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Full Length Research Paper

Construct multi-characteristics quality performance measurement diagram in high-tech industry

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Process capability indices (PCI) have been widely used in the manufacturing industry for providing numerical measures on process precision, process accuracy and process performance in single characteristic and multiple characteristics, such as multi-characteristic process capability analysis (MCPCA). However, the parameters of the manufacturing processes are usually unknown and need to be estimated from the collected samples. Therefore, it is preferable to obtain an interval estimate, for which we can assert with a reasonable degree of certainty that it contains the true index value. This paper proposes a reliable approach to construct confidence intervals of the index values, and plot the corresponding joint confidence regions on multi-characteristics quality performance measurement diagram for monitoring and controlling the performance of all process characteristics simultaneously. Finally, an application example of a super twisted nematic liquid crystal display (STN-LCD) process is presented to demonstrate how the proposed approach can be applied to real applications.

Key words: Capability zones, joint confidence regions, multi-characteristic process capability analysis (MCPCA), process yield index.

INTRODUCTION

The display is the important media through which the people communicate with the machine. Earlier; the main display is cathode ray tube (CRT). With the progress of science and technology, the new display technology of all kinds is being developed continuously. Liquid crystal display (LCD) has advantages such as light, thin, small, low power consumption, no radiates, the whole level showing and the image is steady and without glare. During the past few years, LCD has become the new mainstream of the market to replace CRT display since the gradual reduction of price.

According to the market research and analysis by International Data Corporation (IDC), the technology and market of the display are facing alteration of generations, regardless of the demand used in flat panel LCD or personal computer (PC). The occupation rate of global market on CRT display glides year by year, but the LCD demand of global market is increasing and increasing continuously. Industrial Technology Information Services (ITIS) have investigated that the production of CRT and LCD are just equal during the end of 2003, and such a trend will be maintained until 2007. The display will nearly be changed from products of CRT into LCD products. This becomes new business opportunity for the display industry. In order to deal with the increasing demand in the market, there are many enterprise devoted to research and development. They even establish the display technology graduate school in universities to foster the high ability of talented people in raising the output and technology of the industry.

The yield process at every stage is very important in miscellaneous process of LCD. It includes a lot of chemical materials and glass substrates. Process capability indices (PCIs), such as C_p, C_a, C_{pk}, are an effective and convenient tool for evaluating process precision, process accuracy and process performance. Many statisticians and quality engineers have investigated this area, including Kane (1986), Chan et al.

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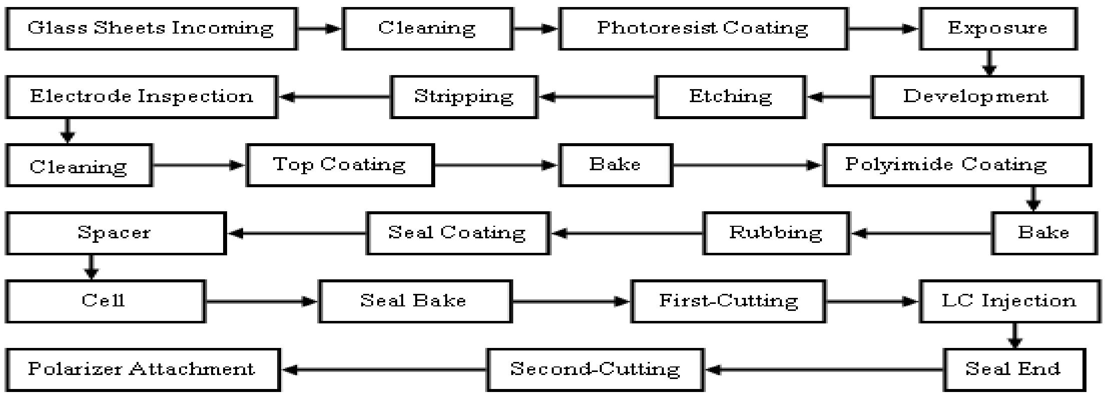

Figure 1. Flow-chart of STN- LCD manufacturing process.

(1988), Boyles (1991), Pearn et al. (1992), Vännman (1995), Kotz and Lovelace (1998), Kotz and Johnson (2002), Wazed, et al. (2010a) and Wazed et al. (2010b). Boyles (1994) proposed a yield index, referred to as S_{pk}, which establishes the relationship between the manufacturing specification and the actual process performance, providing an exact measure of process yield. The index S_{pk} is defined as:

$$S_{pk} = \frac{1}{3}\Phi^{-1}\left\{\frac{1}{2}\Phi\left(\frac{USL-\mu}{\sigma}\right)+\frac{1}{2}\Phi\left(\frac{\mu-LSL}{\sigma}\right)\right\}.$$

where μ is the process mean, σ is the process standard deviation, USL is the upper specification limit, LSL is the lower specification limit, $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution *N*(0, 1) and $\Phi^{-1}(\cdot)$ is the inverse function of $\Phi(\cdot)$. There is a one-to-one correspondence between S_{pk} and the yield process. For a process with S_{pk} = c, we can obtain %yield $= 2\Phi(3c)-1$. Thus, the yield index S_{pk} provides an exact measure of the yield process. For normally distributed processes, the number of non-conformities corresponding to a capable process with S_{pk} = 1.00 is 2700 parts per million (ppm), a satisfactory process with S_{pk} = 1.33 is 63 ppm, an excellent process with S_{pk} = 1.67 is 0.6 ppm, and a super process with S_{pk} = 2.00 is 0.002 ppm.

The use of PCIs to measure process performance is already mature. However, it is generally limited to evaluate the capability for processes with only a single key characteristic. In real applications, a process often has multiple characteristics with each having different specifications. To remedy this situation, Chen et al. (2003) developed a control chart based on the yield index S_{pk} for processes with multiple characteristics, called multi-characteristic process capability analysis (MCPCA) chart, which displays all the characteristic measures in one single chart. Unfortunately, the parameters of the manufacturing processes are usually unknown and need to be estimated from the collected samples. Hence, it is preferable to obtain an interval estimate, for which we can assert with a reasonable degree of certainty that it contains the true index value. In this paper, we propose a reliable approach to construct confidence intervals of the index values, and plot the corresponding joint confidence regions on MCPCA chart for monitoring and controlling the performance of all process characteristics simultaneously. Finally, a case study on a STN-LCD process is provided to demonstrate how the proposed approach can be applied to real applications.

BACKGROUND

The category of the LCD can be divided into Static, Simple Matrix and Active Matrix. Twisted nematic (TN) and super twisted nematic (STN) are two types of Simple Matrix LCD. STN displays provide more contrast than twisted nematic (TN) by twisting the molecules from 180 to 270°. A larger twist angle results in a significantly larger electro-optical distortion. This leads to substantial improvement in the contract and viewing angles over TN displays. STN displays are used in some inexpensive mobile phones and informational screens of some digital products. The characteristic of STN and range of applications are narrated as follow:

(i) Principle: Turn back 180-270°
(ii) Characteristic: Black-and-white, colored (260,000), low contrast.
(iii) Visual angle: Below 40°
(iv) The size of the panel: 12 inches
(v) Range of applications: Electronic dictionary, mobile telephone

Figure 1 displays the flow chart of STN-LCD manufacturing process. A STN-LCD manufacturing

Table 1. Quality characteristic specifications for STN-LCD.

	Process	Quality characteristics	Unit	Target	USL	LSL
1	Photoresist coating	Thickness	Å[a]	14000	16000	12000
2	Top coating	Thickness	Å	1650	1900	1400
3	Polyimide coating	Thickness	Å	810	960	660
4	Seal coating	Thickness	μm[b]	28	36	20
5	Exposure	Position	μm	3.00	3.05	2.95

[a]1Å = 10^{-10} m, [b]1μm = 10^{-6} m.

process consists of three main stages (or processes), which are described as follows:

1. Array: Array is the first stage of STN-LCD process, which is similar to semiconductor process, except that the indium tin oxide (ITO) are fabricated on a glass substrate instead of a silicon wafer.
2. Cell: Cell is the process of midsection. It combines glass sheets with pours into the liquid crystal (LC) among two slices of glass sheets.
3. Assembly: The process of Assembly is the operation of product assembling glass and other many kinds of spare parts such as circuit, seal.

For a particular model of the STN-LCD, the specifications of characteristics are listed in Table 1, which is taken form a manufacturing factory located on science-based industrial park in Taiwan. The five key quality characteristics of a STN-LCD process include the thickness of (1) photoresist coating, (2) top coating, (3) polyimide coating, (4) seal coating process and (5) the position of exposure process.

METHODOLOGY AND EMPIRETICAL CASE STUDY

Based on Table 1, all of the five characteristics are the nominal-the-best. We can apply the index C_{pk} to measure process capability on the liquid-crystal manufacturing process. However, the index C_{pk} only provides an approximate rather than an exact measure of the process yield. Therefore, Boyles (1994) considered a yield index, called S_{pk}, for normally distributed processes. The formula S_{pk} provides an exact measure on the process yield. Based on the yield index S_{pk}, Boyles (1994) developed a tool called the S_{pk} contour plot which is a contour plot of index S_{pk} as a function of the process parameters (μ, σ) for monitoring and controlling process performance. Actually, the S_{pk} contour plot is a useful tool for evaluating multiple processes, as we can obtain the process yield and the process departure ratio by checking the location of the index value falling on the contour plot. But the S_{pk} contour plot is only applicable for multiple processes with the same specification limits on each single process, which may not be used on processes with multiple characteristics where the characteristic specifications are not the same. To extend the applicability of the S_{pk} contour plot for processes with multiple characteristics, Chen et al. (2003) applied the techniques developed by Deleryd and Vännman (1999) who introduced a process capability plot called the (δ, γ)-plot, where $\delta = (\mu - T)/d$, $\gamma = \sigma/d$. Chen et al. (2003) further rewrote the definition of S_{pk} below, which can be expressed as a function of $C_{dr} = (\mu - T)/d$ and $C_{dp} = \sigma/d$. Note that C_{dr} measures the departure ratio, and C_{dp} measures the variation relative to the specification tolerance.

$$S_{pk} = \frac{1}{3}\Phi^{-1}\left[\frac{1}{2}\Phi\left(\frac{1-C_{dr}}{C_{dp}}\right) + \frac{1}{2}\Phi\left(\frac{1+C_{dr}}{C_{dp}}\right)\right].$$

Therefore, using C_{dr} as the *x*-axis, C_{dp} as the y-axis, we can plot the following point set forming the curve of S_{pk} on the (C_{dr}, C_{dp}) coordinates,

$$\left\{\left(C_{dr}, C_{dp}\right) \mid \frac{1}{3}\Phi^{-1}\left[\frac{1}{2}\Phi\left(\frac{1-C_{dr}}{C_{dp}}\right) + \frac{1}{2}\Phi\left(\frac{1+C_{dr}}{C_{dp}}\right)\right] = S_{pk}\right\}.$$

Obviously, the smaller the C_{dr} and C_{dp} values, the higher the process accuracy and process precision, respectively. We note that the process capability plot is invariable irrespective of the value of the specification limits. Processes with multiple characteristics having different characteristic specification limits can thus be plotted simultaneously on a single chart.

Assuming that the five characteristics are mutually independent, and then the actual overall process yield can be measured by the following overall capability index, denoted by S_{pk}^T:

$$S_{pk}^T = \frac{1}{3}\Phi^{-1}\left\{\left[\prod_{j=1}^{5}\left(2\Phi(3S_{pkj}) - 1\right) + 1\right] \Big/ 2\right\},$$

where S_{pkj} denotes the S_{pk} value of the jth characteristic for j = 1, 2, …,5. Thus, if the requirement for the overall capability is $S_{pk}^T \geq C_0$, a sufficient condition (which is minimal) for the requirement to each single characteristic can be obtained as

$$S_{pkj} \geq \frac{1}{3}\Phi^{-1}\left(\frac{\sqrt[5]{2\Phi(3C_0) - 1} + 1}{2}\right), \quad j = 1, 2, \ldots, 5.$$

For example, if the requirement of the overall process capability is $1 \leqq S_{pk}^T \leqq 1.33$, that is, the process yield is between 99.73 and 99.9934% and the process capability is between $\pm 3\sigma$

Table 2. Varieties control zones for STN-LCD process departure and improvement suggestions.

Situation	Process improvement suggestion
The plotted joint confidence region located on I_1 and 1.153≦S_{pkj}≦1.455	The process capability of characteristic is acceptable.
The plotted joint confidence region located on I_1 and S_{pkj}≦1.153	Characteristic departure is tolerable but process capability is unacceptable. Thus, the quality improvement effort could be focused on the reduction of the process variation.
The plotted joint confidence region located on I_1 and S_{pkj}≧1.455	The process capability of characteristic is excellent. Thus, a reduced sampling plan can be considered to lessen sampling cost.
The plotted joint confidence region was not located on I_1 and 1.153≦S_{pkj}≦1.455	Characteristic departure is serious. Thus, the decrease of the process mean from the target is needed to improve the process quality.

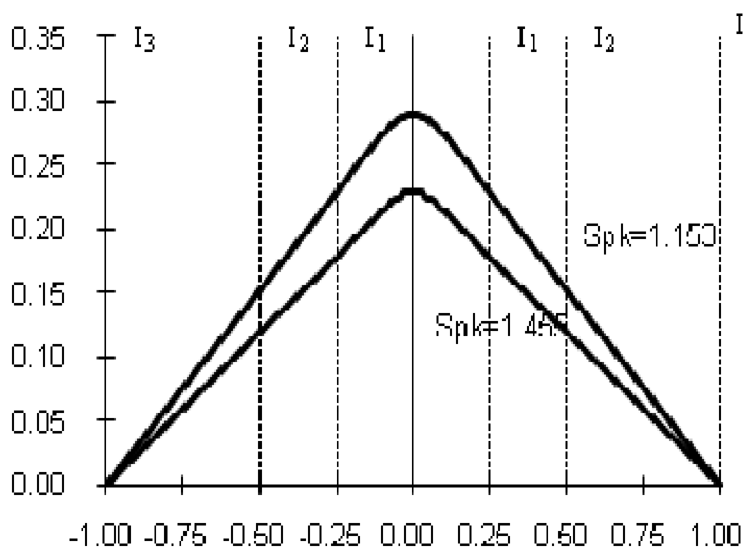

Figure 2. MCPCA chart with control zones and contours of S_{pk} = 1.00 and 1.33.

and $\pm 4\sigma$. Then, if the number of characteristic is five, we can obtain the lower bound S_L = 1.153 and the upper bound S_U = 1.455 for S_{pkj}, j = 1, 2… 5. Under the six-sigma quality improvement program formulated by Motorola (Noguera and Nielsen, 1992) assuming $d = 6\sigma$, the three pairs of control limits I_1, I_2, and I_3 correspond to $|\mu - T| = 1.5\sigma$, 3σ, and 6σ. Research has shown that a typical process is likely to deviate from its natural centering condition by approximately 1.5σ at any given moment in time. Under the six-sigma quality improvement program, the process mean is allowed to shift as much as 1.5σ, that is, all the pair (C_{drj}, C_{dpj}) of the jth characteristic should not locate out of the pair control limits I_1. Therefore, the three pairs of control limits I_1, I_2, and I_3 form various process accuracy (the degree of centering) control zones. Various control zones for process departure and the improvement suggestions are summarized in Table 2. The MCPCA with various control zones and contours of S_{pk} = 1.00 and 1.33 are displayed in Table 2.

The practitioners can judge the degree of centering of characteristic j by checking the location of the corresponding plotted point on the MCPCA chart (Figure 2).

The $\bar{X} - S$ control charts are applied to monitor the process mean and variability of SNT-LCD manufacturing process in this study. Assume that m subsamples of size n are taken from an "in-control" process, the values of C_{drj} and C_{dpj} for each single characteristic can be estimated by their natural estimators as

$$\hat{C}_{drj} = \frac{\bar{\bar{X}}_j - T_j}{d_j}, \quad \hat{C}_{dpj} = \frac{\bar{s}_j}{d_j}, \text{ for } j = 1, 2, ..., 5.$$

where $\bar{\bar{X}}_j = \sum_{i=1}^{m} \bar{X}_{ji} / m$ and $\bar{S}_j^2 = \sum_{i=1}^{m} \bar{S}_{ji}^2 / m$ are the average of all subsample means and variances for the jth

Table 3. Estimated index values and the corresponding confidence intervals for five characteristics.

j	Process	$\bar{\bar{X}}_j$	$\bar{S}_j$	C_{drj}	C_{dpj}	S_{pkj}	Lower bound C_{drj}	Upper bound C_{drj}	Lower bound C_{dpj}	Upper bound C_{dpj}
1	Photoresist coating	13873.20	618.3855	-0.0634	0.3092	1.0571	-0.1015	-0.0252	0.3045	0.3298
2	Exposure	3.00	0.0099	0	0.1975	1.6874	-0.0244	0.0244	0.1946	0.2107
3	Top coating	1590.45	47.6306	-0.2382	0.1905	1.3866	-0.2617	-0.2147	0.1876	0.2032
4	Polyimide Coating	831.34	42.1199	0.1423	0.2808	1.0836	0.1076	0.1769	0.2765	0.2995
5	Seal coating	27.01	2.1192	-0.1244	0.2649	1.1630	-0.1570	-0.0917	0.2609	0.2825

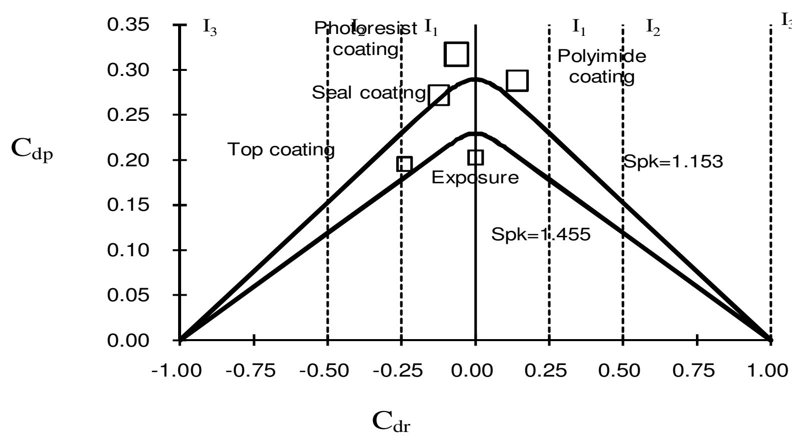

Figure 3. Application of the S_{pk} MCPCA chart.

characteristics, respectively, and $\bar{X}_{ji} = \sum_{k=1}^{n} \bar{X}_{jik}/n$ is the *i*th subsample mean, $S_{ji}^2 = \sum_{k=1}^{n}(X_{jik} - \bar{X}_{ji})^2/(n-1)$ is the ith subsample variance. However, the approach by simply looking at the calculated values of the indices and making a conclusion on whether the given process is capable is highly unreliable since the sampling errors have been ignored. Therefore, we convert the estimated values of C_{drj} and C_{dpj} to a joint confidence region, then plot the corresponding confidence region on the MCPAC chart. The joint confidence region not only gives us a clue minimum performance (precision and accuracy), but also is useful making decisions for quality improvement. The joint confidence region is a rectangle constructed by the $100(1-\alpha)\%$ confidence interval of C_{drj}, $\left[\sqrt{\nu \hat{C}_{dpj}^2/\chi_{\alpha/4}^2}, \sqrt{\nu \hat{C}_{dpj}^2/\chi_{1-\alpha/4}^2}\right]$ and the $100(1-\alpha)\%$ confidence interval of C_{dpj}, $[\hat{C}_{drj} - Z_{\alpha/4}\hat{C}_{dpj}/\sqrt{mn}, \hat{C}_{drj} + Z_{\alpha/4}\hat{C}_{dpj}/\sqrt{mn}]$, where $\nu = m(n-1)$, $\chi_{\alpha/4}^2(\nu)$ and $\chi_{1-\alpha/4}^2(\nu)$ are the upper $\alpha/4$ and $1-\alpha/4$ percentiles of chi-square distribution with ν degrees of freedom. $Z_{\alpha/4}$ is the upper $\alpha/4$ percentile of standard normal distribution.

In the following, we consider a case study on STN-LCD manufacturing process to demonstrate how the S_{pk} MCPCA chart and the proposed joint confidence regions can be used in analyzing processes with multiple characteristics. In this study, 30 subsamples of size 10 are taken from each characteristic of STN-LCD process. The sample statistics, the estimated index values and the corresponding confidence intervals for five characteristics are summarized in Table 3. At the same time, five joint confidence regions are plotted on the MCPCA chart based on the pairs of the confidence interval for C_{drj} and C_{dpj}, which is shown in Figure 3.

Based on the analysis of the chart shown in Figure 3, we can make the following conclusions and recommendations:

1. All of the five characteristics are located between the pair of the control limits l_1. This shows that the process accuracy of these characteristics is satisfactory.
2. The process of exposure is excellent since the index S_{pk} is greater then S_U = 1.455. A reduced sampling plan for quality characteristic of exposure can be considered to lessen sampling cost.
3. The plotted joint confidence region of top coating process is between two contours corresponding to S_L = 1.153 and S_U = 1.455. This shows that the process is capable.
4. Based on the plotted joint confidence region of seal coating on the S_{pk} MCPCA chart, the process of seal coating is need to monitor and improve continuously since it is marginally acceptable.
5. The processes of cleaning photo resist coating and PI coating are incapable since these two plotted joint confidence region are located outside of contour S_L = 1.153. Thus, the quality improvement effort for these two processes could be focused on the reduction the process variation.

FINDINGS AND CONCLUSION

PCIs establish the relationship between the actual process performance and the manufacturing specifications, which quantify process potential and process performance, are essential to any successful quality improvement activities and quality program implementation. Capability measures for processes with a single characteristic have been investigated extensively, but are comparatively neglected for processes with multiple characteristics. In real applications, a process often has multiple characteristics with each having different specifications. MCPCA can be used for evaluating the performance of a multi-process product, sets the priorities among multiple processes for capability improvement and indicates if reducing the variability or the departure of the process mean should be the focus of improvement. However, existing applications on MCPCA chart simply look at the estimated indices values and then make a conclusion on which the given process is classified, is highly unreliable and misleading since they did not considered sampling errors. This paper proposes a reliable approach to convert the estimated index values into the joint confidence regions, and plots the corresponding joint confidence regions on the S_{pk} MCPCA chart. The joint confidence region gives a reliable performance measurement for each single characteristic and overall production yield. Based on the proposed approach, the practitioners can make reliable decisions for capability testing and monitoring the quality performance of all process characteristics simultaneously.

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