A control chart design used in supply chain management system

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Abstract. This paper presents a design of the $\bar{x}$ control chart used in supply chain management system to improve customer satisfaction of supplier. Recently, due to ever increasing competition in supplier markets, it is demanded to offer the low-cost and high quality product in short due time. Therefore, studying the balance of quality and the due time and cost has become a new problem to supplier. In short run process, the time of treating an assignable cause (ACT time) is an important effect to the total cost and due time. To resolve the above problem, in this research, first a design of the control chart is developed in which the ACT time was considered. Then, from an economic viewpoint, the mathematical formulations which correspond to the design are shown. Finally, by numerically consideration, the balance of quality (control limits width) and due time and the total expectation cost is discussed, and the important relations between the due time, ACT time and the total expectation cost are investigated.

Keywords: supply chain management, PDCA design, short due time, economic evaluation, control chart model

1 Introduction

In today's supplier chain management system shown in Fig. 1, because of increasing competition in supplier markets, the supplier (or Manufacturer) is demand to offer low cost and high quality products to maker in short due time.

In this background, it have become more important to study the balance of quality and the due time and cost. Therefore, in this research, we present a design of the $\bar{x}$ control chart in view of quality, due time and cost for supplier to improve customer satisfaction.

Sun, Tsubaki and Matsui^[15] have defined and considered the PDCA model with tardiness penalty of the $\bar{x}$ control chart based on the case which starts from deciding the control lines.

These days, business environments have become competitive, and the due time of products has shortened. In short run process, the time of treating the assignable cause (ACT time) is an important effect to the total cost and due time. However, the ACT time was not considered in Sun, Tsubaki and Matsui^[15].

In this research, first the PDCA design of the $\bar{x}$ control chart is developed in which the ACT time was considered. Then, from an economic viewpoint, the mathematical formulations which correspond to the design are shown. Finally, by numerically consideration, the balance of quality (control limits width), due time and the total expectation cost is discussed, and the important relations between the due time, ACT time and the total expectation cost are investigated.

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Fig. 1. The supply chain management system

2 Review of the PDCA design of control charts

Recently, to improve supplier quality, there has been an increased interest in IT (information technology) control charts which are used to monitor online production processes.

On the other hand, the concept of the PDCA (Plan, Do, Check and Act) cycle originally developed by Walter Shewhart during the 1930's^[12], and implemented and promoted very effectively from the 1950s by W. Edwards Deming, has consequently played a key role in the field of quality control. After that, 'the Deming Cycle' is developed not only as a quality cycle in the quality control field, but also as a management cycle which has played a key role in all of the management fields^[8].

Recently, to clarify the certain points and improve quality more efficiently and effectively, detailed attention has been paid to the PDCA procedure which starts with the check stage for the quality management activity to allow more efficient use of energy in the industry ([6, 10, 13], etc.).

The classical definitions of the control chart's CAPD procedures are known. Recently, the evaluation of the economy of this control chart's PDCA procedures is connected with "daily management".

Since Duncan's pioneering work^[4], many studies have been developed to serve different purposes for the economic model of control charts. From the viewpoint of the production run, Gibra^[5], Ladany and Bedi^[1], Jones and Chase^[7], Saniga^[11] have considered the economic statistical model of the $\bar{x}$ control chart for the infinite-length horizon; Crowder^[3], Del Castillo and Montgomery^[2] have considered models of the control chart for short run cases.

However, the model from the viewpoint of the PDCA process was not considered.

Therefore, Sun, Tsubaki and Matsui^[14] defined the PDCA model of the $\bar{x}$ control chart; and then Sun, Tsubaki and Matsui^[15] considered the PDCA model of the $\bar{x}$ control chart with tardiness penalty.

In the short run production process, the ACT time is an important effect to the cost and the due time. Therefore, the aim of this paper is to present and study the PDCA design in which the ACT time was considered.

3 The design

To improve customer satisfaction of supplier in SCM, this paper presents a PDCA design of the control chart in view of quality, due time and cost. The PDCA design is set up based on the case which starts from deciding the control lines of the $\bar{x}$ chart, in which the ACT time was considered. The procedure (Plan, Do, Check and Act) of the design is defined as follows:

Definition 1. Assuming the production process is monitored by the $\bar{x}$ control chart from this point forward. PLAN is defined as constructing the control lines (center line and upper and lower control limit) for future management. DO is defined as sampling and plotting on the $\bar{x}$ control chart for monitoring the process quality with the decided control lines in the PLAN procedure.

Definition 2. CHECK is defined as judging whether the process is in an in-control state by the result of the comparison between the point plotted on the $\bar{x}$ chart and the control limits (upper and lower control limit). Finally, ACT is defined as correcting the assignable cause for restoring the in-control state.

Fig. 2. Some of the time variables used in the CAPD model considered the ACT time

3.1 The assumption and the notation

The assumptions of the design in this research are as follows:

- (1) The production run length T is short, and the process is repetitive.
- (2) The random variables of in-control interval and out-of-control interval are assumed to be exponentially distributed with the mean λ_1^{-1} and μ_1^{-1} .
- (3) The quality shift occurs in the middle of an interval between samples^[9]

The notation used is as follows:

- C_p : expected cost of PLAN per unit time
- C_d : expected cost of DO per unit time
- C_c : expected cost of CHECK per unit time
- C_a : expected cost of ACT per unit time
- C_t : expected total cost per unit time
- n_1 : the sample size per each sampling
- v_1 : the sampling interval
- T : production run length
- T_p : the interval of PLAN
- I_1 : period from Q to S
- O_1 : period from S to C
- c_0 : fixed sampling cost
- c_1 : variable sampling cost
- c_2 : cost of per unit time for checking the point plotted
- c_3 : cost of a false alarm
- c_4 : cost of restoring an in-control state
- $c_{\beta p}$: cost of per unit time for penalties delay of PLAN
- $c_{\beta d}$: cost of per unit time for penalties delay of DO
- $c_{\beta c}$: cost of per unit time for penalties delay of CHECK
- $c_{\beta 1}$: cost of per unit time for penalties delay of ACT
- f : number of samples taken during $T - T_p$
- δ : size of the quality shift in the mean
- a : the ACT time
- λ_1^{-1} : mean of the I_1 period in the PDCA design
- μ_1^{-1} : mean of the O_1 period in the PDCA design
- k : control limits width
- ϕ_1 : the value of $Pr 0 \leq T < v_1$
- ϕ_2 : the value of $Pr T_p \leq T < T_p + v_1$

3.2 The mathematical formulations

The evaluation function of this PDCA design is the expected total cost per unit time as follows:

$$\begin{aligned}
 C_{t(CAPD)} &= \frac{E[\text{cost per cycle}]}{E[\text{cycle}(PDCA)]} = \frac{E[\text{cost per cycle}]}{E[\min(T_p + I_1 + O_1 + a, T)]} \\
 &= C_p + C_d + C_c + C_a
 \end{aligned} \tag{1}$$

It includes the cost of PLAN, DO, CHECK, ACT. Fig. 1 shows some of the time variables used in the PDCA design considered ACT time.

At the start of the PDCA model, a sufficient plan of deciding control lines is made in T_p time. Therefore, it is thought that the PDCA model starts from the in-control state, because the process is managed by these control lines. Let the process start at the point of Q , and S be the point in time at which the quality characteristic shifts to an out-of-control state as shown in Fig. 1. At the point of C an assignable cause is detected for the first time by the $\bar{x}$ control chart. After that the assignable cause is corrected at the point of D . Here,

the random variables I_1 and O_1 represent the interval from Q to S and the interval from S to C . If T_p denotes the time of PLAN and a denotes the time of ACT, then the time from the start of the production process until removing the assignable cause is equal to $T_p + I_1 + O_1 + a$.

The mathematical formulations correspond to this design are shown as follows:

$$C_p = C_{p(s)} + C_{p(p)} \\ = \{[(c_0 + c_1 n_1)/v_1]E[T_{ps1}] + c_{\beta p \phi_1}\}/E[cycle] \quad (2)$$

$$C_d = C_{d(s)} + C_{d(p)} \\ = \{[(c_0 + c_1 n_1)/v_1]E[T_{ds1}] + c_{\beta d \phi_2}\}/E[cycle] \quad (3)$$

$$C_c = C_{c(c)} + C_{c(e)} + C_{c(p)} \\ = \{(c_2/v_1)(E[cycle] - E[T_{ps1}]) + (c_3/v_1)\alpha E[\min(I_1, T - T_p)] \\ + c_{\beta c}E[(T - T_p - I_1)^+ - (T - T_p - I_1 - O_1)^+]\}/E[cycle] \quad (4)$$

$$C_a = C_{a(a)} + C_{a(p)} \\ = \{c_4 E[(T - T_p - I_1 - O_1)^+ - (T - T_p - I_1 - O_1 - a)^+] \\ + c_{\beta a} Pr\{T_p + I_1 + O_1 \leq T < T_p + I_1 + O_1 + a\}\}/E[cycle] \quad (5)$$

The elements of costs of CHECK, ACT, PLAN and DO are shown as follows:

Table 1. The elements of costs of PLAN, DO, CHECK and ACT

Procedure	Element	
PLAN (C_p)	$C_{p(s)}$	cost of PLAN
	$C_{a(p)}$	cost of the penalty for delaying the PLAN
DO (C_d)	$C_{d(s)}$	cost of DO
	$C_{d(p)}$	cost of the penalty for delaying the DO
CHECK (C_c)	$C_{c(c)}$	cost of CHECK
	$C_{c(e)}$	cost of type I error
	$C_{c(p)}$	cost of the penalty for delaying the CHECK
ACT (C_a)	$C_{a(a)}$	cost of ACT
	$C_{a(p)}$	cost of the penalty for delaying the ACT

If it is assumed that both the random variable I_1 , O_1 are independent and exponentially distributed with mean λ_1^{-1} , μ_1^{-1} , then combining equations (1), (2), (3), (4), (5), the expected total cost per unit time of the PDCA design considered the ACT time is shown as follows:

$$\begin{aligned}
Ct = & \{((c_0 + c_1 n_1)/v_1)[T\phi_1 + T_p(1 - \phi_1)] + c_{\beta p}\phi_1 + [(c_0 + c_1 n_1)/v_1] \\
& \left[\frac{1}{\lambda_1 - \mu_1} \left\{ \frac{\mu_1}{\lambda_1} \left(e^{-\lambda_1(T-T_p-a)} - 1 \right) - \frac{\lambda_1}{\mu_1} \left(e^{-\mu_1(T-T_p-a)} - 1 \right) \right\} + T_p + a - \right. \\
& (T\phi_1 + T_p(1 - \phi_1))] + c_{\beta d}\phi_2 + (c_2/v_1) \left[\frac{1}{\lambda_1 - \mu_1} \left\{ \frac{\mu_1}{\lambda_1} \left(e^{-\lambda_1(T-T_p-a)} - 1 \right) - \right. \\
& \left. \frac{\lambda_1}{\mu_1} \left(e^{-\mu_1(T-T_p-a)} - 1 \right) \right\} + T_p + a - (T\phi_1 + T_p(1 - \phi_1))] + \\
& (c_3/v_1)\alpha \frac{1}{\lambda_1} \left(1 - e^{-\lambda_1(T-T_p)} \right) + c_{\beta c} \left[\frac{1}{\mu_1} + \frac{1}{\lambda_1 - \mu_1} \left(e^{-\lambda_1(T-T_p)} - \right. \right. \\
& \left. \left. \frac{\lambda_1}{\mu_1} e^{-\mu_1(T-T_p)} \right) \right] + c_4 \left[a + \frac{1}{\lambda_1 - \mu_1} \left(\frac{\lambda_1}{\mu_1} e^{-\mu_1(T-T_p)} (1 - e^{\mu_1 a}) - \right. \right. \\
& \left. \left. \frac{\mu_1}{\lambda_1} e^{-\lambda_1(T-T_p)} (1 - e^{\lambda_1 a}) \right) \right] + c_{\beta a} \left[\frac{\lambda_1 \mu_1}{\lambda_1 - \mu_1} \left(-\frac{1}{\mu_1} e^{-\mu_1(T-T_p)} (1 - e^{\mu_1 a}) + \right. \right. \\
& \left. \left. \frac{1}{\lambda_1} e^{-\lambda_1(T-T_p)} (1 - e^{\lambda_1 a}) \right) \right] \} / \left[\frac{1}{\lambda_1 - \mu_1} \left\{ \frac{\mu_1}{\lambda_1} \left(e^{\lambda_1(T-T_p-a)} - 1 \right) - \right. \right. \\
& \left. \left. \frac{\lambda_1}{\mu_1} \left(e^{-\mu_1(T-T_p-a)} - 1 \right) \right\} + T_p + a \right] \quad (6)
\end{aligned}$$

In this paper, the statistical hypothesis is that the mean equals a standard value. When $\bar{\Phi}(Z) = e^{-Z^2/2}/\sqrt{2\pi}$ is the standard normal density, α (the type I error probability) and P_o (power) of the $\bar{x}$ control chart are given by^[2],

$$\alpha = 2 \int_{k_i}^{\infty} \bar{\Phi}(Z) dZ, \quad (7)$$

$$P_o = \int_{-\infty}^{-k-\delta_i \sqrt{n_i}} \bar{\Phi}(Z) dZ + \int_{-k-\delta_i \sqrt{n_i}}^{\infty} \bar{\Phi}(Z) dZ. \quad (8)$$

Where δ is the size of the quality shift in the mean, and k is control limits width. We assume that the out-of-control period O_1 is an exponential random variable with the mean μ_1^{-1} . In this paper we use Ladany and Bedi's assumption (1976) that the shift occurs in the middle of an interval between samples and set μ_1^{-1} as follows:

$$\mu_1^{-1} = v_1(1/P_0 - 1) + v_2/2 = v_1(1/P_0 - 1/2) \quad (9)$$

4 Numerical experiments

In this section, for improving customer satisfaction of supplier, first we study the relations between the due time and ACT time and the total expectation cost, then we investigate the balance of control limits width (k) and due time (T) and the total expectation cost (Ct) by numerically analyzing the above design. Where, $c_0 = 1$, $c_1 = 0.1$, $c_2 = 10$, $c_3 = 50$, $c_4 = 25$, $c_{\beta a} = c_{\beta p} = c_{\beta d} = 200$, $c_{\beta c} = 2400$, $n_1 = 4$, $v_1 = 0.0316$, $T_p = 1$, $\phi_1 = 0.01$, $\phi_2 = 0.001$, $\lambda_1 = 1$. The parameters are based on a real situation. We evaluate a wide range of possible values. Because the result is approximated, we show the results of the above case as an example.

4.1 The balance of k , T and Ct

Fig. 3 shows the balance of the quality (control limits width) and due time and the total expectation cost of the above case, which is useful for setting the optimal due time and control limits width to the supplier.

From Fig. 3, it can be understood that this tables are divided into two areas by the changed control limits width: in the colorlessness area, the expected total cost per unit time (Ct) increases with the increase of due

time (T); in the blue area, the expected total cost per unit time (Ct) decreases with the increase of due time (T).

From Fig. 3 and Fig. 4, it can be noted that the expected total cost per unit time (Ct) increases with the increase of control limits width (k). This is because that the cost of defective goods increases by the increase of control limits width.

From Fig. 4, it also can be understand that a longer due time should be set when the high quality is demanded, while a shorter due time should be set when the low quality is demanded from an economic aspect.

In addition, to clarify it more, we also show the Fig. 5 which is the same as the case of Fig. 3.

T	k													
	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00	5.25	5.50	5.75	6.00
2.50	284.941	285.070	286.938	290.475	295.884	304.187	316.348	334.350	362.096	401.385	465.203	548.437	645.788	748.137
2.75	283.884	283.992	285.869	289.400	294.817	303.106	315.247	333.249	361.005	400.293	464.111	547.345	644.696	747.045
3.00	283.039	283.144	285.020	288.550	294.066	302.355	314.496	332.498	360.254	400.542	464.360	547.594	644.945	747.294
3.25	282.374	282.500	284.375	287.905	293.421	301.710	313.851	331.853	359.609	400.890	464.708	547.942	645.293	747.642
3.50	281.825	281.947	283.822	287.352	292.868	301.157	313.299	331.305	359.061	401.342	465.160	548.394	645.745	748.094
3.75	281.371	281.471	283.346	286.876	292.399	301.690	313.832	331.838	359.594	401.794	465.612	548.846	646.197	748.546
4.00	281.011	281.094	282.969	286.496	292.171	301.462	313.604	331.610	359.366	401.566	465.384	548.618	645.969	748.318
4.25	280.714	280.778	282.653	286.200	291.965	301.256	313.398	331.404	359.160	401.360	465.178	548.412	645.763	748.112
4.50	280.466	280.517	282.392	285.952	291.718	301.009	313.151	331.157	358.913	401.113	464.931	548.165	645.516	747.865
4.75	280.259	280.300	282.185	285.745	291.511	300.802	312.944	330.950	358.706	400.906	464.724	547.958	645.309	747.658
5.00	279.089	279.120	281.015	284.575	290.341	300.632	312.774	330.780	358.536	400.736	464.554	547.788	645.139	747.488
5.25	278.980	279.010	280.905	284.466	290.232	300.523	312.665	330.671	358.427	400.627	464.445	547.679	645.030	747.379
5.50	278.928	278.958	280.854	284.414	290.180	300.471	312.613	330.619	358.375	400.575	464.393	547.627	644.978	747.327
5.75	278.925	278.955	280.851	284.411	290.177	300.468	312.610	330.616	358.372	400.572	464.390	547.624	644.975	747.324
6.00	278.922	278.952	280.848	284.408	290.174	300.465	312.607	330.613	358.369	400.569	464.387	547.621	644.972	747.321
6.25	278.919	278.949	280.845	284.405	290.171	300.462	312.604	330.610	358.366	400.566	464.384	547.618	644.969	747.318
6.50	278.916	278.946	280.842	284.402	290.168	300.459	312.601	330.607	358.363	400.563	464.381	547.615	644.966	747.315
6.75	278.913	278.943	280.839	284.399	290.165	300.456	312.598	330.604	358.360	400.560	464.378	547.612	644.963	747.312
7.00	278.910	278.940	280.836	284.396	290.162	300.453	312.595	330.601	358.357	400.557	464.375	547.609	644.960	747.309
7.25	278.907	278.937	280.833	284.393	290.159	300.450	312.592	330.598	358.354	400.554	464.372	547.606	644.957	747.306
7.50	278.904	278.934	280.830	284.390	290.156	300.447	312.589	330.595	358.351	400.551	464.369	547.603	644.954	747.303
7.75	278.901	278.931	280.827	284.387	290.153	300.444	312.586	330.592	358.348	400.548	464.366	547.600	644.951	747.300
8.00	278.898	278.928	280.824	284.384	290.150	300.441	312.583	330.589	358.345	400.545	464.363	547.597	644.948	747.297

Fig. 3. The balance of k , T and Ct

Fig. 4. The relation between k and Ct ($T = 2$, $T = 5$).

Fig. 5. The relation between T , k and Ct .

T	a													
	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15	1.25	1.35	1.45
2.50	235.694	238.491	238.745	246.552	251.989	252.617	261.364	264.645	268.137	271.545	274.947	278.171	281.696	285.038
2.75	226.160	234.388	242.080	249.321	256.131	259.434	261.364	265.877	268.993	272.060	275.087	278.080	281.046	283.992
3.00	229.371	237.191	244.462	251.266	257.634	260.738	263.750	266.680	269.549	272.360	275.122	277.836	280.501	283.161
3.25	231.698	239.192	246.148	252.632	258.712	261.619	264.447	267.201	269.887	272.512	275.081	277.596	280.070	282.500
3.50	233.331	240.609	247.336	253.582	259.487	262.196	264.897	267.530	270.032	272.509	274.962	277.355	279.635	281.847
3.75	234.539	241.629	248.164	254.235	259.878	262.585	265.168	267.693	270.145	272.538	274.848	277.119	279.317	281.470
4.00	235.334	242.311	248.718	254.647	260.159	262.775	265.306	267.757	270.134	272.448	274.682	276.842	278.945	281.024
4.25	235.902	242.759	249.067	254.985	260.384	262.867	265.344	267.746	270.061	272.303	274.482	276.611	278.671	280.676
4.50	236.242	243.036	249.268	255.073	260.345	262.769	265.186	267.567	269.940	272.146	274.294	276.373	278.371	280.321
4.75	236.424	243.154	249.334	255.033	260.308	262.767	265.211	267.573	269.882	272.134	274.281	276.361	278.360	280.301
5.00	236.482	243.175	249.311	254.976	260.311	262.765	265.199	267.571	269.881	272.142	274.289	276.341	278.356	280.336
5.50	236.338	242.988	248.987	254.950	259.986	262.333	264.694	266.970	269.166	271.287	273.338	275.322	277.242	279.102
6.00	235.981	242.587	248.585	254.581	259.446	261.696	263.934	266.091	268.187	270.209	272.167	274.094	275.986	277.847
6.50	235.430	242.085	248.139	253.776	258.940	261.176	263.372	265.493	267.543	269.567	271.569	273.542	275.481	277.390
7.00	234.852	241.511	247.469	253.217	258.091	260.321	262.517	264.549	266.525	268.479	270.361	272.127	273.826	275.462
7.50	234.289	240.894	246.803	252.427	257.104	260.262	262.418	264.437	266.354	268.183	270.022	271.746	273.402	274.970
8.00	233.757	240.281	246.137	251.638	256.135	259.687	262.784	264.731	266.556	268.311	270.021	271.657	273.259	274.785

Fig. 6. The balance of a , T and Ct

4.2 The relation between t , a and ct

Fig. 6 shows the relation between the due time and ACT time and the total expectation cost, which is useful for setting the optimal due time and ACT time to the supplier.

Fig. 7. The relation between a and Ct ($T = 2, T = 10$). Fig. 8. The relation between T , a and Ct

From Fig. 6, it can be understood that this tables are divided into two areas by the changed ACT time: in the colorlessness area, the expected total cost per unit time (Ct) increases with the increase of due time (T); in the blue area, the expected total cost per unit time (Ct) decreases with the increase of due time (T).

From Fig. 6 and Fig. 7, it can be noted that the expected total cost per unit time (Ct) increases with the increase of Act time (a). This is because that the cost of defective goods increases by the increase of ACT time. Also it can be understood that a longer due time should be set when the ACT time is long, while a shorter due time should be set when the ACT time is short from an economic aspect.

In addition, to clarify it more, we also show the Fig. 8 which is the same as the case of Fig. 6.

5 Conclusions

In this research, from an economic viewpoint, we present a design of the $\bar{x}$ control chart used in supply chain management system in order to improve customer satisfaction of supplier.

Because of competition in supplier markets, studying the balance of quality and the due time and cost has become a new problem to supplier. To resolve this problem, we showed the mathematical formulations which correspond to this design; moreover, by numerically consideration, we studied the balance of quality (control limits width) and due time and the total expectation cost; and discussed the relations between the due time, ACT time and the total expectation cost.

When due time is short and penalty cost for the delay is larger, some comments are drawn as follows, which would become useful references for setting the optimal due time and control limits width to the supplier.

- (1) The expected total cost per unit time (Ct) increases with the increase of control limits width (k).
- (2) A longer due time should be set when the high quality is demanded from an economic aspect.
- (3) The expected total cost per unit time (Ct) increases with the increase of Act time (a).
- (4) A longer due time should be set when the ACT time is long, from an economic aspect.

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