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Integration of production quantity and control chart design in automotive manufacturing

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ABSTRACT

This study presents a two-stage stochastic programming model for the determination of control limits in p-charts when a production process produces above a certain quantity. Consideration of production quantity needed along with control limit determination is important for the following competing two reasons: (1) Wider control limits make it difficult to detect the changes in the process, therefore producing excessive number of cars with paint defects. (2) Narrower control limits, on the other hand, increase the number of unnecessary interventions even if there is no deterioration in the process so that inspection costs increase. In both cases, quantity produced reduces due to defective products and unnecessary interventions. Therefore, it is important to design a control chart for proportion of defects that takes production quantity requirements into account. We consider the problem in an automotive manufacturing setting in which the cars are inspected for paint defects after paint operations.

We formulate the problem as a two-stage stochastic programming model. In the first stage, control limit parameter k is decided for the p-chart and in the second stage, production quantity is determined that minimizes total quality-related and production costs. We solve the model by sample average approximation algorithm (SAA). In a numerical study, we investigate the effect of various factors on control limit parameter k and the total cost. Our numerical study shows that (i) an increase on the mean defect rate increases both the total cost and the total production quantity, (ii) effect of an increasing process variance to the control limit parameter k is significantly small, (iii) frequency of special cause occurrences affects the total cost significantly and (iv) all the experiments show that the commonly used 3σ control limits in practice are wider than required.

1. Introduction

In automobile manufacturing, after body shop operations, welded bodies are directed to the paint shop. Vehicle painting operation includes several steps such as cleaning, primer coat painting, top coating and polishing. Once painting is completed, the vehicles are inspected for paint defects before they are released to the Final Assembly (FA) department. Since paint defects may be as much as 40%, some manufacturers use control charts to monitor the paint process and determine whether the current painting process is out-of-control. An out-of-control situation means that there is a special cause increasing the proportion of paint defects. In vehicle painting operations, defects are categorized as either minor or major ones. Minor defects just need small touchups, usually done on the line, which does not cause any delays in assembly operations. On the other hand, vehicles with major defects must be taken off the line and sent back to paint shop for re-painting. Since minor defects do not add any significant cost and do not disturb the vehicle flows in the line, the scope of this study is confined to major paint defects.

Fig. 1 shows the simplified inspection procedure used in the paint shop of a major car manufacturer's plant located in Turkey. A sample of size n is drawn in a sampling interval of h hours at the end of epoch t from the batch size of X_t vehicles. Number of the defective vehicles in the sample is counted and estimated average defect rate of the process $\hat{p}$, is calculated. The painting process is deemed out-of-control if the defect rate of the sample $\hat{p}$, is above the upper control limit (*UCL*). When the p-chart signals an out-of-control situation, the engineering team searches for special causes that might increase the proportion of paint defects. If a cause for the defect rate increase is found, the painting process is restored to the in-control state at some cost and all the newly painted vehicles in the sampling interval are inspected. Since no action is taken if the defect rate of the sample is below *UCL*, determination of lower control limit in p-charts is of no practical importance.

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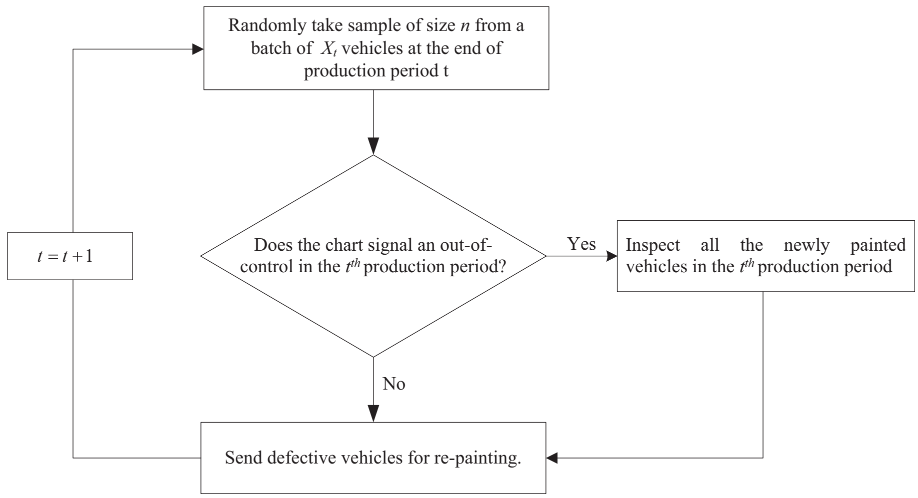

Fig. 1. Simplified procedure of paint control process.

Setting an optimal *UCL* is important to reduce the production and quality costs: A widely set *UCL* decreases the sensitivity of a control chart to detect the special cause occurrences. On the other hand, a narrow *UCL* increases the number of false out-of-control signals in the process even if there is no deterioration in the process.

As Eq. (1) suggests, setting an optimal *UCL* involves finding the optimal k that would minimize quality related costs. Determination of optimal control limits along with optimal sampling size and sampling frequency that minimize quality related costs is known as economical design of chart parameters and is commonly studied in the literature.

$$UCL = p_0 + k\sqrt{\frac{p_0(1-p_0)}{n}} \tag{1}$$

Ladany (1973) is the first paper that considers economical design of p-chart parameters. His model includes cost of sampling, cost of not detecting a change in the process (*Type 2 error cost*), cost of false indication of change (*Type 1 error cost*) and cost of re-adjusting detected change.

Montgomery, Heikes, and Mance (1975) consider the same problem when there are several out-of-control states. Chiu (1975a) presents a model which minimizes loss cost function in an *np*-control chart and Chiu (1975b) investigate the effects of variation in cost factors by drawing loss cost surface as contour plots. Chiu (1976) considers the case where there are several out-of-control states in an *np*-control chart. More recent studies on economical design of chart parameters consider variable sample size, variable sampling interval and both variable sample size/sampling interval and present the advantages of these models rather than traditional p-chart design (Aslam, Azam, Khan, & Jun, 2015; Inghilleri, Lupo, & Passannanti, 2015; Kooli & Limam, 2011; Wu & Luo, 2004).

Recognizing the effect of the monitoring policy on the production capacity, Lee and Rosenblatt (1987) develop a model addressing the problem of joint determination of optimal production run time, number of inspections to minimize quality-related costs in an $\overline{X}$ chart. Lee and Park (1991) consider the same problem by focusing on the difference between rework cost before sale and warranty cost after sale. Rahim (1994) considers the same joint problem by developing a non-Markovian shock model under production setup, inventory holding and maintenance cost. Rahim and Ben-Daya (1998) extend this model to consider the case in which the production is halted not only if there is true alarm but also there is a false alarm. Ben-Daya and Rahim (2000) consider the joint-optimization of preventive maintenance actions and $\overline{X}$ chart parameters when in-control state follows a general probability distribution with increasing hazard rate. Pan, Jin, Wang, and Cang (2012) develop a model to minimize the total expected production costs while jointly determining the optimal parameters of control chart and the maintenance decision policy whereas Bouslah, Gharbi, and Pellerin (2015) consider joint design of production, quality and maintenance control policy problem in c-chart.

In vehicle painting process, since defects in the paint shop occur randomly, it is not possible to know before how many vehicles to paint in order to meet the FA demand. Therefore, a control chart policy should take random paint defect occurrences into account to meet assembly line demand and to minimize quality related costs simultaneously.

Economic design problem of control charts, including p-chart design, involve determination of three important parameters: Control limit width, sampling interval, and sample size. In a p-chart, narrowly determined *UCL* increases the number of false alarms and when a p-chart reports an alarm, all the vehicles painted in between previous and the current sampling epochs are inspected one by one, which increases the unnecessary cost of inspection. This inspection cost depends on the number of vehicles painted in the batch. Therefore, if the number of painted vehicles is more than the optimal number needed, extra inspection costs occur. On the other hand widely determined *UCL* makes difficult to detect the shift in the process so defective vehicles will be sent to the FA department.

In this paper, we develop a two-stage mathematical model that jointly determines the optimal upper control limit in a p-chart and the paint batch size X_t. In the first stage, the control limit parameter k is set and after observing the random paint defects, the paint batch size X_t is decided. The two-stage decision making framework optimizes the first stage decision k given the fact that vehicles are repeatedly painted and paint defects are experienced over and over again. In fact, in statistical process control applications, the control chart parameters are determined first and random process shifts occur repeatedly as process is monitored over time. Therefore, two-stage stochastic programming provides an appropriate modeling framework for incorporating various constraints such as demand, service level, and maximum inventory level extra into control chart design problem. Bouslah, Gharbi, and Pellerin (2013) built a stochastic mathematical model and use a simulation based optimization approach for joint determination of the production quantity, hedging level and the sample size in $\overline{X}$ charts.