Expert Systems With Applications 62 (2016) 293–301

Contents lists available at ScienceDirect

Expert Systems With Applications

journal homepage: www.elsevier.com/locate/eswa

A new approach to detecting the process changes for multistage systems

Jeh-Nan Pan[a,*], Chung-I Li[a], Jhe-Jia Wu[a]

[a] Department of Statistics, National Cheng Kung University, Tainan 70101, Taiwan, ROC

ARTICLE INFO

Article history:
Received 13 January 2016
Revised 18 April 2016
Accepted 16 June 2016
Available online 17 June 2016

Keywords:
Multistage manufacturing system
Residual EWMA control chart
Residual CUSUM control chart
Overall run length
Phase II monitoring

ABSTRACT

The study aims to develop a new control chart model suitable for monitoring the process quality of multistage manufacturing systems.

Considering both the auto-correlated process outputs and the correlation occurring between neighboring stages in a multistage manufacturing system, we first propose a new multiple linear regression model to describe their relationship. Then, the multistage residual EWMA and CUSUM control charts are used to monitor the overall process quality of multistage systems. Moreover, an overall run length (ORL) concept is adopted to compare the detecting performance for various multistage residual control charts. Finally, a numerical example with oxide thickness measurements of a three-stage silicon wafer manufacturing process is given to demonstrate the usefulness of our proposed multistage residual control charts in the Phase II monitoring. A computerized algorithm can also be written based on our proposed scheme for the multistage residual EWMA/CUSUM control charts and it may be further converted to an expert and intelligent system. Hopefully, the results of this study can provide a better alternative for detecting process change and serve as a useful guideline for quality practitioners when monitoring and controlling the process quality of multistage systems with auto-correlated data.

1. Introduction

With the advent of modern technology, manufacturing processes have become rather sophisticated. Most manufacturing industries require several stages/steps to complete their final products, such as semiconductor, printed circuit board, chemical and telecommunication manufacturing processes. Recently, multistage process monitoring and controlling has become an important research issue, especially for the cases in which the process output are auto-correlated.

Traditional SPC control charts merely focus on monitoring the quality characteristics of a single stage manufacturing process. Among them, exponentially weighted moving average (EWMA) and cumulative sum (CUSUM) control charts are proved to be more efficient than Shewhart chart for detecting the small sustained shift in the process mean. On the other hand, residual EWMA and residual CUSUM control charts (see Lu & Reynolds, 1999, Lu & Reynolds, 2001 for details) have been shown to be more suitable for monitoring the auto-correlated processes, which are commonly occurred in the above high-technology manufacturing industries. For examples, automobile crankshaft machining process that consist of two stages (see Lawless et al., 1999), an automotive body assembly that has multiples parts assembled in multiple stations (see Shi, 2006) and print circuit board manufacturing that involves exposure to black oxide, lay-up, hot press, cutting, drilling and inspection (see Zou and Tsung, 2008).

In the above examples of multistage processes, the products are manufactured in several serial stages. The quality characteristics of any intermediate stage can influence the ones of final stage. But, a suitable control chart for monitoring and controlling the process quality of multistage systems with autocorrelation within the stage and correlation between the stages is still lacking. Thus, it becomes necessary to develop a new control chart model suitable for monitoring the quality characteristic of multistage manufacturing systems.

The use of control charts generally involves Phase I and Phase II. In the Phase I study, the parameters of the process are estimated based on a set of historical data and used to establish control limits for the Phase II monitoring. In the Phase II monitoring, the data are sequentially collected over time to assess whether the parameters of the process have changed from the estimated values in the Phase I study. In this paper, focusing on Phase II study, a new multiple regression model for multistage manufacturing processes is developed by considering the effect of correlation between the

* Corresponding author Fax: 011-886-6-2342469.
E-mail addresses: jnpan@mail.ncku.edu.tw (J.-N. Pan), chunyilee1@gmail.com (C.-I. Li), qqaazz800624@gmail.com (J.-J. Wu).

http://dx.doi.org/10.1016/j.eswa.2016.06.037
0957-4174/

neighboring stages and the residual EWMA and CUSUM control charts for each stage can be constructed accordingly. Then, we propose a new Overall Run Length (ORL) for evaluating the overall detecting ability of new control chars for multistage manufacturing systems. In addition, the cumulative density function (CDF) of ORL is derived and its correctness has also been confirmed. Subsequently, a simulation study is conducted to explore various combination of control parameters for multistage residual control charts when the average of Overall In-Control Run Length (AOIRL) is fixed at 370 (i.e. we fix the type I error rate of the overall multistage system at 0.27%). Once the AOIRL is fixed at 370, the average of Overall Out-of-Control Run Length (AOORL) is used to evaluate the detecting ability of multistage residual control charts when the multistage system is out of control. Furthermore, a sensitivity analysis is performed to explore the effect of AOORL on the detecting ability of multistage residual control charts when the number of stage increases. Finally, a numerical example with oxide thickness measurements of a three-stage silicon wafer manufacturing process is used to illustrate the usefulness of our proposed multistage residual control charts in the Phase II monitoring.

2. Literature review

2.1. Monitoring the process quality for multistage systems

In a multistage manufacturing system, the quality characteristics of interest are often highly dependent. To monitor and diagnose the multistage manufacturing system, Zhang (1984), Zhang (1987), Zhang (1990) & Zhang (1992) proposed the Cause-Selecting Charts (CSCs). The advantage of this method is that once an out-of-control signal or a special cause occurs in the process, it can effectively distinguish which stage/subprocess is out of control.

To monitor quality of a process with multivariate variables, Hawkins (1991) proposed Shewhart and CUSUM control charts based on regression-adjusted variables. He further proposed the concept of group charts. Tsung & Xiang (2004) proposed Group EWMA Chart with One-Step Forecasting Errors (OFSE) combining quality characteristics from multistage manufacturing system into a single stage control statistic. The control statistic is defined as:

$$MZ_j = \max_{1\le k\le N}\left(\left|Z_{k,j}\right|\right)$$

where $Z_{k,j}$ is the EWMA statistics of jth OFSE. Even though this control statistics combine the multistage control charts into a single stage control chart, it doesn't preserve the structure of CSCs and thus loses the advantage of using CSCs. Moreover, it is not easy to trace back to the root stage where the subprocess is out of control.

Yang & Yang (2006) considered a two-step process in which the observations X in the first step can be modeled as an auto-correlated autoregressive model of order 1 (AR(1)) model and the observations in the second step Y can be modeled as a transfer function of X. The AR(1) model they used can be written as:

$$X_t = (1-\phi)\xi_X + \phi X_{t-1} + a_t,\ \ t = 1, 2, \ldots$$

where ξ_X is the process mean of the first step, ϕ is the autoregressive parameter satisfying $\phi < 1$ and a_t are assumed to be independent normal random variables with mean 0 and variance σ_a^2. The transfer function to express the relationship between X and Y is:

$$Y_t = C_Y + V_0X_t + V_1X_{t-1} + N_t, t = 1, 2, \ldots$$

where C_Y is a constant and N_ts are independent normal random variables with mean 0 and variance σ_N^2. Recently, Davoodi and Niaki (2012) proposed a maximum likelihood method to estimate the step-change time of the location parameter in multistage processes.

2.2. Residual-based EWMA control chart

Lu & Reynolds (1999) proposed a residual-based EWMA control chart for monitoring the mean of process in which the observations can be described as an ARMA(1,1) model. The residual of ARMA(1,1) model can be expressed as:

$$e_k = X_k - \xi_0 - \phi(X_{k-1} - \xi_0) + \theta e_{k-1},$$

where ξ_0 is the process mean, ϕ is the autoregressive parameter and θ is the moving average parameter. The control statistics of the residual EWMA control chart is defined as:

$$R_k = (1-\lambda)R_{k-1} + \lambda e_k$$

where λ is smoothing constant and e_k the residual.

Lu & Reynolds (1999) assessed the performance of observation-based and residual-based EWMA control charts respectively when dealing with auto-correlated observations. It was found that their performances were fairly close when monitoring low or medium auto-correlated process. But, for a highly auto-correlated process, the residual EWMA control chart is more effective in detecting a process mean shift.

2.3. Residual-based CUSUM control chart

Lu & Reynolds (2001) introduced a two-sided residual CUSUM control chart and its control statistics is defined as:

$$CR_k^+ = max\left\{0, CR_{k-1}^+ + (e_k - r\sigma_e)\right\},$$

$$CR_k^- = max\left\{0, CR_{k-1}^- - (e_k + r\sigma_e)\right\}$$

where r is the reference value, $CR_0^+ = CR_0^- = 0$. If the control statistic CR_k^+ or CR_k^- exceeds $\pm\ c\sigma_e$, then control charts sends out a warning signal. Lu & Reynolds (2001) further assessed the performance of residual-based CUSUM control chart when dealing with auto-correlated observations. It was found that the residual-based CUSUM control chart has similar performance with the residual-based EWMA control chart proposed by Lu & Reynolds (2001).

Asadzadeh et al. (2012) pointed out that their proposed control charts can be applied to multistage manufacturing processes (MMPs) and multistage service operations (MSOs), such as survivability measures in healthcare services. Asadzadeh et al. (2013) developed a cause-selecting CUSUM control chart based on proportional hazard model and binary frailty model. Moreover, Asadzadeh et al. (2015) revised proportional hazard model to handle autocorrelation within observations and proposed one CUSUM and two EWMA control charts. The other type of EWMA control chart can be referred to Yang et al. (2011) in which they proposed a nonparametric version of the EWMA Sign chart without assuming a process distribution.

3. Development of multistage residual control charts

Yang & Yang (2006) considered a two-step process in which the observations X in the first step can be modeled as an AR(1) model and observations in the second step Y can be modeled as a transfer function of X. However, they did not take the autocorrelation of Y_t into account when constructing multistage system models. In this section, a new multiple regression model for multistage manufacturing processes is developed by considering both the autocorrelation within stage and the correlation occurring between the neighboring stages. Then, the residual EWMA and CUSUM control charts for each stage can be constructed accordingly.