Using Off-Line Quality Engineering in Textile Processing

Part I: Concepts and Theories

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ABSTRACT

In recent years, there has been a significant change in quality implementation through the application of off-line quality engineering in several industries in both Japan and the U.S. Off-line quality engineering uses parameter design and tolerance design to reduce product development costs. In this part of the study, an overview of the concepts and theories of off-line quality engineering is presented and methods are suggested for implementing these concepts in textile applications.

The old concept of quality assurance was based on inspection of 100% of product items to sort the good from the bad before the products reached consumers. To avoid 100% inspection, this concept was later developed into a set of inspection procedures and product specification rules. These rules are referred to as acceptance sampling, and they simply represent a set of communication tools between the user and the producer of a product [3]. For convenience in inspection, quality characteristics of a product were usually stated in terms of an interval consisting of lower and upper specification limits. This practice suggests that a consumer of a product remains equally satisfied with products conforming to the interval specifications. A process "fallout" or units that do not conform to the specifications are rejected.

The second generation of quality assurance development was the use of statistical process control (SPC). To minimize rejection, an SPC program monitors the quality characteristic using the familiar Shewhart control chart [1, 4, 8]. The main objective of such a program is to keep the variability of a process or product within the customer specification limits (Figure 1). A control chart consists of a center line representing the mean quality parameter and upper and lower control limits representing 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 "out of control." These points call for corrective actions of the process.

In recent years, there has been widespread interest in SPC implementation in different sectors of the textile industry. The reasons for this include the rapidly changing and developing technology in textile machinery and product specifications, which imposes new quality demands; the availability of electronic monitoring and repairing systems, which permit real-time control charts and make it possible for timely corrective actions; the increasing competition at both local and international levels; and the increasing computing power and the availability of numerous SPC software programs.

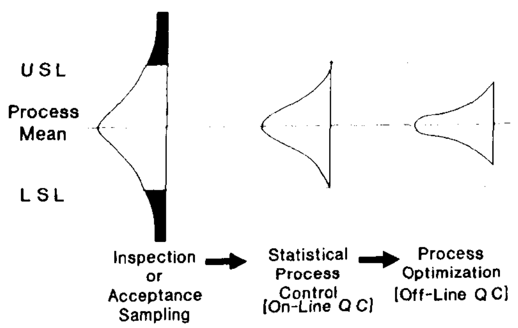

FIGURE 1. Development of the quality assurance approach.

The third generation of quality assurance development is referred to as "off-line" quality engineering. This concept was first introduced to the Japanese industry by Genichi Taguchi [12, 13]. The great success achieved by applying Taguchi methods in Japan has led American companies such as AT&T, Ford, and Xerox to use these methods in their quality programs.

There are two main differences between the "off-line" quality engineering concept and the classical SPC concept: First, in an SPC program, quality is measured by conformance to arbitrary specifications. In an off-line quality engineering program, quality is measured by the loss resulting from a departure from a target value of quality characteristic and the variability in this characteristic. Second, in an SPC program, corrective actions are basically local actions (*e.g.*, correction of obvious mistakes, re-adjusting process conditions, etc.). In an off-line quality engineering program, the emphasis is on design-related actions (*i.e.*, process and product designs). This is accomplished by reducing the sensitivity of an engineering design to different sources of variation and by making a product design robust against these variations [7, 10].

At first glance, the features presented in an off-line quality engineering program may appear simple. It is generally known that quality deteriorates when a product deviates from its design target value or when the quality characteristic exhibits high variability, leading to some quality loss. This is a simple interpretation of the first feature given above. Similarly, many believe that implementing design aspects in quality programs is more expensive than monitoring and re-adjusting the process as variation of assignable causes occurs (the second feature). As we will illustrate in this paper, over-simplification of these two vital features has been the real problem in handling quality aspects in traditional quality assurance systems.

Adopting off-line quality engineering concepts in textile processing is a very challenging task because it requires a different approach to dealing with both technological and quality aspects. Traditionally, these aspects have been dealt with mainly on the basis of knowledge of process and product specifications, which were mainly the results of long experience with conventional textile processes and traditional textile products. In recent years, revolutionary developments have been made in textile technology, and textile products have been widely used in industrial applications (*e.g.*, composites, geotextiles, and medical products). These developments call for a new approach to quality based on design aspects that permit interchanging of quality specifications between the textile industry and other industrial sectors.

In this part of the study we will introduce basic concepts and theories of off-line quality engineering, using textile examples. In Part II, we will present specific applications based on typical implementations of off-line quality engineering.

Product Development Cycle

Before proceeding with a discussion of off-line quality engineering, it is important to identify the different stages involved in developing a product. A product's development cycle can be partitioned into three separate but overlapping stages: product design, process design, and manufacturing [7, 12]. The purpose of product design is to develop complete design specifications. In textile processing, these include (a) raw material specifications such as fiber type, fiber characteristics, and blend composition, (b) intermediate product specifications such as weight and uniformity of slivers, rovings, and yarns, fabric thickness, fabric weight, and fabric density, (c) additive specifications such as type and properties of size liquor and type of dyeing and finishing agents, and (d) final product specifications and features such as appearance, durability, washability, flame resistance, stain resistance, and color fastness.

In the design phase, engineers design a manufacturing process that may involve creating (or purchasing) a new process or eliminating or modifying an existing process. Examples of textile process design include (a) rebuilding old carding machinery or cleaning equipment to accommodate high production rates of spinning, (b) by-pass systems to allow different levels of opening and cleaning when different raw materials are used, (c) eliminating roving and winding processes when open-end or air-jet spinning replaces conventional spinning, and (d) linking ring spinning to winding to improve product consistency and productivity and reduce labor costs.

The manufacturing operations then make use of both product and process designs to produce many units of the product. The basic criterion of a manufacturing implementation of product and process designs is the mutual understanding between different personnel involved in the product's development cycle.

All three stages of the product's development cycle are influenced by manufacturing variations. Accordingly, countermeasures against such variations can be built into the product's development cycle [7, 11]. When the product is finally in the hands of the consumer, there can be two sources of eventual variation—environmental variation and product deterioration. These two determine the lifetime of the product. Accordingly, they are mainly related to product design. In other words, countermeasures against these two sources of variation can only be built into the product design stage.

The concept of a product's development cycle becomes more pronounced in manufacturing industrial textiles (*e.g.*, composites, nonwovens, and geotextiles) and in carpet technology. For example, the durability of a geotextile against environmental conditions and soil/fiber interaction is expected to be controlled by product design. It is for this reason that three main types of polymers are used in geotextile applications—polypropylene, polyester, and polyethylene. Another example of the influence of product design is the dominant use of nylon in the carpet industry because of its performance and manufacturing flexibility.

On- and Off-Line Quality Control

As we mentioned earlier, on-line quality control has been traditionally used to describe statistical process control (SPC) concepts, including control charts (the main tool), cause and effect diagrams, and process capability studies [1, 4, 8]. In the product's development cycle discussed above, SPC or on-line quality control concepts concentrate almost exclusively on manufacturing. Accordingly, the expected objectives of an SPC program are to keep the manufacturing process "in control" and to reduce manufacturing imperfections in the product.

Off-line quality control expands quality improvement efforts to cover both product design and process design stages in a product's development cycle [2, 5, 7, 10, 11]. Accordingly, it is generally called off-line quality engineering. According to Kackar [7], the overall aim of off-line quality engineering is to improve product "manufacturability" and reliability and to reduce product development and lifetime costs.

The basic methods in an on-line SPC program include monitoring, testing, and statistical analyses. In an off-line quality engineering system, production of high quality products requires methods such as design reviews, sensitivity analyses, prototype tests, accelerated life tests, and reliability studies. These scientific methods are essential in identifying optimum product and process design specifications.

The difference between on-line and off-line approaches to quality control may be further illustrated using a typical textile example. In the sizing process, it is well known that due to the use of conduction drying with steam-heated cylinders, the drying process is not uniform on both sides of the warp sheet. This problem becomes more pronounced when the sizing machine is operated at creep speed (about 6 yards/minute), which is much slower than the normal operating speed (60 to 100 yards/minute). At this low speed, the warp may suffer from overdrying, leading to brittleness of yarns and, consequently, poor weaving performance. An on-line quality program can easily detect this problem by monitoring the moisture regain of the warp sheet at the delivery stage. Corrective actions for such a problem go beyond the capability of an on-line quality control program.

In an off-line quality engineering program, this problem reflects deficiencies in both process design (the drying technique) and manufacturing (frequent running at creep speed). Examples of process design alternatives may include modifying the drying process using a combination of conduction and air drying, developing a mechanism that allows less contact between the warp sheet and the drying cylinders during creep speed, or using noncontact convection drying techniques (*e.g.*, radio frequency and infrared drying). Obviously, these alternatives may seem to be quite costly and unjustifiable from an economic viewpoint, but cost analysis of the effect of overdrying on warp breakage during weaving [4] has shown that overdrying can actually lead to significant losses due to poor weaving performance.

If a process design seems to be costly and time consuming, a manufacturing approach may be taken. For example, the correlation between warp breakage and overdrying resulting from operating the slasher at creep speed was about 0.83, so the suggestion was to limit creep speed to extremely necessary conditions. In this regard, increasing operators' awareness of the problem of creep speed-related overdrying was the key to improving the process. Since moisture regain was monitored in real time, it was suggested that a target value of moisture regain should be selected using an experimental design and that values of moisture regain should be displayed with associated loss ($) when there were deviations from the target value.

System, Parameter, and Tolerance Design—The Design Cycle

In an off-line quality engineering program, nominal values and tolerances to product and process design characteristics are assigned using three approaches: system design, parameter design, and tolerance design. According to Taguchi [12, 13] and Kackar [7], system design is the process of applying scientific and engineering knowledge to produce a basic functional prototype design. The prototype model defines the initial settings of product or process design characteristics. For example, in a particular spinning system, engineers may decide to select a tentative product and process settings based on knowledge of the product and experience with the process. A hypothetical set of system design specifications is shown below.

Product design characteristics

fiber type: 100% cotton
fiber characteristics: target values:
  fiber strength = 27 g_f/tex
  fiber fineness = 3.0 Micronaire
  fiber length = 1.0 inch
  length uniformity = 80
  Shirley N.L.C. = 1.5%
intermediate product characteristics:
  sliver weight = 55 grains/yd
  sliver CV% = 4%
final product characteristics:
  yarn count = 25's
  yarn twist multiplier = 4.0
CV% = 16%
skein break factor = 1800 lb·Ne

Process design characteristics

opening and cleaning: 1000 lb/hr throughput
number of bales/laydown = 30
cleaning efficiency = 75%
carding: rate = 40 lb/hr
drawing: two stages
spinning: rotor speed = 70,000 rpm
take-up tension = 20 cN
opening-roller speed = 7000 rpm

It is important to remember that system design has been the primary practice in the textile industry in many areas around the world. This is due to the simple approach involved in implementing system design and the total dependence on on-line quality control programs to monitor process and product characteristics. However, system design only sets the concepts without a specific quantitative target value associated with quality. For instance, setting the rotor speed at an arbitrary value of 70,000 rpm recommended by the machine manufacturer does not always guarantee optimum spinning performance.

Parameter design uses engineering, statistical design, and sensitivity analysis to set the quality target. As we mentioned in the beginning this is accomplished by reducing the sensitivity of an engineering design to different sources of variation and by making a product design robust against these sources of variation. In mathematical terms, the principle of parameter design consists of two steps: First, suppose that controllable process parameters that are known by system design to influence a particular quality characteristic y are identified as $x_1, x_2, \ldots, x_m$. The function relating these inputs to y may be written as

$$y = f(x_1, x_2, \ldots, x_m; \epsilon_1, \epsilon_2, \ldots, \epsilon_n) \quad ,$$

where $\epsilon_1, \epsilon_2, \ldots, \epsilon_n$ are noise or uncontrollable factors. The quality characteristic y is then optimized by selecting the factor level combination

$$x_0 = [x_1^*, x_2^*, \ldots, x_m^*] \quad ,$$

which yields a target value y^* of a minimum sensitivity to the noise factors $\epsilon_1, \epsilon_2, \ldots, \epsilon_n$.

Noise factors may be divided into two types [7]: external and internal. External noise includes temperature, humidity, and dust. Internal noise is mainly manufacturing and product related and can be found in numerous situations in textile processing, including draft and twist variations, short fiber content resulting from harsh machine/material interaction, excessive sugar content in cotton in some unpredictable lots, within- and between-product variation, and human errors.

Tolerance design determines tolerances around the nominal settings that are identified by parameter design. Ideally, if all the variables influencing the quality characteristic are controllable (*i.e.*, no noise factor), the tolerance interval will approach zero.

In the discussion above we clearly distinguish between the traditional SPC or on-line quality control and off-line quality engineering. While the strength of on-line quality control lies in its ability to detect process variation resulting from assignable causes, off-line quality control emphasizes stabilization and optimization of quality, so that frequent corrective actions can be minimized or virtually eliminated. In Part II of this study, we will discuss typical applications of parameter and tolerance design.

NEW DEFINITION OF QUALITY

For many years, an association between quality and loss has been recognized, but determining a quantitative loss resulting from deviation from a target value or from high variability has been difficult. Although quality cost concepts can be traced back to Juran [6], Taguchi [12, 13] was able to formulate these concepts and to associate them with a designed target value. In general, the Taguchi approach of quality engineering defines the quality of a product as the (minimum) loss imparted by the product to the society from the time the product is shipped. Loss may include interruption of a process, waste, rejection, manufacturer or customer dissatisfaction, added warranty cost to the producer, and loss of market share.

In the textile industry, loss to society can be associated with every product (intermediate or final) that is shipped or transferred to a user. For example, the user of the fiber is the spinner, the user of the yarn is the weaver, and the chain continues down to the consumer of apparel or any textile product. Thus, each intermediate operation in a textile manufacturing line should be considered as an independent society.

THE LOSS FUNCTION

The primary purpose of implementing off-line quality engineering concepts is to minimize the expected loss by optimizing parameter settings. The expected loss is measured in terms of the degree of performance variation.

Off-line quality engineering suggests that loss occurs not only when the product is outside arbitrary specifications, but also when the product falls within the specification limits. In other words, the loss is considered as a continuous function of the departure from a target value. As shown in Figure 2, the loss continually increases as the product deviates further from the target value T. While a loss function may take several different forms, a quadratic function approximates the behavior of loss in many cases. The theoretical basis for this selection is presented below.

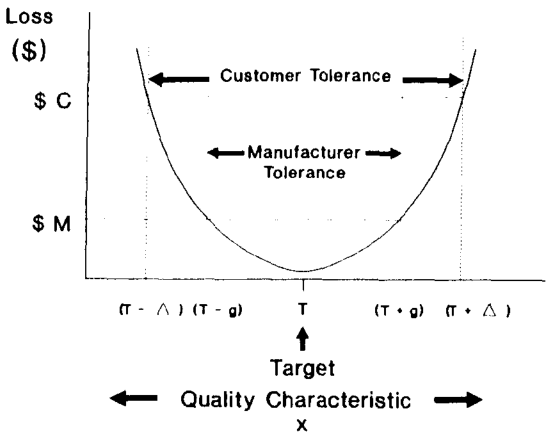

FIGURE 2. The loss function.

For a quality characteristic x and a target value T, a general form of a loss function $L(x)$ may be given by the Taylor expansion [9]:

$$L(x) = K_o + K_1(x - T) + K_2(x - T)^2 + K_3(x - T)^3 + \dots \quad ,$$

or

$$L(x) = \sum_{i=0}^{\infty} K_i(x - T)^i \quad . \tag{1}$$

Clearly, $K_o = L(T)$, and assuming the target is set such that the loss is minimum when $x = T$, one can make a series of differentiations at $x = T$ to obtain the values of constants K. If the loss at the target value is assumed to be zero, the values of K will be as follows:

$$K_o = 0$$

$$K_1 = 0$$

$$K_j = (1/j!)[d^jL/dx^j]_m, \quad j = 2, 3, 4, \dots \quad .$$

Therefore, the possible approximations for the loss function, beyond what is incurred at T, are

$$L(x) \approx K_2(x - T)^2 \quad , \tag{2}$$

$$L(x) \approx K_2(x - T)^2 + K_3(x - T)^3 \quad , \tag{3}$$

or

$$L(x) = \sum_{j=2}^{4} K_j(x - T)^j \quad . \tag{4}$$

The equation above reveals two points: Since x represents an individual observation of quality, $L(x)$ should be considered as the loss per unit. The equation incorporates the effects of variance, skewness, and kurtosis into the quality loss function.

Of the different forms of loss functions, the quadratic form (Equation 2) represents the simplest and most convenient expression. In addition, variability may be sufficiently expressed by the variance of quality, which is clearly indicated in this equation.

Applications of the Loss Function

As indicated above, the loss that comes with deviation from a target value of a quality characteristic can generally be expressed as follows:

$$L(x) = K(x - T)^2 \quad , \tag{5}$$

where $L(x)$ is the loss per unit, x is the actual value of quality characteristic, and T is the target value. The unknown constant K can be determined if $L(x)$ is known for any value of x. Suppose $(T - \Delta, T + \Delta)$ is the customer's tolerance interval (Figure 2). If the unsatisfactory quality characteristic at these intervals leads to a loss of C dollars, then from Equation 5, $C = K\Delta^2$. Thus,

$$K = C/\Delta^2 \quad . \tag{6}$$

Figure 2 also shows the manufacturer's tolerance intervals $(T - g, T + g)$. This sort of tolerance is extremely important in situations where the manufacturer realizes defects or problems in the product before it is shipped or transferred. In these situations, an additional manufacturing cost ($\$M$) will be added as a result of repairing, modifying, or downgrading the item to make it acceptable. These tolerance intervals can be obtained from the loss function as follows:

$$M = (C/\Delta^2)(x - T)^2$$

$$(x - T) = [M\Delta^2/C]^{1/2}$$

$$x = T \pm (M/C)^{1/2}\Delta \quad , \tag{7}$$

where $g = (M/C)^{1/2}\Delta$. In the discussion that follows, we give a hypothetical example to demonstrate the use of the loss function.

Example: Quality Loss of Size Pickup

One typical situation in which loss resulting from a departure from a target value is largely visible is when too much or too little size liquor is applied to warp yarns. In either case, weaving performance deteriorates, resulting in loss. Thus, a target value of size pickup should be determined in relation to its effect on weaving performance. When size pickup is below its lower specification limit, the yarn suffers from a lack of abrasion resistance, leading to a high rate of warp breakage during weaving. When size pickup is above its upper specification limit, the yarn suffers from a lack of extensibility, and thick places become too stiff to pass through loom guides (drop wires, heddle eyes, etc.), causing yarn breakage. Parameter and tolerance designs can be used to determine a target value and weaver tolerance intervals.

Figure 3 shows a loss function representing this situation. The quality characteristic in this case is the percent size pickup. Size pickup is defined as the ratio of the weight of size added onto a given weight of yarn. For the sake of simplicity, the loss (in dollars) is estimated by the cost of warp breakage resulting from too low or too high size pickup on the warp.

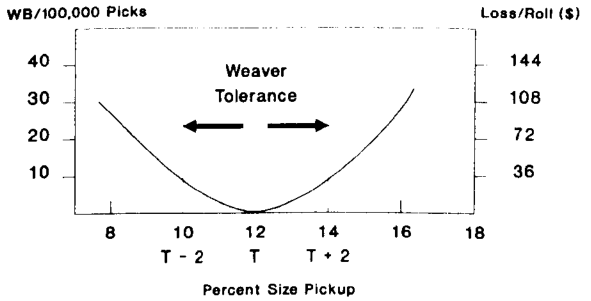

FIGURE 3. Effect of size pickup on warp breakage and associated loss per fabric roll (2000 yd. length, 600 picks/min, 20 ends/inch).

According to Figure 3, the target value of size pickup is 12%, and lower and upper specification limits are 10 and 14%, respectively. Thus, the typical weaver tolerance is 12 ± 2%. At the specification limits (10 and 14%), the rate of warp breakage is about 7/100,000. In a 2000 yard roll, 600 PPM loom speed and about 20 picks/inch fabric, the corresponding absolute warp breakage number is approximately 100. Thus, during weaving of the entire length of the roll, 100 warp breakages are expected to occur. At an estimated cost of a single warp breakage of $0.25, the loss per roll will be about $25.00. Thus, from Equation 6, the loss constant K can be calculated as follows:

$$K = C/\Delta^2$$

and

$$K = 25/(2)^2 = 6.25 \quad ,$$

so the loss function for the size pickup is

$$L(x) = 6.25(x - 12)^2 \quad .$$

This equation can then be used to determine the loss at any size pickup. For example, if the size pickup accidentally reaches 7%, the loss incurred per roll will be

$$L(7) = 6.25(7 - 12)^2 = \$156.25/\text{roll} \quad .$$

Note that the warp breakage value of $0.25 assumed in this example represents a typical cost per single warp breakage. In a recent survey of different textile companies in the U.S., we found that the cost of a single warp breakage could range from $0.10 to $2.50, depending on several factors including loom speed, nature of break, and quality of fabric to be made.

We determined the nominal setting in the example above on the basis of the effect of size pickup on warp breakage. A more realistic loss function should be based on other factors involved in determining size pickup. One of the important factors in this particular example is the cost of the size liquor, which represents over 75% of the total cost of sizing. An increase in the size pickup above the target value, in addition to its adverse effect on weaving performance, also leads to excessive use of unnecessary size liquor and, consequently, loss of costly chemicals.

Categories of Quality Specifications

In the example above, the quality characteristic was specified by a target value and lower and upper specification limits or weaver tolerance intervals. This case is classified in quality engineering as "nominal the best" category of quality specification. Examples of these quality characteristics include fiber properties (*e.g.*, Micronaire, length, and strength), yarn properties (*e.g.*, count, twist, strength, and toughness), and fabric properties (*e.g.*, weight, thickness, width, strength, and cover factor).

Another category of quality specification is "smaller the better" (Figure 4a). Examples in this category include trash content, short fiber content, sugar content, yarn irregularity (CV%), and yarn hairiness. In this category, the quadratic form of the loss function may be expressed as follows:

$$L(x) = Kx^2 \quad . \tag{8}$$

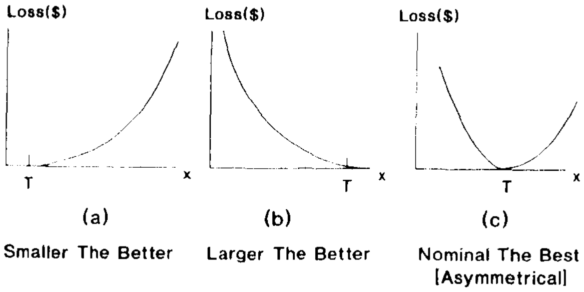

FIGURE 4. Examples of loss functions.

When the quality characteristic is to be high, the specification falls in the "larger the better" category (Figure 4b). Examples of this category include fiber maturity, color reflectance, length uniformity, fabric crease recovery, abrasion resistance, fire or flame resistance, and piling resistance. In this category, the quadratic form of the loss function may be expressed as follows:

$$L(x) = K/x^2 \quad . \tag{9}$$

Another situation that often exists in textile processing is the asymmetric loss function [Figure 4c]. In a quadratic form, this function may be expressed as follows:

$$L(x) = K_1(x - T)^2 \quad \text{if} \quad x \leq T$$

and

$$L(x) = K_2(x - T)^2 \quad \text{if} \quad x > T \quad . \tag{10}$$

Suppose that in the size pickup example discussed above, the cost of size liquor above the target value is added to the loss resulting from warp breakage. In this case, the loss function will be accelerated due to the addition of loss resulting from excessive size liquor. This will lead to an asymmetrical loss function (see Figure 5).

EFFECT OF TOLERANCE INTERVALS ON QUALITY LOSS

One of the important criteria in establishing tolerance intervals is minimization of loss at these intervals. To illustrate the effect of tolerance design on quality loss, let us consider the two hypothetical loss functions shown in Figure 5. Suppose that the first function is symmetrical and that it is developed only on the basis of loss resulting from warp breakage at too low or too high size pickup. Suppose that the second function is asymmetrical, with the loss above the target value being estimated based on the sum of losses resulting from both warp breakage and cost of excessive use of size liquor.

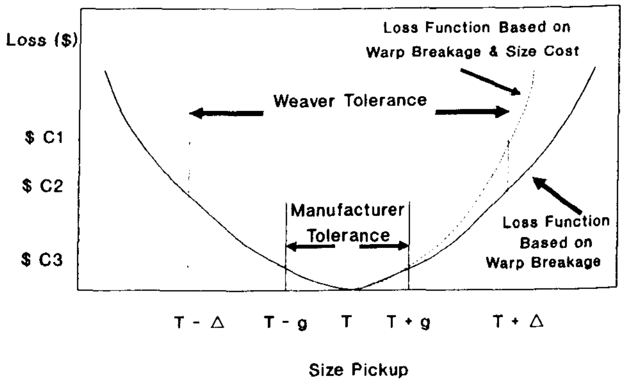

FIGURE 5. Illustration of loss functions developed for the same quality characteristic at two different design conditions.

At the upper weaver's tolerance limit ($T + \Delta$), the symmetrical loss function is shown to yield a loss of $\$C_2$, which is lower than that of the asymmetrical loss function $\$C_1$. This is due to the acceleration of loss resulting from the use of unnecessary excessive size material. Normally, this excess loss would not be realized by the weaver, since his measure of the quality characteristic is based solely on the performance of warp during weaving. Thus, the merits of establishing a realistic loss function taking into account all sources of loss is clearly illustrated in this example.

In addition, tolerance intervals should be based on both parameter and tolerance designs. When this is accomplished, more tight tolerance intervals can be established. As shown in Figure 5, at tight manufacturer's tolerance intervals, the loss is substantially reduced to $\$C_3$.

Effect of Quality Variability on the Loss Function

The discussion above dealt with the departure of a quality characteristic value of one unit (a cloth roll, a yarn package, a carpet, etc.) from a target value and its corresponding loss. When more than one unit is considered, variability between units should be taken into consideration in determining the expected loss. Traditionally, high variability has been known to result in a substantial loss due to the existence of several nonconforming units in a highly variable process. In the following discussion, we quantify loss resulting from high variability using the loss function approach.

Suppose that n units of a product are produced from a process with a target value T. Each unit has a value x_i of the quality characteristic. The deviation of any particular value from the desired target value is $(x_i - T)$. The sum of the squared values of these deviations divided by the number of units yields the so-called mean squared deviation or $MSD(x)$:

$$MSD = \sum_{i=1}^{i=n} (x_i - T)^2/n \quad . \qquad (11)$$

The loss function is determined by the average of the individual losses over the n items or the expected loss [7, 9]:

$$\begin{aligned} E[L(x)] &= \bar{L}(x) = (1/n) \sum L_i(x) = KE(x - T)^2 \\ &= (K/n) \sum (x_i - T)^2 \\ &= K\,MSD(x) \quad . \qquad (12) \end{aligned}$$

The mean squared deviation MSD is related to the variance by the following equation:

$$MSD(x) = s^2 + (\bar{X} - T)^2 \quad , \qquad (13)$$

where s^2 is the variance of the observed values of the quality characteristic $[\Sigma\, (x_i - \bar{X})^2/n]$, and $\bar{X}$ is the actual average of the quality characteristic. From Equations 12 and 13,

$$\text{Loss (\$)} = K[s^2 + (\bar{X} - T)^2] \quad . \qquad (14)$$

Equation 14 indicates that the quality loss can be minimized by minimizing the difference between the average value of a quality characteristic and the target value $(\bar{X} - T)^2$ by minimizing the variance s^2 or both. These two factors are illustrated in Figures 6a and b.

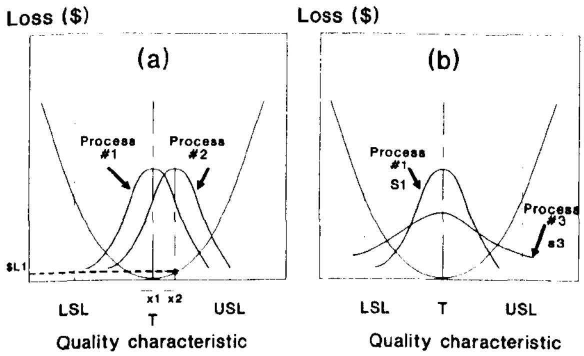

FIGURE 6. Effects of deviations from the target value and variability on quality loss.

As shown in Figure 6a, process #2, which has an average value deviating from the target value, exhibits loss L_1 at the center of its distribution, while process #1 exhibits zero loss at its center. As shown in Figure 6b, process #3, which has higher variability than process #1, also exhibits higher loss, which can be precisely quantified from Equation 14. The example below quantifies the loss resulting from variability and departure from a target value.

Example: Effect of Mean Value and Variability on the Quality Loss of Yarn Strength

Consider the four processes of yarn manufacturing shown in Figure 7. Each one of the four yarns is produced to meet a target value of 2000 lb × Ne and lower and upper specification limits of 1850 and 2150, respectively. Processes a and b both have the same variance (identical normal curves), with the difference being in the average value. Processes b, c, and d all have the same average but different variances.

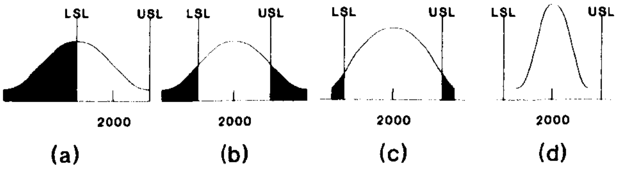

FIGURE 7. Distributions of yarn strength produced for weaving from four spinning processes (target value = 2000, weaver tolerance interval = USL − LSL = 2150 − 1850 = 300).

In a traditional SPC program, process capability analysis can be used to compare the four processes. One of the common parameters is the process capability ratio, which is defined as follows [4]:

$$PCR = \frac{USL - LSL}{6\sigma} \quad ,$$

where σ is the standard deviation of the quality characteristic produced by the process, LSL is the lower specification limit, and USL is the upper specification limit. A process capability ratio higher than 1 indicates that the process is doing well. Suppose that standard deviations of processes a, b, c, and d are 100, 100, 80, and 30, respectively. These values yield process capability ratios of 0.5, 0.5, 0.625, and 1.667 for a, b, c, and d, respectively. One obvious conclusion here is that process d is superior to all other processes, but the process capability ratio fails to distinguish between processes a and b. In addition, the value of the process capability ratio may indicate which process is superior, but does not quantify the loss resulting from using other processes that are not as good.

Suppose that loss constants for the four operations are the same (say, 0.0005). Using Equation 14, values of the average quality loss calculated for the four yarn processes are as follows:

$$\text{Loss}(\$) = K[s^2 + (\bar{X} - T)^2] \quad ,$$

Process a: Loss ($)

$$= 0.0005[100^2 + (1850 - 2000)^2] = \$16.25 \quad ,$$

Process b: Loss ($)

$$= 0.0005[100^2 + (2000 - 2000)^2] = \$5.00 \quad ,$$

Process c: Loss ($)

$$= 0.0005[80^2 + (2000 - 2000)^2] = \$3.20 \quad ,$$

Process d: Loss ($)

$$= 0.0005[30^2 + (2000 - 2000)^2] = \$0.450 \quad .$$

These results clearly show the differences between the four processes. In addition, the extent of variability and departure from the target value are quantified in terms of loss (in dollars).

Conclusions

The focus of this part of the study is on basic concepts and theories involved in off-line quality engineering and possibilities of implementing these concepts in textile processing. We have discussed differences between on-line quality control or statistical process control (SPC) and off-line quality engineering. In summary, the main difference lies in the design aspect of off-line quality engineering, which does not exist in the traditional SPC programs. In the textile industry, this difference is reflected quite clearly in the kinds of corrective actions normally taken when a textile process is out of control. In the second part of this study, we will give proper emphasis to specific methods used to apply parameter and tolerance design in textile processing.

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Manuscript received June 28, 1991; accepted August 15, 1991.