{ ------------ (4)}$$

The coefficient of variation, denoted as V (%) based on Equation (4), is given by

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

where, mean $\bar{X} = V \cdot W \cdot H \cdot d \cdot t$

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

Substituting the value of L from above we get,

$$V = \frac{t}{2c}\, e^{-t/c} \qquad \text{--------------- (5)}$$

c) Mass Variation in Drawing

Let *'V'* be the irregularity C V, *'n'* the number of doublings, *'V_0'* the irregularity of the input, *'A'* and *'B'* the coefficients where *'A'* is due to the increasing 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* [11],

$$V^2 = \frac{1}{n}\left[V_0^{\ 2} + AN_0(z-1) + BN_0\,(z-1)^2 z\right] + V_\alpha^{\ 2} \text{ --------- (6)}$$

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

As V from Equation (5) is the input of the drawing process, Equation (6) becomes

$$V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^{\ 2}} + AN_0(z-1) + BN_0\,(z-1)^2 z\right] + V_\alpha^{\ 2} \text{ ------- (7)}$$

The relative variance (V_α^2) added by drafting at the roving frame is given [12] as

$$V_\alpha^2 = \frac{AN_0}{n}\left(\frac{S-\bar{L}}{\bar{L}}\right)(z-1) + d \qquad \text{--------- (8)}$$

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.

Substituting the value of $V_\alpha^{\ 2}$ from Equation (8) in Equation (7), we get

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

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

--------- (9)

<u>Example 2</u>*: Strength of Spun Yarns as a Function of Cotton Fiber Properties*

We considered the yarn strength in terms of fiber properties such as fiber strength, fiber length and micronaire value at the end of spinning process.

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

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

Yarn Strength is α to Length and Uniformity of fiber and is $\frac{1}{\alpha}$ to Square of its Micronaire value.

II. Variance Tolerancing and Variance Channeling

Variance tolerancing is achieved from a unique functional relationship between the input and output variables by computing the variance of the output function based on the variances of the input parameters. Based on the final structural equation, a set of dynamic upper and lower control limits will be constructed at each process stage. A bias B_k at the k^{th} stage is sum of all biases generated up to that stage.

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

As a final step, a set of dynamic control limits responsive to the time-dependent biases will be constructed. These cumulative biases and variances are used to establish dynamic process control limits.

<u>Variance Tolerancing for Example 1</u>*: Mass Variation in Spinning*

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 channelling 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 (9) as

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

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

$$Var[V_0^2] = \frac{1}{n^2} Var[V_i^2] \quad \text{(since the other terms are constants).}$$

By letting, *t/c= x*,

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

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

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

$$E\ \ f(x) = E\left[\mu^2 e^{-2\mu}\right] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \ldots = \mu^2 e^{-2\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + \ldots$$

$$E\left[\{f(x)\}^2\right] = E\left[\mu^4 e^{-4\mu}\right] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + \ldots = \mu^4 e^{-4\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + \ldots$$

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

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

Equation (10) below gives us the output variance of the "mass variance of roving" as a function of the input mean μ and the input variance σ for $x = t/c$, as defined.

$$\text{Var}\,[V_o^2] = \frac{1}{n^2}\left[e^{-4\mu}\{\ \sigma^4(8\mu - 20\mu^2 + 16\mu^3 - 4\mu^4 - 1)\}\ + \sigma^2(6\mu^2 - 16\mu^3 + 8\mu^4)\ - \sigma\,(2\mu^2 - 8\mu^3 + 4\mu^4)\right] \qquad \text{-------- (10)}$$

<u>Variance Tolerancing for Example 2</u>*: Variation in Strength of Spun Yarns*

Similarly variance tolerancing and channelling are accomplished by estimating the variance of the output variance of the "strength variance of yarn" 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_M and σ_U.

$$\begin{aligned} \text{V(Y)} = \frac{1}{\mu_M^8}\Big[& \sigma_L^2\ \ \mu_M^4 \mu_u^2 + 20\sigma_M^2 \mu_u^2 + \sigma_u^2 \mu_M^4 + 20\sigma_M^2 \sigma_u^2 \\ & + \sigma_u^2\ \ \mu_L^2 \mu_M^2 + 12\mu_L^2 \mu_M^2 \sigma_M^2 + 8\sigma_M^2 \mu_L^2 \mu_M^2 + 36\sigma_M^2 \mu_L^2 - 36\sigma_M^4 \\ & + \sigma_M^2\ \ 8\mu_L^2 \mu_M^2 \mu_u^2 - 36\mu_u^2\ \Big] \end{aligned}$$

Summary

A conceptual framework has been built to construct a *Dynamic Textile Process and Quality Control System* 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. Structural equations were developed for the mass variation observable in the early stages of staple yarn spinning, and also for the strength of staple yarns as a function of cotton fiber properties. The expected levels of "mass variance" and their variances were computed for opening/blending, carding, drawing and roving processes. Similar approaches have been used for the strength of spun yarns. For each case, the variance tolerancing was attempted between input and output parameters. While the algebraic expressions appear to be complex, the processes are shown to be simple and straightforward, thus enabling us to generate a set of dynamic control limits at the end of roving and at the end of spinning.

Future Work

Our next step will be to consolidate multiple equations obtained by different researchers into one manageable equation using an algorithm. A computational method will be 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 algorithm will be used for performing variance tolerancing and formulation of dynamic control limits also.

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