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Quality Capability Assessment for Thin-Film Chip Resistor

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ABSTRACT Chip resistors are a type of resistor among passive components; they are mainly used to regulate the voltage and current in electronic products. A single electronic product may be embedded with dozens of or even more than a thousand thin-film chip resistors varying in resistance. Thin-film chip resistors have low temperature coefficients, which makes them stable and reliable. They have five primary nominal-the-best (NTB) quality characteristics: length, width, height, upper width, and lower width. To increase the quality of thin-film chip resistors and prevent losses from customers returning low-quality or defected products, this study proposes a quality capability assessment method. The proposed method takes sampling errors into account and includes acceptance criteria for individual quality characteristics and the total quality capability. If either of the criteria is not fulfilled, then the manufacturer must improve quality capabilities. A case study of a manufacturer in central Taiwan is presented to illustrate the feasibility of the proposed method. Finally, conclusions and recommendations for future work are presented.

INDEX TERMS Thin-film chip resistor, process capability index (PCI), quality capability analysis chart (QCAC), normal-the-best (NTB), lower confidence limit (LCL).

I. INTRODUCTION

Taiwan's electronic industry has unrivaled manufacturing capabilities. There are over 55 passive component manufacturers in Taiwan, among which Yageo is the top chip resistor manufacturer in the world. The output value of Taiwan's passive component industry is the second highest in the world. In 2017, the value of Taiwan's passive component exports reached USD 2.58 billion, 23.6% of which was from chip resistors. In 2018, the value of chip resistor exports reached USD 743 million, which was 30.47% more than that of the previous year [1]. Chip resistors are a type of resistor among passive components and are mainly used to lower the circuit voltage and limit the current in electronic products. They are essential components of the majority of high-tech electronic products. The chip resistors can be divided into thin-film chip resistors and thick-film chip resistors. The former offer better precision and lower temperature coefficients, which means more stable and reliable resistance.

Figure 1 displays the five primary nominal-the-best (NTB) quality characteristics of a thin-film chip resistor, namely, length (L), width (W), height (H), upper width (UW), and lower width (LW).

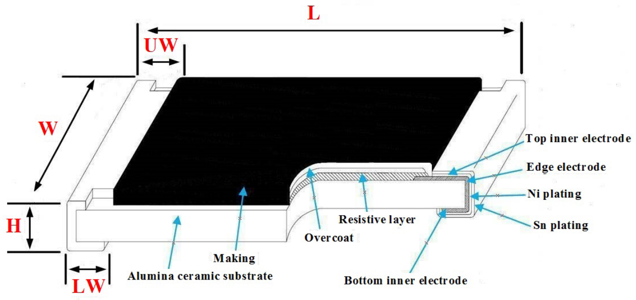

FIGURE 1. Quality characteristics of thin-film chip resistor.

Small in volume, thin-film chip resistors are mainly used in consumer electronics such as laptop computers, digital cameras, and mobile phones. They are also being used in emerging industries for the Internet of Things, wearable devices, and intelligent control. A single electronic product may be embedded with dozens of or even more than a thousand chip resistors varying in tolerance. Thus, installing a thin-film chip

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TABLE 1. Corresponding values of C_{pm}, yield, and defect rate (PPM) under different quality levels.

Quality level	C_{pm}					
	Normal	Yield	Defect rate	1.5 sigma shift	Yield	Defect rate
6 sigma	2.0000	99.9999998	0.002	1.1094	99.99966	3.4
5 sigma	1.6667	99.999943	0.57	0.9245	99.9767	233
4 sigma	1.3333	99.9937	63	0.7396	99.379	6200
3 sigma	1.0000	99.73	2700	0.5547	93.32	66803

resistor of poor quality or that does not meet specifications can prevent a product from functioning as designed, thereby affecting customer satisfaction.

Process capability indices (PCIs) are powerful tools that are currently widely used in manufacturing industries to assess and analyze process quality. They employ a function of the process mean μ, standard deviation σ, and specification limits to measure product quality and performance. Any deviations or variances in a process will immediately be reflected in PCI values [2]. Hsu *et al.* [3] stated that higher PCI values indicate higher quality yield and lower quality loss. Thus, effectively monitoring PCI values can help a company reduce production costs and scrap losses and ensure that the customers receive products of stable and satisfactory quality [4]. Numerous quality managers and researchers have used PCI analysis results to make and gauge improvements as well as enhance product quality and performance [5]–[13].

The first PCI to measure NTB quality characteristics, C_p, was proposed by [14] based on specification interval length and natural tolerance 6σ. Considering the degree of shift in process mean μ from the process center, Kane [15] proposed a PCI for NTB quality characteristics, C_{pk}. Later, Chan *et al.* [16] took into account the degree of shift between the target value T and process mean μ and proposed C_{pm}, a PCI for NTB quality characteristics. These indices were defined as follows:

$$C_p = \frac{USL - LSL}{6\sigma} \tag{1a}$$

$$C_{pk} = \min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} \tag{1b}$$

$$C_{pm} = \frac{d}{3\sqrt{\sigma^2 + (\mu - T)^2}} \tag{1c}$$

where USL and LSL are respectively the upper and lower specification limits, σ is process standard deviation, and $d = USL - LSL/2$ is the half-length of the specification interval.

According to the six-sigma concept, even a stable process may present a shift of 1.5σ [17]. When this takes place, the six-sigma quality level is still acceptable. Based on the definitions above, we can say that in the process of an NTB quality characteristic, the distance between the T and μ is $|\mu - T| = 1.5\sigma$. Obviously, when the quality level of a quality characteristic reaches $k\sigma$ level (i.e., $d = k\sigma$), then index C_{pm} with a process mean shift of 1.5σ can be calculated as follows:

$$C_{pm} = \frac{d}{3\sqrt{\sigma^2 + (\mu - T)^2}} = \frac{k\sigma}{3\sqrt{\sigma^2 + (1.5\sigma)^2}} = \frac{k}{3\sqrt{3.25}} \tag{2}$$

Table 1 shows the corresponding values of C_{pm}, yield, and defect rate (PPM) under 6σ, 5σ, 4σ, and 3σ. It also includes yield, and defect rate (PPM) for case involving a process mean shift of 1.5σ.

A quality capability analysis chart (QCAC) is an effective and convenient way of assisting thin-film chip resistor manufacturers in swiftly checking the process capabilities for each quality characteristic pertaining to their products. The underlying principle behind a QCAC is collecting, sorting, and calculating process data, converting the results into a chart, and then determining whether process capabilities meet requirements based on the chart [11]. Although QCACs are effective and easy to use, the population parameters (μ and σ) are usually unknown, which introduces a reliability issue. Furthermore, sampling errors are inevitable due to the sampling method as well as environmental and human factors. In view of this, we derived the lower confidence limit (LCL) of index C_{pm} to analyze and evaluate quality capabilities regarding the various quality characteristics of thin-film chip resistors. Next, we used the LCL of index C_{pm} and the six-sigma level to construct a QCAC. We further calculated the total quality capability of thin-film chip resistors to assist companies in determining whether the quality of their products meet required standards.

The remainder of the paper is organized as follows. Section 2 derives the LCL of index C_{pm} for NTB quality characteristics. Section 3 presents a procedure for the quality capability assessment of thin-film chip resistors. Section 4 utilizes a case study of a manufacturer in central Taiwan to demonstrate the efficacy of the proposed method. Finally, conclusions and future work are presented in the Section 5.

II. LOWER CONFIDENCE LIMIT FOR CPM

Under the assumption of normality (i.e., $X \sim N(\mu, \sigma^2)$), index C_{pm} has an unequal relationship with process yield $Yield\% \geq 2\Phi(3C_{pm}) - 1$ for $C_{pm} > 0.6$ [18]. Thus, a higher value for C_{pm} represents a lower process loss.

With accurate calculations and explanations, PCIs can provide useful process information and serve as effective tools in determining whether a product meets the quality capabilities required by manufacturers or customers [4]. In practice, manufacturers utilize PCI estimators such as the process mean μ and process variance σ to determine whether the process capability regarding a quality characteristic reaches customer requirements [3]. Environmental and human factors may cause conditions in which crucial quality characteristics deviate from normal. Therefore, process parameters μ and σ should be estimated from preliminary samples or subsamples taken when the process is perceived to be in control [19].

Assume that X_h represents the relevant quality characteristic of a manufacturing process for an important quality characteristic h which follows a normal distribution, i.e. $X_h \sim N\left(\mu_h, \sigma_h^2\right)$. Let $Y_h = (X_h - T)/d$, which is distributed normally with process mean $\delta_h = (\mu_h - T)/d$ and process variance $\gamma_h^2 = \sigma_h^2/d$, i.e. $Y_h \sim N\left(\delta_h, \gamma_h^2\right)$. Thus, index C_{pm} for the five quality characteristics of thin-film chip resistor can be rewritten as follows:

$$C_{pmh} = \frac{d}{3\sqrt{\sigma^2 + (\mu - T)^2}} = \frac{1}{3\sqrt{\left(\frac{\sigma^2}{d}\right) + \left(\frac{\mu - T^2}{d}\right)}}$$
$$= \frac{1}{3\sqrt{\delta_h^2 + \gamma_h^2}}, h = 1, 2, \ldots 5 \tag{3}$$

If we let $C_{pmh} = k$, we obtain

$$\frac{1}{3\sqrt{\delta_h^2 + \gamma_h^2}} = k \tag{4}$$

Equivalently,

$$\delta_h^2 + \gamma_h^2 = \left(\frac{1}{3k}\right)^2 \tag{5}$$

Equation (5) meets the standard equation of a circle. Hence, we can use the information presented in Table 1 to construct a QCAC using given value k as an acceptance quality standard. The resulting QCAC is as shown in Figure 2 (when $k = 6$ sigma $= 1.1094$).

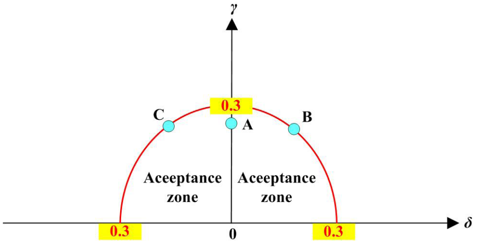

FIGURE 2. **QCAC (when k = 6 sigma = 1.1094).**

Let $Y_{h1}, Y_{h2}, \cdots, Y_{hn}$ be a random sample of an important quality characteristic h. Then the sample mean and sample standard deviation can respectively be derived as follows:

$$\hat{\delta}_h = \frac{1}{n}\sum\nolimits_{i=1}^{n} Y_{hi} \text{ and } \hat{\gamma}_h = \sqrt{\frac{1}{n-1}\sum\nolimits_{i=1}^{n}\left(Y_{hi} - \hat{\delta}_h\right)^2}$$

where n is the total sample size.

Under the assumption of normality, let

$$\tau = \frac{\hat{\delta} - \delta}{\hat{\gamma}_h/\sqrt{n-1}} \text{ and } \chi = \frac{(n-1)\hat{\gamma}_h^2}{\gamma_h^2}$$

where τ follows t distribution with $n-1$ degrees of freedom; i.e., t_{n-1} and χ follows chi-square distribution with $n-1$ degrees of freedom, i.e. χ^2_{n-1}.

Thus, we have

$$\begin{aligned}1 - \frac{\alpha}{2} &= p\left\{-t_{\alpha/4;n-1} \le \tau \le t_{\alpha/4;n-1}\right\}\\ &= p\left\{-t_{\alpha/4;n-1} \le \frac{\hat{\delta} - \delta}{\hat{\gamma}_h/\sqrt{n-1}} \le t_{\alpha/4;n-1}\right\}\\ &= p\left\{\hat{\delta} - t_{\alpha/4;n-1} \times \frac{\hat{\gamma}_h}{\sqrt{n-1}} \le \delta \le \hat{\delta}\right.\\ &\qquad \left. + t_{\alpha/4;n-1} \times \frac{\hat{\gamma}_h}{\sqrt{n-1}}\right\}\end{aligned} \tag{6}$$

and

$$\begin{aligned}1 - \frac{\alpha}{2} &= p\left\{\chi \ge \chi^2_{\alpha/2;n-1}\right\} = p\left\{\frac{(n-1)\hat{\gamma}_h^2}{\gamma_h^2} \ge \chi^2_{\alpha/2;n-1}\right\}\\ &= p\left\{\gamma_h^2 \le \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2\right\}\end{aligned} \tag{7}$$

where $t_{\alpha/4;n-1}$ is the upper $\alpha/4$ quintile of t_{n-1} distribution, $\chi^2_{\alpha/2;n-1}$ is the lower $\alpha/2$ quintile of χ^2_{n-1} distribution and α represents the significance level.

To derive the $(1-\alpha) \times 100\%$ LCL for C_{pmh}, we define two events as follows:

$$E_{\delta h} = \left\{\hat{\delta} - t_{\alpha/4;n-1} \times \frac{\hat{\gamma}_h}{\sqrt{n-1}} \le \delta \le \hat{\delta} + t_{\alpha/4;n-1} \times \frac{\hat{\gamma}_h}{\sqrt{n-1}}\right\} \tag{8}$$

and

$$E_{\gamma h} = \left\{\gamma_h^2 \le \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2\right\} \tag{9}$$

In fact, $P\left(E_{\delta h}\right) = P\left(E_{\gamma h}\right) = 1 - (\alpha/2)$ and $P\left(E^C_{\delta h}\right) = P\left(E^C_{\gamma h}\right) = \alpha/2$. Based on Boole's inequality and de Morgan's theorem, we obtain

$$P\left(E_{\delta h} \cap E_{\gamma h}\right) \ge 1 - P\left(E^C_{\delta h}\right) - P\left(E^C_{\gamma h}\right) = 1 - \alpha$$

Equivalently,

$$\begin{aligned}p&\left\{\hat{\delta}_h - t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)} \le \delta_h\right.\\ &\left.\le \hat{\delta}_h + t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)},\ \gamma_h^2 \le \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2\right\} \ge 1 - \alpha\end{aligned} \tag{10}$$

Therefore, the $100\,(1-\alpha)\,\%$ confidence region of $\left(\delta_h, \gamma_h^2\right)$ can be obtained as follows:

$$CR_h=\left\{\left(\delta_h, \gamma_h^2\right)\middle|\, \hat{\delta}_h-e_h\le\delta_h\le\hat{\delta}_h+e_h,\ \gamma_h^2\le\frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2\right\} \tag{11}$$

where $e_h = t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)}$.

According to [20], we can use mathematical programming to derive the $100\,(1-\alpha)\,\%$ LCL of C_{pmh} as follows:

$$\begin{cases} LC_{pmh} = Min\dfrac{d}{3\sqrt{\delta_h^2+\gamma_h^2}} \\ s.t.\ \hat{\delta}_h - e_h \le \delta_h \le \hat{\delta}_h + e_h \\ \quad\ \gamma_h^2 \le \dfrac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2 \end{cases} \tag{12}$$

Next, we define two cases for deriving the $100\,(1-\alpha)\,\%$ LCL of C_{pmh}:

Case 1: $0 \in \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right]$

When $0 \in \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right]$, $\left(\delta_h, \gamma_h^2\right) = \left(0, \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2\right)$ is closest to the origin. Thus, the maximum LCL of C_{pmh} appears on the γ axis (see point A in Figure 2) and can be written as follows:

$$LC_{pmh} = \frac{1}{3\sqrt{\frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2}} \tag{13}$$

Case 2: $0 \notin \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right]$

When $0 \notin \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right]$, the maximum LCL of C_{pmh} appears to the sides of the γ axis (see point B and point C in Figure 2) and the equation is as shown at the bottom of this page.

From these relationships, let

$$I = \begin{cases} 0 & if\ 0 \in \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right] \\ 1 & if\ 0 \notin \left[\hat{\delta}_h - e_h, \hat{\delta}_h + e_h\right] \end{cases} \tag{15}$$

Then, the $100\,(1-\alpha)\,\%$ LCL of C_{pmh} is as shown at the bottom of this page.

III. PROCEDURE OF PROPOSED METHOD

In this section, we propose a quality level assessment method for thin-film chip resistors. The proposed method demonstrates how to measure the quality levels of thin-film chip resistors, identify unacceptable quality characteristics that need to be improved, and thereby realize continuing quality enhancement in production. A QCAC is first constructed based on minimum and maximum required quality capabilities. Next, index LC_{pm} is used to calculate the quality capability values for the quality characteristics of thin-film chip resistors and reduce the likelihood of error associated with estimation of process parameters μ and σ. Finally, the total quality capability value of all quality characteristics is calculated to assist companies in determining whether product quality reaches the required level. The procedure for this method is as follows:

Step 1: Specifies the maximum and minimum required quality capabilities from Table 1 for five key quality characteristics of the thin-film chip resistor.

Step 2: Construct the QCAC using values k from Table 1. An acceptance zone can also be constructed between the maximum and minimum required quality capabilities (see Figure 3).

Step 3: Determine significance level α, the total sample size n, and specifications (USL, LSL, T and d) for the five key quality characteristics.

Step 4: Calculate the values of $\hat{\delta}_h$, $\hat{\gamma}_h$, and LC_{pm}.

Step 5: Sign the values of LC_{pm}.

Step 6: Calculate the total quality capability value λ using the following equation [21]:

$$\lambda = \frac{1}{3}\Phi^{-1}\left\{\left[\left(\prod_{h=1}^{5}\left[2\Phi(3C_{pmh})-1\right]\right)+1\right]\div 2\right\} \tag{17}$$

Step 7: Set the product acceptance criteria as follows: (1) All quality characteristics must fall between the minimum and maximum required quality capabilities, which means falling within the acceptance zone depicted in Figure 3. (2) Total quality capability λ must be higher than the minimum required quality capability. If either of these criteria is not fulfilled, then the manufacturer must improve quality capabilities.

IV. CASE STUDY

Chip resistors are mainly used to lower the circuit voltage and limit the current in electronic products. Thin-film chip resistors offer the advantages of small volume, high stability, and low costs and are thus an essential component in the majority of high-tech electronic products. Thin-film chip resistors are a

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$$LC_{pmh} = \frac{1}{3\sqrt{Min^2\left\{\hat{\delta}_h - t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)},\ \hat{\delta}_h + t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)}\right\} + \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2}} \tag{14}$$

$$LC_{pmh} = \frac{1}{3\sqrt{I \times Min^2\left\{\hat{\delta}_h - t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)},\ \hat{\delta}_h + t_{\alpha/4;n-1}\sqrt{\hat{\gamma}_h^2/(n-1)}\right\} + \frac{n-1}{\chi^2_{\alpha/2;n-1}}\hat{\gamma}_h^2}} \tag{16}$$

TABLE 2. Specifications and sample statistics of quality characteristics for R-type thin-film chip resistor.

Unit: mm

Quality characteristic	USL	T	LSL	d	$\hat{\delta}_h$	$\hat{\gamma}_h$	LC_{pm}	λ
Length (L)	1.200	1.000	0.800	0.200	0.2825	0.3833	0.938	0.5491
Width (W)	0.550	0.500	0..450	0.050	-0.3412	0.0842	0.946	
Height (H)	0.400	0.350	0.300	0.050	0.2239	0.6836	0.656	
Upper Width (UW)	0.300	0.200	0.100	0.100	0.2584	0.1248	1.212	
Lower Width (LW)	0.300	0.200	0.100	0.100	0.4667	0.1925	0.676	

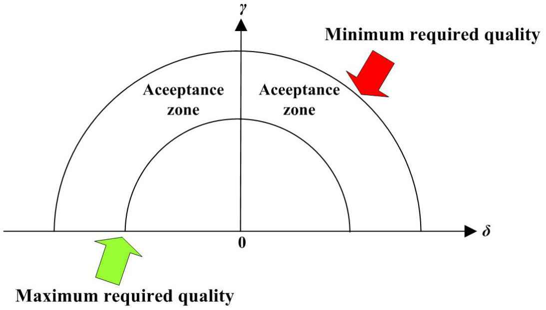

FIGURE 3. QCAC with maximum and minimum required quality capabilities.

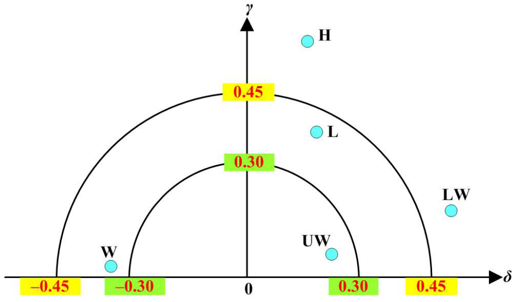

FIGURE 5. QCAC for R-type thin-film chip resistor.

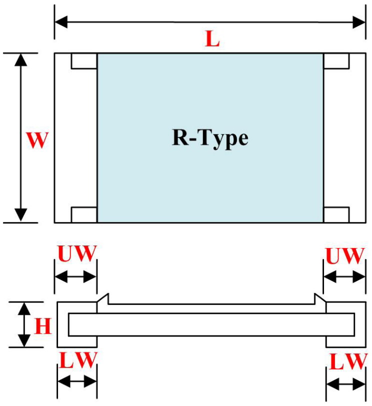

FIGURE 4. R-type thin-film chip resistor.

primary product of Company Q, a company located in Central Taiwan. Company Q manufactures various types of thin-film chip resistors, among which the R-type thin-film chip resistor currently has the highest sales volume in the market. The structure of the R-type thin-film chip resistor is presented in Figure 4, and its five key quality characteristics are listed in Table 2.

To ensure the quality and safety of their products and maintain customer satisfaction, Company Q needs a set of standards to effectively determine whether the quality capabilities of their thin-film chip resistors meet requirements. The method proposed in Section 4 is used to conduct quality capability assessment for the R-type thin-film chip resistor; the operating procedure is summarized as follows:

Step 1: Company Q specifies the maximum required quality capability is “6 Sigma” and minimum required quality capability is “4 Sigma” for five key quality characteristics of the R-type thin-film chip resistor.

Step 2: From Table 1, we obtained 6 Sigma = 1.1094 and 4 Sigma = 0.7396. Using these values, a QCAC can be constructed as shown in Figure 5.

Step 3: Company Q specified $\alpha = 0.05$ and $n = 300$. Table 2 presents the USL, LSL, T and d for the five key quality characteristics of the R-type thin-film chip resistor.

Step 4: Table 2 shows the values of $\hat{\delta}_h$, $\hat{\gamma}_h$, and LC_{pm} for the five key quality characteristics.

Step 5: Figure 5 shows the values of LC_{pm} on the QCAC for the five key quality characteristics.

Step 6: The total quality capability value of the R-type thin-film chip resistor is calculated as $\lambda = 0.5491$.

Step 7: As shown in Table 2, three quality characteristics, namely, height ($LC_{pm} = 0.656 < 0.7396$), lower width ($LC_{pm} = 0.676 < 0.7396$), and upper width ($LC_{pm} = 1.212 > 0.7396$), fell outside the acceptable zone, meaning that the quality capability for these three key quality characteristics is “unqualified”. Furthermore, the total quality capability is also lower than the minimum required quality capability ($\lambda = 0.5491 < 0.7396$). It is worth noting that the upper width ($LC_{pm} = 1.212 > 0.7396$) was not acceptable because the corresponding quality capability was too high. From a practical perspective, this means that too many resources have been invested in this quality characteristic, so production resources should be adjusted and reallocated.

V. CONCLUSION

PCIs are useful tools in the continuing improvement of production processes. This study successfully used the PCI C_{pm} to develop a quality capability assessment method for checking the performances of thin-film chip resistor. The proposed method includes acceptance criteria, which can assist manufacturers in identifying quality characteristics for which excessive resource investments have been made and in ensuring that various quality characteristics and the total quality capability of the product meets requirements. We applied the proposed method to a thin-film chip resistor manufacturer in central Taiwan, Company Q, and assisted them in measuring the quality capability of their R-type thin-film chip resistors. Inadequate quality was found in two quality characteristics of the thin film chip resistors manufactured by Company Q, namely height and lower width, and excessive quality capabilities were discovered in the quality characteristic upper width. Thus, Company Q must modify the quality of these three quality characteristics.

We conclude with remarks on the limitations of this study and suggestions for future research. A limitation to consider when drawing conclusions from this study is that it is connected mainly with assembling of thin-film chip resistors. Therefore, this study can be followed up by further empirical work investigating the reliability and effectiveness of proposed method for the quality of electronic circuits of thin-film chip resistors [22], [23]. Furthermore, the proposed method can be extended to other PCIs, and also to be researched in terms of processes with non-normal distributions and fuzzy data.

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