

Integrated Control Chart System: A New Charting Technique

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Abstract

A multi-stage and multi-stream manufacturing system has several process stages each of which consists of one or more streams (e.g. machines) depending on some factors (e.g. bottleneck machines, different production rates). A number of methods were developed for implementing Statistical Process Control (SPC) for multi-stream manufacturing processes, but none of them proposed an SPC scheme for a multi-stage and multi-stream manufacturing system in an integrative and optimal manner. This article reviews the basic procedures for the designs of the integrated control chart systems for monitoring multistage and multi-stream manufacturing processes. Finally, some future research directions are given.

Keywords

Quality control, Integrated control chart system, Multistage and multi-stream manufacturing system

1. Introduction

Products are typically fabricated through various stages in a manufacturing process. The integration of all these stages results in a *multistage manufacturing system*. In the manufacturing of a mechanical part, each stage corresponds to the machining of a dimension. The dimensions machined at some stages are critical to the overall quality of the product and have to be monitored by the control charts. A *control chart system* is defined as an integrated system consisting of all of the charts used to monitor the critical stages of a manufacturing system [1, 2].

Due to the differences in production rate and other factors, some process stages may have more than one parallel stream (e.g. machine) (or a single machine with several heads) with each machine or head performing identical operation or producing identical product. In some applications, a single Shewhart chart or group chart is used to monitor the outputs from all the streams of a stage. However, a separate chart can be applied to the output of each individual stream. This scenario helps to detect and diagnose the out-of-control stream [3]. Ott and Snee [4] studied filling weight data from a machine which had twenty-four heads. The focus of the article was to show a variety of methods to analyze the data and the different results. They used plots, residual analysis and ANOVA technique to determine the differences in heads, times, and groups of heads. Woodall and Ncube [5] investigated the multivariate CUSUM control procedures and defined the out-of-control condition for a system comprising several charts. Their procedures for independent quality characteristics can be applied to the multi-stage and multi-stream manufacturing systems. Nelson [6] proposed and developed group control charts for a single stage process with multiple streams. He pointed out that if the output streams are highly correlated then a single chart can be used to monitor the output from the multiple streams, but if the output streams are not correlated then separate chart for each stream should be used. Montgomery [3] reviewed Nelson's [6] approach for multi-stream process. He discussed the control scheme for detecting a shift in the mean of all of the product streams and also for detecting a shift in the mean of an individual product stream in the multiple stream process. To detect a shift in the mean of all of the streams he suggested taking a sample from each of the streams and then plotting the largest and smallest sample means. He also presented tables of out-of-control average run length (*ARL*) for various numbers of streams and consecutive times that a particular stream has the largest (or smallest) value. Mortell and Runger [7] proposed a pair of control charts for monitoring a large number of streams. The first chart (Shewhart chart) is used to monitor shifts common to all product streams and the second chart (CUSUM chart) is used to monitor a change in one stream with respect to the others. Runger *et al.* [8] and Runger and Fowler [9] considered the highly automated environment with dozens to hundreds of streams. They showed how some additional control charts could be used to supplement the pair of

charts recommended by Mortell and Runger [7]. Runger *et al.* [8] used principal component analysis to develop the control charts that are able to detect the assignable causes that affect all streams and assignable causes that affect one or a few streams in multiple process streams. Amin *et al.* [10] proposed the MaxMin EWMA control chart based on the smallest (Min) and largest (Max) observations in each sample. When there is any change in the process, the chart shows which parameters have increased or decreased. They explained the design procedure and implemented the charting technique in a single stage multi-stream process. Zhang [11], Fong and Lawless [12], Lawless *et al.* [13], Ding *et al.* [14] and Zantek *et al.* [15] discussed the variation transmission through multiple process stages. Nonetheless, in all of the previous studies, the charting parameters (e.g. control limits, sample size or sampling interval) have not been designed in an integrative and optimal manner. Instead, identical parameter values have been used by each of the individual charts.

Traditionally, each individual chart in a chart system monitoring a process of a multistage manufacturing system is designed in isolation. For example, in a traditional \bar{X} chart system, sample size n is usually set around 5, the sampling interval h is mainly decided by the working shifts (i.e. the rational subgrouping) and control limits coefficient k is made identical (typically taken as 3) for each chart in the system.

In contrast, in an integrated chart system, all of the charts monitoring the multistage manufacturing processes are designed in an integrative and optimal manner. The optimization design of the integrated control chart system results in different n , h and k values or allocate different power to different charts in a system based on the values of certain parameters (e.g. process capability, magnitudes of the process shifts) that would affect the performance of the control chart system. As a result, the overall effectiveness of the chart system is improved significantly.

This article discusses the design procedures and reviews the available literatures on the optimization designs of the integrated control chart systems. In Section 2, the performance measures and the optimization algorithms are briefly discussed. Section 3 reviews the available statistical and economical models for the optimization designs of the integrated control charts systems. Finally, Section 4 draws conclusions and gives some directions for the future research.

2. Designs of Integrated Control Chart Systems

The optimization designs of the integrated control chart systems involve two major tasks, such as

- to derive formula for the evaluation of the performance of the chart system, and
- to develop algorithms for the optimization of the charting parameters i.e. sample size n_i , sampling interval h_i , and Lower Control Limit LCL_i and Upper Control Limit UCL_i of each chart in the chart system ($i = 1, 2, \dots, s$; where, s is the number of stages in the chart system).

2.1 Performance Measures

In the statistical designs, the performance of the control charts is measured by the frequency of the false alarms and by the speed with which it detects the occurrence of assignable causes. Thus, the most widely used statistical measures of performance are the in-control average time to signal ATS_0 and the out-of-control average time to signal ATS . On the other hand, in economical designs, the control chart performance is measured in terms of some monetary value. The performance measures used in both statistical and economical designs of the integrated control chart systems are briefly discussed below.

2.1.1 Statistical Design

Calculation of in-control ATS_0 of the control chart system

In a single time unit, the probability that the i th control chart (or a duplicate of the i th chart in a stream) in the i th stage produces a false alarm due to type I error probability α_i is approximately equal to α_i/h_i . The probability that it does not produce a false alarm is nearly equal to $(1 - \alpha_i/h_i)$. Since each of the g_i streams in the i th stage runs a duplicate of the i th control chart, therefore, the probability p_0 that the whole control chart system generates a false alarm in a time unit is [1, 16].

$$p_0 = 1 - \prod_{i=1}^s \left(\prod_{j=1}^{g_i} (1 - \alpha_i / h_i) \right) = 1 - \prod_{i=1}^s (1 - \alpha_i / h_i)^{g_i} \quad (1)$$

Finally,

$$ATS_0 = 1/p_0 \quad (2)$$

Calculation of out-of-control ATS of the control chart system

The out-of-control ATS of the integrated chart system is defined as the average time that one of the control charts in the chart system gives an out-of-control signal subsequent to any process in a manufacturing system going out of control [1].

When one of the g_i parallel streams in the i th stage ($1 \leq i \leq s$) is out of control, the out-of-control ATS of the chart system is calculated by,

$$ats_i = \frac{1}{Z_i} \cdot h_i \quad (3)$$

$$Z_i = 1 - \prod_{k=1}^s (w_k \mid \text{stage } i \text{ is out of control}) \quad (4)$$

In Equation (3), $1/Z_i$ is the Average Run Length (ARL) of the chart system. The power Z_i of the chart system is the probability that an out-of-control case happens in stage i and is signaled during a time period of h_i , and w_k ($k \neq i$, $k = 1, 2, \dots, s$) is the probability that stage k does not signal the process shift during a same time period.

The special feature of a multistage manufacturing system is the dependency between the process stages. If an out-of-control case occurs in a stage the dependent downstream stages are affected. Therefore, a mechanism must be developed to identify the effects between the process stages and to determine the induced process shifts due to the process shifts of the influencing stages. The power Z_i handles both the process shifts produced by the out-of-control stage i itself and the induced process shifts received by the dependent downstream stages [1, 2]. In some applications, the process stages may not be interdependent; in those cases, the power Z_i does not consider the induced process shifts [16, 17]. Since an out-of-control case may occur in any of the s stages, the final ATS for the control chart system is

$$ATS = \sum_{i=1}^s (ats_i \cdot p_i) = \sum_{i=1}^s \frac{h_i \cdot p_i}{Z_i} \quad (5)$$

where, p_i is the probability that the out-of-control case takes place in the i th stage.

2.1.2 Economical Design

Various models have been proposed for economically choosing the control chart parameters. The advantages of the economical design models over the statistical models are that they select the chart parameters in such a way that the total cost (including the cost of inspection, cost of producing non-conforming items, cost of detecting out-of-control signals and other costs) is minimized. That means the economic models minimize the expected total cost per unit time associated with the SPC schemes. Many researchers criticized that the conventional economic models generally have poor statistical properties and produce excessive number of false alarms. Moreover, the complex mathematical models and optimization techniques and, especially, the difficulty in estimating costs and other model parameters result in the lack of practical implementation of the economic charts. In view of this, a simple model for the economical design of the integrated control chart system has been proposed [18]. The total cost per unit time associated with an integrated control chart system is calculated based on the deployed manpower in SPC activities.

$$C_{total} = C_{quality} + C_{man} \quad (6)$$

Both the quality cost, $C_{quality}$ and manpower cost, C_{man} are direct or implicit functions of manpower M .

$$C_{man} = C_m \times M \quad (7)$$

$$C_{quality} = \int_0^{\infty} \left[\frac{1}{MTBO} \cdot q(\delta) \cdot L(\delta) \cdot f(\delta) \right] d\delta \quad (8)$$

Where, C_m is the manpower cost per operator per unit time and $MTBO$ is the Mean Time Between Out-of-control cases. The $C_{quality}$ is the cost incurred by the out-of-control cases. It depends on the frequency ($1/MTBO$) of the out-

of-control cases, the average number $q(\delta)$ of units produced after the occurrence of a mean shift of size δ , the expected loss function $L(\delta)$ per product for a given δ and, finally, the distribution of the mean shifts δ .

2.2 Optimization Search Algorithm

The search algorithm for the optimization designs of the integrated control chart systems is quite difficult as it involves many variables such as n_i, h_i, LCL_i, UCL_i ($i = 1, 2, \dots, s$). Some of the variables are integers and others are fractions. The general strategy is to search from point to point until the improvement is negligible. Like most of the optimization strategies employed in SPC, the proposed algorithms make no attempt to secure a global optimal solution. Instead, it focuses on deriving a convenient and systematic procedure for identifying a satisfactory and workable solution that could be adopted in practice.

Optimization of control limits LCL_i and UCL_i of the chart system

In the optimization design, the control limits LCL_i and UCL_i ($i = 1, 2, \dots, s$) or equivalently the control limit coefficients (k_1, k_2, \dots, k_s) are replaced by the corresponding type I error probabilities ($\alpha_1, \alpha_2, \dots, \alpha_s$). The underlying idea of the optimization design is to enhance the power of those charts which take a very long period to produce a signal when the corresponding processes become out of control. This procedure must sacrifice the power of some other charts in the system. However, if the α_i values of all charts are adjusted in an integrative and optimal manner, the overall (average) effectiveness of the control chart system will be improved. Wu *et al.* [1] proposes a dynamic search algorithm where the following equation (Equation (9)) is used to determine the range of possible α_i value in the i th level search.

$$\alpha_i = h_i \left[1 - \left(\frac{1 - 1/\tau}{\prod_{j=1, j \neq i}^s (1 - \alpha_j / h_j)^{g_j}} \right)^{1/g_i} \right] \quad (9)$$

where, τ is the minimum allowable in-control ATS_0 . In the proposed algorithm, the optimal values of α_i of the first ($s - 1$) control charts are searched step by step in ($s - 1$) levels, using the same step size $d\alpha$. The last α_s is finally determined so that the resultant ATS_0 is exactly equal to the specified value (i.e. the false alarm rate is not increased).

Optimization of sample size n_i and sampling interval h_i of the chart system

The optimization of n_i and h_i ($i = 1, 2, \dots, s$) ensures that no extra manpower (or the time spends on SPC activities) is required. A gradient based search algorithm [2] is employed to approach the optimal set of n_i and h_i step by step. The amount of manpower M required by an intergrated chart system is

$$M = \sum_{i=1}^s \frac{n_i g_i t_i}{h_i} \quad (10)$$

The minimum increment of sample size n_i is one. Therefore, the step size (Δn_i) of n_i for all stages is taken as one. Then, for an increment ($\Delta n_i = 1$) of every sample size, the corresponding manpower increment is

$$\overline{\Delta M}_n = \sum_{i=1}^s \frac{\partial M}{\partial n_i} \Delta n_i = \sum_{i=1}^s \frac{g_i t_i}{h_i} \quad (11)$$

It is rational to make the step size Δh_i of h_i proportional to h_i itself, that is

$$\Delta h_i \propto h_i, \text{ or, } \Delta h_i = b h_i \quad (12)$$

where, b ($b > 0$) is a proportionality constant. Then, for a decrement of ($-\Delta h_i$) of every sampling interval, the increment of manpower is

$$\overline{\Delta M}_h = \sum_{i=1}^s \frac{\partial M}{\partial h_i} (-\Delta h_i) = \sum_{i=1}^s \left(-\frac{n_i g_i t_i}{h_i^2} \right) (-b h_i) = b \sum_{i=1}^s \frac{n_i g_i t_i}{h_i} \quad (13)$$

By equating $\overline{\Delta M}_n$ and $\overline{\Delta M}_h$,

$$b = \left(\sum_{i=1}^s \frac{g_i t_i}{h_i} \right) / \left(\sum_{i=1}^s \frac{n_i g_i t_i}{h_i} \right) \quad (14)$$

Generally, this b value will make the increment of M due to a decrease of h_i by one Δh_i similar to the increment of M because of an increase of n_i by one Δn_i .

Now, the sample sizes n_i and the sampling intervals h_i can be increased or decreased step by step with the step size Δn_i and Δh_i . It is well known that, increasing n_i by Δn_i results in decrease of out-of-control ATS (or gaining detection power) and decreasing n_i by Δn_i results in increase of ATS (or losing detection power). Conversely, decreasing h_i by Δh_i means moving the sampling interval in the gaining direction and increasing h_i by Δh_i means moving the sampling interval in the losing direction.

If all n_i and h_i are substituted by the general variable X_j ($j = 1, 2, \dots, 2s$) (i.e. an X_j may be a sample size or a sampling interval), the gaining factor G_j pertaining to an X_j for an increment of manpower M is given by (suppose the objective is to minimize the out-of-control ATS of the chart system),

$$G_j = \frac{|\Delta ATS_j|}{\Delta M_j} = \frac{-\Delta ATS_j}{\frac{\partial M}{\partial X_j} \Delta X_j} \quad (15)$$

where, ΔATS_j is the change in the out-of-control ATS when an X_j moves one step in the gaining direction (i.e. 1 for n_i , or $-\Delta h_i$ for h_i) and all other X_j s are kept unchanged. The quantity ΔATS_j is always smaller than zero. Specifically, if an X_j is a sample size,

$$G_j = \frac{-\Delta ATS_j}{\frac{\partial M}{\partial n_j} \Delta n_j} = \frac{-\Delta ATS_j}{\frac{g_i t_i}{h_i} (1)} = \frac{(-\Delta ATS_j) \cdot h_i}{g_i t_i} \quad (16)$$

And if an X_j is a sampling interval,

$$G_j = \frac{-\Delta ATS_j}{\frac{\partial M}{\partial h_j} \Delta h_j} = \frac{-\Delta ATS_j}{(-\frac{n_i g_i t_i}{h_i^2})(-bh_i)} = \frac{(-\Delta ATS_j) \cdot h_i}{n_i g_i t_i b} \quad (17)$$

If the gaining factor G_j of an X_j is larger, then, when this X_j moves in the gaining direction, greater reduction in ATS will be obtained with relatively smaller increase in M . Conversely, a lower G_j means that if the corresponding X_j moves in the losing direction, greater reduction in M will be obtained with relatively smaller increase in ATS . Therefore, the general variables X_j are first ranked according to the descending order of G_j . Then, at each design point, N general variables X_j with the largest G_j values will be moved one step in their gaining directions (that is, if an X_j is a sample size, increase it by Δn_i ; if an X_j is a sampling interval, decrease it by Δh_i). This will usually lead to a substantial reduction in ATS with an insignificant increase of M . In order to balance out the increase in M , the rest $(2s - N)$ general variables X_j with smaller G_j will be moved one step in their losing directions. This second movement may adversely increase ATS , but this increase in ATS must be smaller than the decrease of ATS in the first movement. A searching mechanism is employed to identify the maximum possible value for N , which ensures that, in each search step, the maximum reduction in ATS is achieved, and meanwhile, the required manpower M is equal to the specified value.

3. Available Models for the Optimization Designs of the Integrated Control Chart System

Few models have been developed based on the performance measures and the optimization algorithms described in Section 2.

3.1 Statistical models

Integrated \bar{X} control chart systems

Wu *et al.* [1], Lam *et al.* [2], and Shamsuzzaman *et al.* [16] developed integrated \bar{X} control chart systems for monitoring process means at different process stages in a multistage manufacturing system. The optimization design minimizes the out-of-control ATS of the chart system on condition that neither the false-alarm rate nor the required manpower is greater than the specified value (the calculation of ATS_0 and ATS are briefly discussed in section 2.1.1). In some applications, the changes of sample size (n_i) and sampling interval (h_i) at different process stages may not be allowed because of fixed working shifts or fixed resource allocation or other difficulties. Under such circumstances, the lower control limit (LCL_i) and upper control limit (UCL_i) can be easily adjusted without changing the regular working schedule. The optimization of LCL_i and UCL_i ($i = 1, 2, \dots, s$) improves the performance of the

chart system to some degree [1, 16]. However, the optimization of n_i and h_i ($i = 1, 2, \dots, s$) in addition to the optimization of LCL_i and UCL_i further enhances the effectiveness of the chart system [2]. Some useful guidelines are also provided to aid the users to adjust the sample size, sampling interval and control limits of the control charts in a system, even when more complicated computation has not been carried out. According to the guidelines [2], the following charts should be made more powerful,

- (1) The control chart that is used in a stage with smaller number of streams; and/or
- (2) The control chart that is used to monitor a process with larger variance; and/or
- (3) The control chart that is used to monitor a process with smaller allowable mean shift; and/or
- (4) The control chart that is used to monitor a process stage where an out-of-control case is more likely to occur; and/or
- (5) The control chart that is used to monitor a process stage where the time required to inspect a unit is smaller; and/or
- (6) The control chart that is used to monitor a stage the quality characteristic of which depends on that of other stages.

Integrated \bar{X} & S control chart systems

Wu and Shamsuzzaman [17], and Shamsuzzaman and Wu [19] developed the integrated \bar{X} & S control chart systems for monitoring the mean and variance of the processes in different stages in a manufacturing system. It designs control limits, as well as sample sizes and sampling intervals, of all the \bar{X} charts and S charts in a system in an integrative and optimal manner. The design algorithm optimally allocates the detection power of the system among different stages as well as between the \bar{X} chart and S chart within each stage based on the values of certain parameters such as process capability and magnitude of the process shift that would affect the performance of the chart system.

A parameter T called the *average informative time* is used to measure the performance of the \bar{X} & S chart system.

$$T = \sum_{i=1}^s \frac{h_i p_i}{z_i} \quad (18)$$

where, z_i is the power of the out-of-control stage i , that is, the power generated by the \bar{X} & S charts in a stream in stage i when process shift occurs in this stream. Like the out-of-control ATS, the smaller is T , the more effective is the chart system in detecting out-of-control cases. The consideration of the power due to the induced process shifts received by the dependent downstream stages not only increases the complexity of the design procedure, but may also mislead the follow-up investigation of the assignable causes and increase the Mean Time To Repair (MTTR) [17]. In view of this, the optimization model proposed in designing the integrated \bar{X} & S chart system minimizes the average informative time T (considering only the power due to the process shift of the out-of-control stream) rather than the out-of-control ATS (considering both the power due to the process shift of the out-of-control stream and the power due to the induced process shifts arises because of the dependency between the process stages).

Integrated TBE control chart systems

In today's manufacturing industry, processes have achieved a low level of nonconformities or defects due to technological advancement and automation. In a low defect environment, quality control based on traditionally used Shewhart chart results in high false alarm rates and inability to detect further process improvements. The use of time between events (TBE) charts may be a good alternative in a low defect environment. The TBE charts monitor the time between successive events, where, the time between two successive events is exponentially distributed. The main advantages of TBE charts are that it does not need any subjective sample size, and it can detect further process improvement.

Shamsuzzaman *et al.* [20] developed a control chart system consisting of several individual TBE charts, each of which is used to monitor the time between successive events at different process stages in a multistage manufacturing system. The term "events" is defined as the production of defects and the term "time" refers to the time between the occurrence of the events. The proposed model designs the control limits of all the TBE charts in a system in an integrative and optimal manner in order to minimize the out-of-control ATS of the system. The false alarm rate is used as the constraint.

3.2 Economical Models

Integrated \bar{X} control chart systems

Wu *et al.* [18] develops a model for the economic designs of the integrated \bar{X} chart systems for monitoring multistage manufacturing processes. The design algorithm minimizes the total cost including manpower cost and quality cost (as described in Section 2.1.2) associated with the implementation of the SPC system based on the amount of allocated manpower and the random process shift. The main focus is on the optimal deployment of the manpower M to the SPC system. In the mean time, the sample size, sampling interval and control limits are also optimized. The whole optimization process is carried out in three levels. The high-level optimization is a single-variable search for the optimal value of M using the Successive Quadratic Estimation method. Then, for a value of M determined in the high level, mid-level search [2] is employed to find the optimal values of n_i and h_i ($i = 1, 2, \dots, s$). Finally, a dynamic low-level search [1] is invoked to find the optimal LCL_i and UCL_i ($i = 1, 2, \dots, s$) which jointly make the resultant ATS_0 exactly equal to the specified value and, in the mean time, minimize the total cost for a set of values of (M, n_i, h_i) that are determined in the high and middle levels (the mid- and low-level searches have been briefly described in Section 2.2). Some useful guidelines are also provided so that the users can deploy manpower to different SPC system rationally and effectively. According to the guidelines [18], a relatively large amount of manpower should be deployed if,

- (1) The production rate is high; and/or
- (2) The cost for fixing an out-of-specification product is high; and/or
- (3) The inspection rate of an inspector is high; and/or
- (4) The required in-control ATS_0 is high; and/or
- (5) The upper specification limit is small; and/or
- (6) The mean time between out-of-control cases is small; and/or
- (7) The manpower cost is low; and/or
- (8) The mean value of the process shifts is low.

Integrated TBE control chart systems

The implementation of the TBE chart system has significant economic impact as it involves various costs, such as the cost incurred by the occurrence of the event, cost of false alarms, cost of locating and removing the assignable cause and cost of allowing the system to operate in an out-of-control state. Zhang *et al.* [21] introduced these issues in the algorithms for the optimization designs of the economic integrated TBE chart systems. It designs control limits of all the TBE charts in a system in an integrative and optimal manner in order to maximize the profit associated with the implementation of the SPC system. The false alarm rate is used as the constraint.

4. Conclusions and Future Research

This article describes design technique and reviews the available models on the optimization designs of the integrated control chart systems for monitoring multistage manufacturing processes. It is found that the integrated design algorithms improve the system performance significantly. The optimization design also ensures that no extra resources for conducting the quality control activities are required and the false-alarm rate is not increased.

The design of the integrated chart system is more difficult than that of the traditional chart system. However, the design procedure can be easily computerized. The design of an integrated chart system is to be conducted only once, and the resultant system can be used continuously until the process parameters are changed.

The performance measures and the optimization design algorithms of the integrated \bar{X} , \bar{X} & S, and TBE chart systems are available in the literatures (a summary of the available literatures are shown in Table 1. Interested readers are also referred to [22]). However, there are still many research topics in the same direction and can be conducted in the future.

- (1) The Shewhart \bar{X} chart as well as the \bar{X} & S charts are considered as the most widely used variable control charts because of their simplicity for implementation and easy to understand. However, the Shewhart chart is relatively insensitive to small shifts in the process. Two important alternatives to the Shewhart control chart may be used when the shifts in the process are small. They are the CUSUM control chart and the EWMA

control chart. Future research can develop the integrated control chart system considering the CUSUM chart and the EWMA chart

- (2) Attribute charts are generally not as informative as variable charts because there is typically more information in a numerical measurement than in a mere classification of the conformity or the nonconformity. However, the attribute charts do have important applications. They can help move the firm's processes toward a zero percentage defective rate. They are particularly useful and necessary in service industries, healthcare, and other non-manufacturing sections, since many quality characteristics found in these sections are not easily measured on a numerical scale. Therefore, future research can develop the integrated control chart system considering the attribute control charts such as the p charts and the np charts. The integrated design of the p chart or the np chart will further improve the performance of the chart system.
- (3) Some researchers proposed the algorithms for the designs of the adaptive (or dynamic) control chart schemes, in which either the sample size or sampling interval or both are changed depending on the value of the sampling statistic. Further research can develop the adaptive integrated control chart system for a manufacturing system.
- (4) The concept of the integrated TBE control chart systems can be used to develop a control chart system for machine or machine components reliability monitoring in a multistage manufacturing system
- (5) The designs of integrated control chart systems for monitoring different processes of a job-shop manufacturing system or short production runs may be an interesting work.
- (6) The available literature on the optimization design of the integrated control chart system considers univariate quality characteristic. In many applications, the quality of a product depends on more than one characteristic. Producing products with multiple quality characteristics is always one of the concerns for an advanced manufacturing system [23]. The concept of the univariate integrated control chart system can be applied to develop a control chart system for monitoring multivariate quality characteristics in a multistage manufacturing system.
- (7) The available model on the integrated control chart system uses a separate chart for monitoring the output of each individual stream (e.g. machine) in a stage; usually, the parallel streams in a stage of a multistage manufacturing system have the same mean, standard deviation and target [8], and therefore, all of them use an identical control chart. This means that the number of charts in the chart system increases as the number of machines in different streams and stages of the manufacturing system increases. Practically, it may be difficult to handle all the charts in a chart system monitoring a large manufacturing system. It will also increase the complexity in diagnosis of the out-of-control stream or stage. Future research can check the possibility of using a single chart for monitoring all the parallel streams in a stage; this will reduce the number of charts in the chart system to a significant degree and simplify the monitoring process.

Table 1. Summary of the literatures on the integrated control chart systems

Type of control chart system	Statistical design		Economic design	
	Parameters optimized LCL_i, UCL_i		Parameters optimized LCL_i, UCL_i	
Integrated \bar{X} chart system	Wu <i>et al.</i> (2004) Shamsuzzaman <i>et al.</i> (2005)	n_i, h_i, LCL_i, UCL_i Lam <i>et al.</i> (2005)	---	$M, n_i, h_i, LCL_i, UCL_i$ Wu <i>et al.</i> (2007)
Integrated \bar{X} & S chart system	Wu and Shamsuzzaman (2005)	Shamsuzzaman and Wu (2010)	---	---
Integrated TBE chart system	Shamsuzzaman <i>et al.</i> (2009)	---	Zhang <i>et al.</i> (2011)	---

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This article presents a review note on the optimization designs of the integrated control chart systems and provides some research directions for interested readers. The author gratefully acknowledges the constructive comments and suggestions of the reviewers.

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