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An Economic Analysis of Inspection Costs for Failsafing Attributes

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Abstract

Failsafing devices (or *poka-yoke* devices) are used to inspect the conditions for high quality production (source inspection) or for inspecting work as it is completed to provide the fastest possible feedback (self-checks). These techniques involve 100% inspection and are economical only if the cost of inspection is very low. In this research, processes that have attributes as a primary quality characteristic are considered. An existing model for the economic design of np-charts will be used to determine how low inspection costs must be before self-checks become economical. An existing model for checking proper operating conditions will be used to find how low the cost of source-inspection must be in order for it to be economical.

1. Introduction

Setup time reduction is one of the techniques that is usually associated with the Just-in-time (JIT) approach to production and inventory management. The critical insight that made JIT practical was the realization that setup times for production runs, which had previously been assumed to be fixed, could be reduced by management. By reducing setup times, smaller lot sizes, and the attendant flexibility to respond more effectively to changing customer demand, could be economically justified.

Shigeo Shingo was one of the industrial engineers at Toyota who has been credited with identifying setup time reduction as a step in improving manufacturing flexibility and efficiency. Shingo was also largely responsible for creating and formalizing Zero Quality Control (ZQC), an approach to quality management that relies heavily on the use of *poka-yoke* (pronounced POH-kah YOH-kay) devices. *Poka-yoke* is Japanese for mistake-proofing. *Poka-yoke* is also commonly called failsafing [1,2]. These devices are used either to prevent the special causes that result in defects, or to inexpensively inspect each item that is produced to determine whether it is acceptable or defective. Effective *poka-yoke* devices reduce the cost of inspection, making it economical to increase both the frequency and quantity of inspection. If the cost can be reduced enough, 100% inspection may become economically viable. Thus *poka-yoke* devices may potentially have an effect on statistical process control (SPC) analogous to the effect setup time reduction had on the frequency and length of production runs in manufacturing. Shingo believed that dramatically improved quality levels would result from using 100% inspection as part of ZQC .

A *poka-yoke* device is any mechanism that either prevents a mistake from being made or makes the mistake obvious at a glance. The ability to find mistakes at a glance is essential because, as Shingo writes, "The causes of defects lie in worker errors, and defects are the results of neglecting those errors. It follows that mistakes will not turn into defects if worker errors are discovered and eliminated beforehand[1]"[3, p.50]. He later continues that "Defects arise because errors are made; the two have a cause-and-effect relationship. ... Yet errors will not turn into defects if feedback and action take place at the error stage"[3, p. 82].

An example cited by Shingo early in the development of *poka-yoke* shows how finding mistakes at a glance helps to avoid defects. Suppose a worker must assemble a device that has two push-buttons. A spring must be put under each button. Sometimes a worker will forget to put the spring under the button and a defect occurs. A simple *poka-yoke* device to eliminate this problem was developed. The worker counts out two springs from a bin and places them in a small dish. After assembly is complete, if a spring remains in the dish, an error has occurred. The operator knows a spring has been omitted and can correct the omission immediately. The cost of this inspection (looking at the dish) is minimal, yet it effectively functions as a form of inspection. The cost of rework at this point is also minimal, although the preferred outcome is still to find the dish empty at the end of assembly and to avoid rework even when its cost is small. This example also demonstrates that *poka-yoke* performs well when corrective action involves trying to eliminate oversights and omissions. In such cases, *poka-yoke* devices are

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[1] We suspect that Shingo and Deming would have a protracted discussion about whether workers or management are responsible for defects. No resolution of that issue is undertaken here.

often an effective alternative to demands for greater worker diligence and exhortations to "be more careful."

An example of a *poka-yoke* device at General Motors (GM) was described by Ricard [4]:

> "We have an operation which involves welding nuts into a sheet metal panel. These weld nuts will be used to attach parts to the car later in the process. When the panel is loaded by the operator, the weld nuts are fed automatically underneath the panel, the machine cycles, and the weld nuts are welded to the panel. You must remember these nuts are fed automatically and out of sight of the operator, so if the equipment jams or misfeeds and there is no part loaded, the machine will still cycle. Therefore, we have some probability of failure of the process. An error of this nature is sometimes not detected until we actually have the car welded together and are about to attach a part where there is not a nut for the bolt to fit into. This sometimes results in a major repair or rework activity.
>
> To correct this problem, we simply drilled a hole through the electrode that holds the nut that is attached to the panel in the welding operation. We put a wire through the hole in the electrode, insulating it away from the electrode so as it passes through it will only make contact with the weld nut. Since the weld nut is metal, it conducts electricity and with the nut present, current will flow through, allowing the machine to complete its cycle. If a nut is not present, there will be no current flow. We try to control the process so that the machine will actually remain idle unless there is a nut in place."

Shingo identified three different types of inspection: judgment inspection, informative inspection, and source inspection. Judgment inspection involves sorting the defects out of the acceptable product, sometimes referred to as "inspecting in quality." Shingo agreed with the consensus in modern quality control that "inspecting in quality" is not an effective quality management approach, and cautioned against it.

Informative inspection uses data gained from inspection to control the process and prevent defects. Traditional SPC is a type of informative inspection. Both successive checks and self-checks in ZQC are also a type of informative inspection. Successive checks were Shingo's response to the insight that improvements are more rapid when quality feedback is more rapid [3, pp. 67-69]. Work-in-process undergoes many operating steps as it is moved through a manufacturing facility. Often inspections are conducted at intermediate stages in the process. Shingo's concern was that the inspections may not occur soon enough after production to give the best information necessary to determine the cause of the quality problem so that it can be prevented in the future. By having each operation inspect the work of the prior operation, quality feedback can be given on a much more timely basis. Successive checks are having the nearest downstream operation check the work of the prior operation. Each operation performs both production and quality inspection. Effective *poka-yoke* devices make such an inspection system possible by reducing the time and cost of inspection to near zero. Because inspections entail minimal cost, every item may be inspected. Provided that work-in-process inventories are low, quality feedback used to improve the process can be provided very rapidly.

While successive checks provide rapid feedback, having the person who performs the production operation check their own work provides even faster feedback. Self-checks use *poka-yoke* devices to allow workers to assess the quality of their own work. Because they check every unit produced, operators may be able to recognize what conditions changed that caused the last unit to be defective. This insight is used to prevent further defects. Self-checks are preferred to successive checks whenever possible.

Since the main difference between successive checks and self-checks is which work station performs the inspection, in this research we do not distinguish between the two types of informative inspection. From an economic perspective, the difference between them will have a minimal effect on their cost. Thus we confine our discussion to self-checks while making the observation that our conclusions apply to successive checks as well.

Both successive and self-checks provide information "after the fact." Source inspection determines beforehand whether the conditions necessary for high quality production exist[2]. Shingo writes, "It had dawned on me that the occurrence of a defect was the *result* of some condition or action, and that it would be possible to eliminate defects entirely by pursuing the cause" [3, p.50]. He further writes that "I realized that the idea of checking operating conditions before the operations rather than after them was precisely the same as my concept of source inspection" [3, p.51].

With source inspection, *poka-yoke* devices ensure that proper operating conditions exist prior to actual production. Often these devices are also designed to prevent production from occurring until the necessary conditions are satisfied. Norman [5] refers to this type of device as a "forcing function." The example from GM that "forces" the nut to be present before welding can occur is an example of source inspection.

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[2]Note that Shingo's use of the term *source inspection* is not the practice of having the buyer's representative inspect the quality of work-in-progress at the supplier's facility, which is also called source inspection.

Source inspection, self-checks, and successive checks are inspection techniques used to understand and manage the production process more effectively. Each involves inspecting 100 percent of the process output. In this sense, *zero* quality control is a misnomer. These inspection techniques are intended to increase the speed with which quality feedback is received. And although every item is inspected, Shingo was emphatic that the purpose of the inspection is to improve the process and prevent defects, and therefore is not intended to sort out defects (although in some cases that may also be an outcome) [3, p. 57]. Shingo believed that source inspection is the ideal method of quality control since quality feedback about conditions for quality production is obtained before the process step is performed. Source inspection is intended to keep defects from occurring. Self-checks and successive checks provide feedback about the outcomes of the process. Self-checks and successive checks should be used when source inspection cannot be done or when the process is not yet well enough understood to develop source inspection techniques. Additional information about ZQC and failsafing is provided by Robinson & Schroeder [6], Bandyopadhyay [7], Chase & Stewart [1, 8], and Nikkan Kogyo Shimbun/Factory Magazine [9].

In Shingo's seminal book on ZQC [3], he criticized SPC and suggested that ZQC should supplant SPC as the preeminent tool for defect elimination in quality control. His main argument against SPC was that it is by nature an intermittent form of inspection, and therefore allows for some number of defects to occur. He further argued that SPC is designed to maintain the current level of defects , rather than to aggressively seek to eliminate them. In addition, Shingo claimed that "...a look at SQC methods as they are actually applied shows that feedback and corrective action - the crucial aspects of informative inspections - are too slow to be fully effective." [3, p.68]

Given the fact that applications of SPC generally have substantial intervals between the taking of samples, it seems reasonable to argue that feedback will be faster with source inspection and informative inspection in ZQC. However, it is not clear that ZQC should be systematically faster than SPC at insuring corrective actions. Indeed, according to Shingo [3, p.71], "Defects will never be reduced if the workers involved do not modify operating methods when defects occur." The willingness to take corrective action is a function of the attitude and commitment of both managers and workers, not an intrinsic attribute of a particular approach to quality management. Shingo's complaint about the actual implementation of SPC may also apply to ZQC.

To this point, no researchers have attempted to reconcile Shingo's contrary views on SPC with traditional thinking, nor have the economic implications of ZQC been rigorously explored. This research demonstrates that certain elements of ZQC can be viewed as special cases of traditional SPC using attribute data. An analysis of ZQC using traditional economic models of SPC will show that there are cases where ZQC is appropriate, and other cases where traditional SPC methods provide the most economical and effective process control.

It will be shown that for processes that are controlled using attribute data, self-checks can be treated as a special case of an np-chart. Existing models for the economic design of np-charts due to Chiu [10] and Duncan [11] will be used to demonstrate that inspection cost can reduced sufficiently to make self-checks become economical.

This research will also explore the economics of source inspection. An existing model for checking proper operating conditions, due to Iyer and Vecchia [12], will be used to demonstrate how low the cost of source inspection must be in order for it to be economical.

This paper first presents a brief review of the relevant literature on the economic design of control charts. In the next section, our strategy for examining self-checks in the context of the economic design of control-charts for attribute data is discussed. The economics of source inspection are then presented, followed by conclusions.

2. Economic design of control charts

Control charts were invented by Shewhart [13] and form the basis of SPC methodology. Variable charts are used when the characteristics of the process being controlled may be expressed as measurements. Attribute charts are used when the characteristics of the process being controlled may be expressed as the outcome of a Bernoulli trial, typically as defective or non-defective. The basic control chart methodology is that samples of a fixed size n are taken at some regular interval and a sample statistic (e.g., a sample mean or the number of defective items in the sample) is computed and plotted on a chart. The resulting graph is therefore a time series plot. The unique feature of control charts are predetermined control limits, often set three standard deviations from some measure of central tendency. If a plotted point falls outside of these control limits it is called an out-of-control signal. Such a signal must be either an extremely unlikely occurrence in a normally functioning process, or else an indication that some new source of variation has entered the process (i.e., a special or assignable cause) causing it to produce output that deviates from the desired specification. This will frequently lead to an increase in the amount of defective output. The typical response to an out-of-control signal is therefore to go investigate the process and try to identify and remove the assignable cause.

The choice of a sample size, of an interval between samples (expressed as either a period of time or as a number of units of production), and of appropriate control limits is called the *design* of a control chart. A substantial amount of research has examined the optimal economic design of control charts, where *optimal* is defined as the design that minimizes the total operating cost of the sampling design, expressed either as a cost per hour or as a cost per unit of product.

The first economic model, proposed by Duncan [14], was an example of the former. Under the assumption that only one assignable cause would be present, a loss-cost function for x-bar charts was developed and then minimized using numerical methods. Other researchers working with x-bar charts have included Chiu and Wetherill [15], Gibra [16], and more recently Lorenzen and Vance [17].

Ladany [18] developed an economic model for attribute data using p-charts. Chiu [10] and Duncan [11] present economic designs for np-charts. These models are similar in their derivation to the approach of Duncan [14]. The three components of cost functions included by these researchers are discussed below.

The first, which we may call *inspection costs*, are those costs, both fixed and variable, arising directly from taking a sample and calculating the appropriate statistics. With the possible exception of destructive testing, the primary cost is the time of the operator collecting the sample. Inspection costs are influenced by both the sample size and by the size of the interval between samples. It is important to note that a necessary condition for Shingo's ZQC to be effective is a drastic reduction in sampling cost. ZQC or any other 100% inspection technique cannot be used for destructive testing.

Search and repair costs are those costs which arise from responding to an out-of-control signal from a control chart. These costs have two components. The first is the expense incurred investigating the out-of-control signal and locating the assignable cause. Models exist for situations where the process is stopped while remedial action is taken to eliminate assignable causes, and also the case where the process will continue to operate while the assignable cause is identified and corrected. Gibra [19, 20] has recently proposed alternative models for each case which can be used in the economic design of attribute control charts. The other cost component is the expense incurred when responding to an out-of-control signal when no assignable cause is present. Since statistical control charts test the hypothesis that no assignable causes are present, a false alarm is a Type I error. These costs are a function of the frequency with which the process goes out-of-control, and also of the risk of a Type I error as determined by the control limits. Type I error search costs increases as the sampling interval decreases. The practical problem of increased Type I error when 100% inspection is used was identified by Papadakis [21]. Not all models differentiate between the cost of locating an assignable cause and the cost of investigating a false alarm, although it is reasonable to believe the costs will be different.

Defect costs are those costs which arise as a result of failing to detect the presence of an assignable cause and consequently producing defective items. Like any method based on statistical inference, control charts are vulnerable to Type II error. This may occur when an assignable cause is present and one or more samples are taken which do not result in an out-of-control signal. The presence of an assignable cause will generally result in the production of an increased number of defective items until its presence is detected and corrected.

Montgomery [22] wrote a review and survey of the control chart literature. Several important conclusions were presented about the various models that have been proposed. While the economic models of x-bar charts have been more extensively researched, the following observations appear to be valid for all types of control charts. Montgomery [22] reports that the cost functions are generally flat in the vicinity of the optimum, making the models insensitive to estimates of the cost coefficients. He also reports that these functions tend to be steeper in the vicinity of the origin, making it better to overestimate rather than underestimate the cost parameters. Second, it is reported that the cost models are fairly sensitive to estimates of the process parameters. In the case of x-bar charts these are the magnitude of the process shift *d*, the in-control process mean x_0, and the in-control process standard deviation σ. Fortunately, these parameters may generally be estimated with greater precision than the cost parameters. Finally, Montgomery [22] notes that economic models are generally insensitive to the number of out-of-control states included in the model. He writes that (p. 81)

> ...it seems reasonable to conclude that very complex multi-state processes can be satisfactorily approximated by a model containing only a few states, provided those states are properly defined.

The question of whether or not a model should assume that a process will be stopped while assignable causes are investigated is process specific.

3. The economics of self-checks for attribute data

An economic design of an np-chart specifies the sample size, the acceptance number (the number of defects in a sample which triggers an out-of-control signal), and the interval between samples. If *n* is the sample size, *h* is the time between samples in multiples of the time to produce one unit and *d* is the acceptance number, then self-checks are equivalent to an np-chart where n=1, h=1, d=0. Further reference to the design of np-charts will use the vector (n,h,d).

According to Shingo [3], a *poka-yoke* device must be used to inspect each item to determine whether it is acceptable or defective. If the unit being inspected is defective, Shingo indicated that remedial action should be taken to detect the cause of the defect and to insure that this cause is eliminated. Since each unit is inspected, the time interval between samples is the time required to produce one unit of output. Thus using a *poka-yoke* device to inspect for the presence of product attributes can be viewed as an instance of an np-chart with a sampling design of (1,1,0).

The economic models of np-control chart design considered by Chiu [10] and Duncan [11] are very similar. Both are an extension the economic design of x-bar chart research of Duncan [14] to np-charts. The primary difference between the two models is that Duncan assumes that the process continues while a search for an assignable cause is undertaken. Chiu's model includes separate terms to account for the cost incurred by stopping the process to search for an assignable cause. We use both in our analysis to emphasize that the economic implications of *poka-yoke* are invariant for the two scenarios. The complete formulations of Duncan's cost function L(n,h,d) and Chiu's cost function F(n,h,d) are both shown in the appendix.

Because of the complexity of the cost functions involved, most of the research in the economic design of control charts has not resulted in analytic solutions. The optimal sampling designs have been found using enumerative search methodologies. Even the generalizations that have been made in this area by Montgomery [22] use numerical examples to draw conclusions. Since both the Duncan and the Chiu models have so far proven to be intractable, the results which follow are based on a numerical analysis of examples from Duncan [11] and Chiu [10], which are presented below in Table 1. The Duncan parameters sets are listed by their number from Duncan's paper. Chiu only provides a single example parameter set.

The possible solutions to the economic design of np-charts is the set of all integer values of (n,h,d). The variables n and d are clearly discrete integers. In Duncan [11] and Chiu [10], the variable h is defined with hours as the unit of time. They do not require integer values of h for their solutions. In this paper, h is defined in time units that are multiples of the time required to produce one unit. It is reasonable to sample in integer intervals of the amount of time required to produce one unit. The variables n, h, and d must have the following relationships: $d<n\leq h$. If $h<n$, then not enough units are produced during the interval between samples to provide a sample of size n. If $n\leq d$, then the acceptance number is larger than the sample size so out-of-control points can not possibly occur. Some of the feasible combinations of (n,h,d) are shown in Figure 1. This figure also shows that only three other combinations are adjacent to the (1,1,0). They are (1,2,0), (2,2,0) and (2,2,1). If self-checks are optimal, the cost at (1,1,0) must be less than or equal to the adjacent designs, although that alone may not be sufficient.

<<< Figure 1 about here >>>

Given the complexity of the models, it may not possible to show that F(n,h,d) and L(n,h,d) are convex over the relevant range of integer values. Figure 2 shows a plot of L(n,h,d) using the parameters from Duncan's [11] example number one. The function is increasing in all three variables in the vicinity of (1,1,0). This is typical of the examples we have encountered.

<<< Figure 2 about here >>>

Shingo was involved in Toyota's realization that setup reduction is critical to JIT. A significant parallel exists between JIT and self-checks. To create a situation where EOQ=1, you can increase the holding cost rate, the cost of the product or reduce annual demand, or set up cost. Of these, some are not easily controlled by management. Others are not desirable, like reducing annual demand. Only one change is both under managerial control and desirable: reducing setup cost. Likewise, to create a situation where an np-chart of (1,1,0) is optimal, many model parameters can be changed.

Using a simple line search, parameters from Duncan's and Chiu's examples were used to find indifference points where self-checks (i.e., the (1,1,0) design) and an adjacent design had equal and minimum costs. The various model parameters were changed one-at-a-time, holding all other parameter values constant. The results are presented in Table 1 below. The table shows which variables could be altered to cause (1,1,0) to be optimal. Unlike the basic EOQ formula, the cost functions have multiple terms in their numerators and denominators. Thus, when model parameters are reduced to zero or increased by several orders of magnitude, the impact on the model may not be sufficient to make (1,1,0) minimum cost. Those parameters for which no value exists that makes the cost of the

(1,1,0) design less than or equal to all three adjacent designs are indicated with a dash. For those parameters for which an indifference point exists, the change in the parameter value is indicated along with the effect of that change on the cost function value. In each case where an indifference point was found, it was between (1,1,0) and (2,2,0).

It should be noted that since inspecting production after the fact by itself does not make production proceed more rapidly, the cost of self-checks was assumed to be non-negative. While the feedback provided by inspection can result in process improvements that increase the rate of production, this indirect effect was not considered.

<<< **Table 1 about here** >>>

An examination of Table 1 shows that the following changes to the model parameters tend to make the use of self-checks (i.e., the (1,1,0) sampling design) more economically attractive:

- decreasing fixed cost of inspection
- increasing the size of process shifts
- increasing the rate of arrivals of process shifts
- increasing the cost of being out of control
- increasing the time to produce one unit
- increasing the time required to take samples.

Of the changes in model parameters that made self-checks more economically appealing, only decreasing the fixed cost of inspection, and increasing the size of the process shift resulted in decreasing the optimal cost function value. Clearly, none of the last five changes would normally be considered a sensible approach to process improvement. Hence, the results of this analysis closely parallel the results in JIT. Reductions in inspection cost do for np-charts what setup reduction does for EOQ.

Another insight from this analysis is that without managerial action to reduce the cost of inspection, use of self-checks is probably not cost minimizing. A manager who decides to do self-checks instead of np-charts is likely to experience increased costs. Specifically, inspection and type I error costs are likely to go up because of the increased sampling intensity.

4. The economics of source inspection.

Source inspection insures that a condition that will lead to a defect does not go undetected. In situations where the defect can occur if and only if the condition exists, source inspection for that condition will eliminate the particular type of defect. Performing the source inspection may be costly because production may be slowed by using *poka-yoke* devices. As noted in §1, source inspection is one form of what Norman [5] calls "forcing functions". Norman discusses forcing functions in the context of designing everyday things. He reports that forcing functions may make the process slower. "If a forcing function is really desired, it is usually possible to find one, although at some cost to normal behavior. It is important to think through the implications of that cost..." [5, p.134]. "The clever designer has to minimize the nuisance value while retaining the safety, forcing-function mechanism, to guard against the occasional tragedy." [5, p.137].

Iyer and Vecchia [12] provide a model for optimally inspecting a two state discrete time system. When a process is in state 0 the process is operating properly and output from the process is acceptable. When the process is in state 1, the process is not functioning properly and defective output results. Once in state 1, the process remains in that state until an operator intervenes to reset the process. Three costs are considered:

C_i = cost of an inspection,

C_r = cost of repair or adjustment,

C_d = loss due to non-conforming unit.

Let n represent the inspection interval. If n=1, then 100% inspection would be used. Let q=1-p, where p be the probability of failure, that is, the probability of changing from state 0 to state 1.

Iyer and Vecchia provide a derivation of the long-term cost per unit of the inspection interval n, which is

$$Q(n) = \left[C_i + C_r - \frac{q}{p} C_d \right] \frac{1-q^n}{n} + C_i \frac{q^n}{n} + C_d. \tag{1}$$

Iyer and Vecchia were interested in the general solution to this problem, their model is discussed here for the specific purpose of finding conditions necessary for 100% inspection to be optimal. They indicate that 100% inspection is optimal when

$$\frac{pC_i}{qC_d} + \frac{pC_r}{pC_d} = 0 \tag{2}$$

This condition is correct, but more restrictive than necessary. Their own examples show circumstances where the left hand side of (2) is greater than zero and n=1 is still optimal.

The maximum acceptable cost for 100% source inspection (i.e. n=1) occurs when the long run total cost per unit is less than or equal to the total cost per unit of 50% source inspection (i.e., n=2). Using equation (1), the long term cost per unit when n=1 is set less than or equal to the long term cost per unit when n=2 and then solving for C_i yields:

$$C_i \le p(C_d q - C_r p). \tag{3}$$

This in turn leads to $C_i \ge 0$ when

$$\frac{C_d}{C_d + C_r} \le p. \tag{4}$$

Consider the *poka-yoke* device used by GM as a source inspection for the presence of nuts in the welding machine. In this context, C_i is the cost of performing the source inspection. This cost could be the result of decreased output resulting from implementing the source inspection. In the GM example, the source inspection may not involve any marginal cost per unit. C_r is the cost to change the process from state 1 to state 0. In the GM example, it is the cost to unjam the chute that delivers nuts. Conceivably, bumping the machine might be enough to jar the nuts loose. C_d is the cost of lost production when the machine stops.

Suppose that in the GM example, the cost of correcting any misfeeding or jamming of the machine cost \$1. The cost of a defect, a body panel sent downstream without a nut in place, is \$20. Prior to implementing source inspection, the probability of a missing nut is p=0.005.

Using equation (3), the maximum economic cost of inspection can be found to be $0.099475. Unless the cost per unit of inspecting exceeded this amount, source inspection should be implemented. Conversely, if initially the cost of inspection exceeded this amount, The *poka-yoke* device used to reduce the cost of inspection would need to reduce it to this less than $0.099475. The behavior of the maximum economic C_i as p changes is shown in Figure 3. The larger C_d relative to C_r, the higher the maximum of the curve. The maximum economic C_i converges to zero as p decreases for all parameter values. When p is small, the value of C_r has minimal effect on C_i.

<<< Figure 3 about here >>>

Typically, one expects all three costs to be positive. However, C_i can reasonably be negative if it expedites the production process. An example of such a scenario was observed by the authors at a railcar manufacturer. Workers would prepare to weld various parts onto the railcar chassis by using a measuring tape and chalk to determine the location where the parts were to be welded. As part of their TQM implementation process, the team that performed this task was asked to find a way to position the parts and weld them without using a measuring tape. The team designed and fabricated a jig with cut-outs in the locations where the parts go. The jig is accurately positioned on the chassis using stops attached to the back of the jig. The parts are then placed in the cut-outs and spot welded in place. After the jig is removed, welding is completed. The use of the jig has eliminated measurement error and also makes missing parts obvious. It takes less time to position and use the jig than to find the location of each part by measuring, so the cost of this source inspection device is actually negative.

5. Conclusions

An analysis of self-checks and source inspection with attribute quality data has shown that failsafing or ZQC is not economical under all circumstances. In order for these techniques to be economical, the cost of inspection must be relatively low.

Self-checks were shown to be a special case of np-chart. The fixed cost of inspection is the only model parameter that both reduces the total cost of the sampling plan and is capable of making self-checks the minimum cost sampling plan. The other model parameters either increase the cost of the sampling plan, are not controllable, or do not make self-checks cost minimizing. Without managerial action to reduce the fixed cost of inspection, the use of self-checks is probably not cost minimizing. If self-checks are used without reducing the cost of inspection then the likely result will be increased type I error costs and increased inspection costs.

The use of source inspection also requires that inspection costs are low. Specifically, the cost of inspection must be low relative to the cost of repairs and adjustments and to the cost of producing defects. The maximum cost of inspection such that source inspection is minimum cost is characterized. The maximum inspection cost is concave in the probability of failure. When the probability is high, the maximum inspection cost may be negative.

Negative inspection costs are possible since situations exist where the production rate can increase as a result of source inspection.

Shingo's assertion that ZQC with 100% inspection is superior to traditional SPC is not economically justifiable. This research has shown that the 100% inspection required by ZQC will not be economically preferable unless certain conditions are satisfied. In some cases, managerial action to reduce inspection costs will be insufficient to make ZQC preferred. Indeed, self-checks and successive checks have been shown to be a special case of SPC. Further, source inspection can be used to be proactive about variance reduction regardless of the type of informative inspection used.

This paper has addressed the use of failsafing with processes that are controlled using attribute data. Future research will examine how failsafing and measurement data control charts are related, and under what circumstances failsafing is effective and economical.

Appendix

This appendix provides the notation and models developed by Duncan [11] and Chiu [10].

Duncan's notation follows:

b = Fixed cost of inspection

c = variable cost of inspection

D = average hours required to find an assignable cause

g = hours per item on average to test the sample

M = loss per hour due to increased percentage of defects

p_0 = proportion defective when process is in-control

p_1 = proportion defective when process is out-of-control

T = cost of determining a false alarm

W = average cost to find an assignable cause

δ = the size of the process shift in standard deviations

λ = the arrival rate of process shifts, exponentially distributed.

$$L(n,h,d) = \frac{\lambda MB + \lambda AT + \lambda W}{1+\lambda B} + \frac{b}{h} + \frac{cn}{h} \tag{5}$$

where

$$\alpha = 1 - \sum_{x=0}^{d} \left(\frac{n!}{x!(n-x)!} \right) \cdot p_0^x \left(1 - p_0\right)^{n-x}, \tag{6}$$

$$P = 1 - \sum_{x=0}^{d} \left(\frac{n!}{x!(n-x)!} \right) \cdot p_1^x \left(1 - p_1\right)^{n-x}, \tag{7}$$

$$\tau = \frac{1-(1+\lambda h)\cdot e^{-\lambda h}}{\lambda\left(1-e^{-\lambda h}\right)}, \quad (8)$$

$$B = \frac{h}{P} - \tau + gn + D \quad (9)$$

$$A = \frac{\alpha \cdot e^{-\lambda h}}{1-e^{-\lambda h}} \quad (10)$$

Chiu's notation follows:

n = sample size

d = acceptance number. If the number of defects exceeds d, it indicates the likely presence of an assignable cause.

λ = the arrival rate per hour of the assignable cause

p_0 = Proportion of defective items

p_1 = increased proportion defective caused by a single assignable cause

A_0 = average search cost for assignable cause when none exists

A_1 = average search cost required to find and correct an assignable cause when one exists

t_0 = search time for assignable cause when none exists

t_1 = time required to find and correct an assignable cause when one exists

V_0 = profit per hour earned when process is in control

V_1 = profit per hour earned when process is out of control

b+cn = cost of inspection is a linear function of n

The total cost functions of Chiu's model is

$$F(n,h,d) = \frac{\lambda M B_1 + T B_0 + \lambda W + (b + cn) \cdot \frac{1 + \lambda B_1}{h}}{1 + \lambda B_1 + t_0 B_0 + \lambda t_1}, \quad (11)$$

where

$$\alpha = 1 - \sum_{x=0}^{d} \left(\frac{n!}{x!(n-x)!} \right) \cdot p_0^x \left(1 - p_0\right)^{n-x}, \quad (12)$$

$$P = 1 - \sum_{x=0}^{d} \left(\frac{n!}{x!(n-x)!} \right) \cdot p_1^x \left(1 - p_1\right)^{n-x}, \quad (13)$$

$$\tau = \frac{1 - (1 + \lambda h) \cdot e^{-\lambda h}}{\lambda - \lambda e^{-\lambda h}}, \quad (14)$$

$$B_0 = \alpha \cdot \frac{1 - \lambda \cdot \tau}{h}, \quad (15)$$

$$B_1 = \frac{h}{P} - \tau, \quad (16)$$

$$M = V_0 - V, \quad (17)$$

$$T = A_0 + V_0 \cdot t, \quad (18)$$

$$W = A_1 + V_0 \cdot t, \quad (19)$$

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Table 1

Finding indifference points between self-checks and adjacent designs using numerical examples

Duncan #1 P_0=.01				
Parameter	**Start Value**	**Favorable Direction**	**Value at indifference**	**Change of Cost Function**
λ	0.01	⇑	—	—
T	25	⇓	—	—
W	12.5	⇓	—	—
D	2	⇓	—	—
M	20	⇑	790	+577.5
g	0.05	⇑	7	+0.17
b	1	⇓	.015	-0.09
c	0.1	⇓	—	—
r	6	⇑	→ ∞	approaching +4.86
δ	0.1	⇑	2.695	-11.4

Duncan#19 P_0=.05				
Parameter	**Start Value**	**Favorable Direction**	**Value at indifference**	**Change of Cost Function**
λ	.01	⇑	.0282	+25
T	—	⇓	—	—
W	—	⇓	—	—
D	—	⇓	—	—
M	100	⇑	167	+20.18
g	.05	⇑	.377	+0.32
b	5	⇓	2.818	-0.15
c	—	⇓	—	—
r	7	⇑	9.775	+6.82
δ	.5	⇑	.867	-7.83

Chiu P_0=.015					
Parameter	**Start Value**	**Comparable to in Duncan's parameter**	**Favorable Direction**	**Value at indifference**	**Change of Cost Function**
λ	0.01	λ	⇑	0.14	+56.26
A_1	30	T	⇓	—	—
t_1	0.3	T	⇓	—	—
A_0	10	W	⇓	—	—
t_0	0.1	W	⇑	—	—
V_0	150	M	⇑	538	+50.55
b	0.5	b	⇓	0.097	-0.13
c	0.01	c	⇓	—	—
r	1.53	r	⇑	3.64	+12.68
P_1	0.1	δ	⇑	.372	-9.19

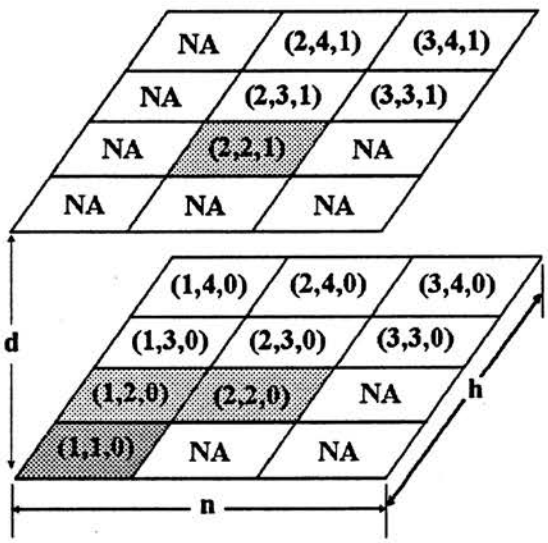

Fig. 1. Feasible Solutions to the economic design of np-charts. Points adjacent to self-checks (1,1,0) are located at (1,2,0), (2,2,0), and (2,2,1). Infeasible solutions are marked with NA.

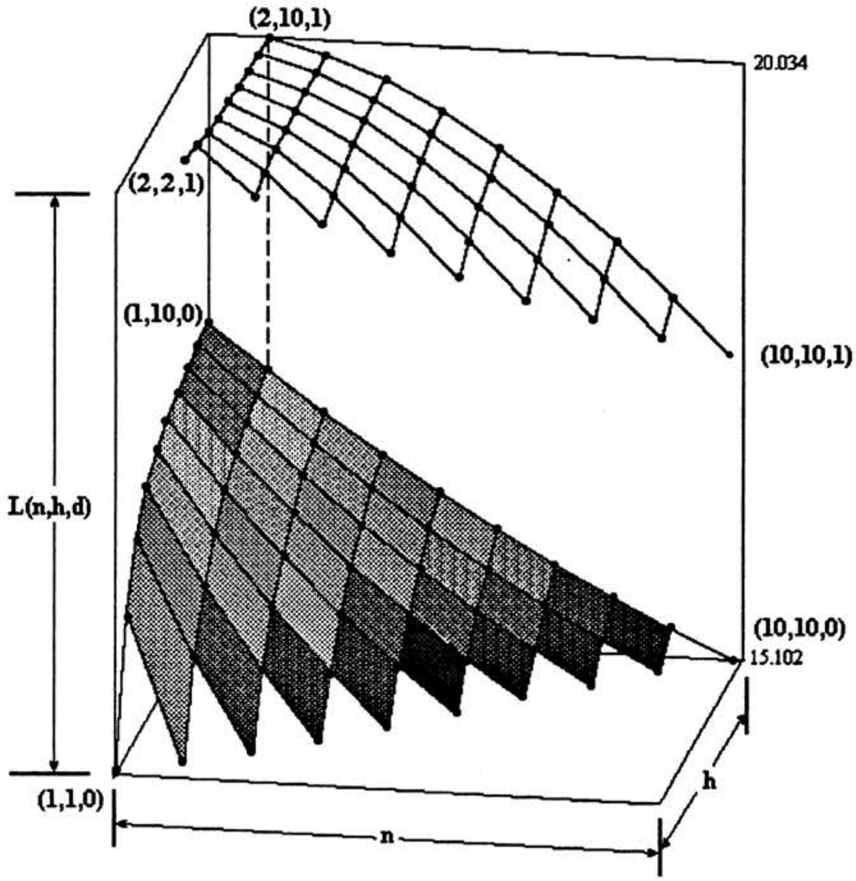

Fig. 2. Numerical values of the cost function L(n,h,d) for duncan's model number 1 parameter values. For the shaded surface, d=0. For the unshaded surface d=1.

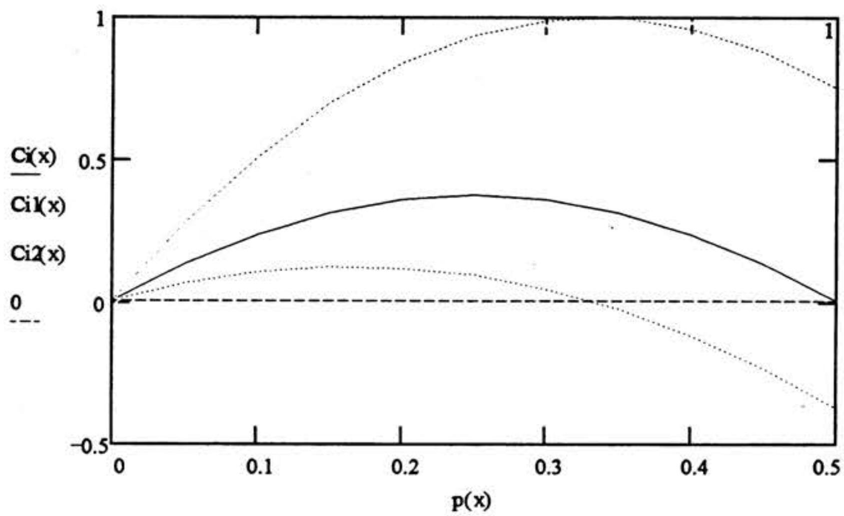

Fig. 3. The cost of inspection as a function of the probability of failure. Ci(x) is a graph of equation (5) when $C_d = C_r$. Ci1(x) is when $C_d = .5C_r$. Ci2(x) is when $C_d = 2C_r$.

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