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Research note

Integrated process capability analysis with an application in backlight module

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Abstract

Backlight application specializes in supplying light, with notable examples including liquid crystal display (LCD), hand-phone LCD, and PDA LCD. The integrated process capability and integrated process yield for cold cathode fluorescent lamp backlight are unknown. Process capability analysis is a highly effective means of assessing the process ability of backlight that meets specifications. A larger process capability index (PCI) implies a higher process yield, and lower expected process loss. Chen et al. [Int. J. Product. Res. 39 (2001) 4077], applied indices C_{pu}, C_{pl}, and C_{pk} to evaluate the integrated process capability for a multi-process product with smaller-the-better, larger-the-better, and nominal-the-best specifications, respectively. However, C_{pk} suffers from the weakness of being unable to reflect the specific process yield. This study selects index C_{ps} to replace C_{pk}. Meanwhile, an integrated PCI for the entire backlight module is proposed, and the relationship between the PCI and process yield is described. A multi-process capability analysis chart, which reasonably accurately indicates the status of process capability for the backlight module, is designed for practical applications.
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1. Product description—backlight module

Initially, backlight module was used primarily in advertising light boxes. However, because of the vigorous marketing of liquid crystal display (LCD) manufacturing and customer demand for night version and full color LCD, backlight module is closely associated with optical products. Generally, backlight module comprises a piece of light-guide plate, which guides a spontaneous light source from a light emitting diode or light tube to create a lager and more uniform surface illuminant. Backlight module is generally simply termed backlight. The application of backlight specializes in supplying the light required by liquid crystal. LCD, Hand-phone LCD, and PDA LCD are examples of backlight applications. The advantages of backlight are uniform light distribution and high brightness. Backlight module provides the light source for TFT monitors. TFT monitors are growing in size, and the present production size ranges from 13 to 18 inches. Generally, the brightness equalization becomes increasingly difficult to control as TFT monitors increase in size.

The backlight modules of LCD are categorized into LED, EL, and cold cathode fluorescent lamp (CCFL). Forhouse Corporation is located in central Taiwan and specializes in CCFL production. The bright white light provided by CCFL offers clear and even illumination over a large viewing area. The features of CCFL backlight include high brightness, long lifetime, low power consumption, and white color. A thin structure with even illumination emits light from a tube-like light source over a large area. CCFL inverters output a high pressure AC current. A CCFL comprises mold frame, lamp, film, AL-case and light guide panel (LGP). Fig. 1 illustrates the structure of the backlight module.

The key quality variables of the backlight module currently produced by Forhouse Corporation include:

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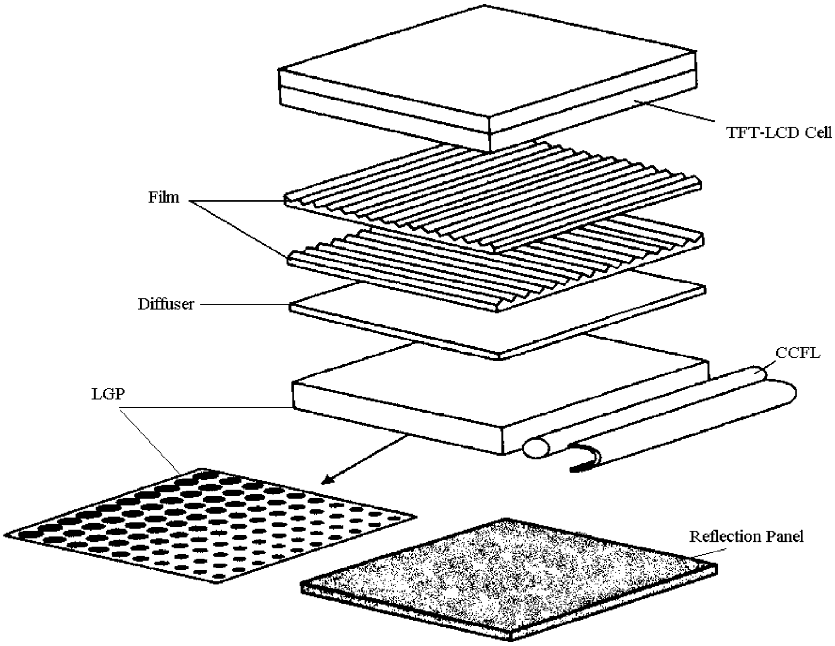

Fig. 1. Structure of a backlight module.

Table 1
Specifications for key quality characteristics of a backlight module

Quality characteristic	USL	Target	LSL
(1) Length	366.65 mm	366.45 mm	366.25 mm
(2) Width	295.15 mm	294.95 mm	294.75 mm
(3) Thickness	15.30 mm	15.00 mm	14.70 mm
(4) Brightness	–	–	4800 cd/m^2
(5) Equalization	–	–	75%

(1) length, (2) width, (3) thickness, (4) brightness, and (5) equalization. Table 1 describes the specifications for the above quality characteristics.

Currently, the $\overline{X}$–R control chart and process capability indices C_p, and C_{pk} are using to assess each quality characteristic. Meanwhile, the integrated process capability and integrated process yield for the CCFL backlight are unknown.

2. Process capability evaluation for a backlight module

Process capability indices are widely used to assess whether product qualities meet specifications in semiconductor and IC assembly industries. Numerous statisticians and quality engineers, such as Kane [9], Chan et al. [5], Choi and Owen [1], Boyles [6], Pearn et al. [11], Kotz and Johnson [10], Boyles [7], Singhal [8], Vännman [15], Chen [2] and Spiring [14], have investigated process capability indices with the aim of proposing more effective methods of assessing process potential and performance.

The key quality characteristics of a backlight module include (1) length, width and thickness, which are nominal-the-best specifications, and (2) brightness and equalization, which are larger-the-better specifications. Customers expect all of the quality characteristics of a backlight module to meet or exceed expected levels. Chen et al. [3] has noted that the integrated process capability for multi-process products cannot be evaluated by either univariate process capability indices or multivariate process capability indices. Furthermore, in assessing the integrated process capability for a multi-process product, Chen et al. [3] has applied indices C_{pu}, C_{pl}, and C_{pk} to assess the process capability for a multi-process product with smaller-the-better, larger-the-better, and nominal-the-best specifications, respectively. Since a backlight is designed to have two larger-the-better specifications and three nominal-the-best specifications, the integrated process capability index (PCI) for a backlight module becomes

$$\mathrm{PCI} = \left(\frac{1}{3}\right)\Phi^{-1}\left(\left[\left(\prod_{i\in\omega}\prod_{j=1}^{n_i}\left[2\Phi(3C_{pij})-1\right]\right)+1\right]\Big/2\right),$$
$$i \in \omega = \{l,k\},\ j = 1,2,\ldots,n_i,\ n_l = 2 \text{ and } n_k = 3.$$

The two well-known process capability indices C_{pu} and C_{pl}, proposed by Kane [9], which measure unilateral tolerances, including smaller-the-better and larger-the-better process capabilities, are:

$$C_{\mathrm{pu}} = \frac{\mathrm{USL} - \mu}{3\sigma},$$

$$C_{\mathrm{pl}} = \frac{\mu - \mathrm{LSL}}{3\sigma},$$

where USL and LSL denote, respectively, the upper and lower specification limits, μ represents the process mean and σ is the process deviation. Under normal assumptions, the relationship between process yield (%Yield) and unilateral capability indices C_{pu} and C_{pl} is

$$\%\mathrm{Yield} = \Phi(3C_{\mathrm{p}i}), \quad i = \mathrm{u} \text{ or } \mathrm{l}$$

where Φ denotes the standard normal cumulative distribution function. A one-to-one mathematical relationship exists between process yield and the unilateral process capability indices. As shown in Fig. 2, the process yield increases and decreases with the process capability index. Consequently, C_{pu} and C_{pl} reasonably accurately reflect the process yield.

The first well-known bilateral PCI C_{p}, introduced by Kane [9], measures process capabilities solely in terms of process variation and does not consider process location. In fact, 1.33 has become the standard benchmark index value for capable processes. The second bilateral PCI, C_{pk}, was created to offset some of the weaknesses in C_{p}. C_{pk}, proposed by Kane [9], quantifies the process capability for the worst half of the data, while still considering a value of 1.33 to be the standard minimal boundary for a capable process. 'Larger the better' is the rule for the commonly used capability index.

When the process mean is located on the midpoint of the specification interval ($\mu = m$), the relationship between index C_{p} and the process yield is $\%\mathrm{Yield} = 2\Phi(3C_{\mathrm{p}}) - 1$. Meanwhile, the inequality relationship between index C_{pk} and the process yield is $2\Phi(3C_{\mathrm{pk}}) - 1 \leqslant \%\mathrm{Yield} < \Phi(3C_{\mathrm{pk}})$. The larger C_{pk} implies a higher process yield.

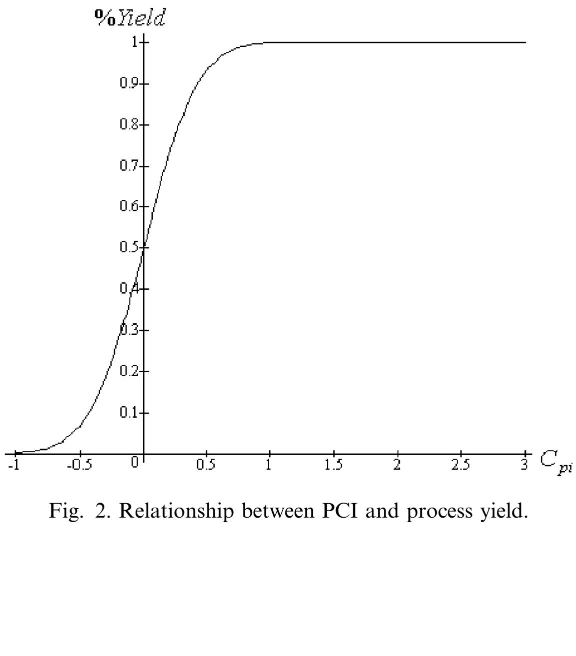

Fig. 2. Relationship between PCI and process yield.

Boyles [7] proposed a novel bilateral PCI, possessing a one-to-one mathematical relationship with the process yield, as below:

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

According to Chen and Pearn [4], C_{pk} can reflect the process yield when the process mean is located on the midpoint of the specification interval ($\mu = m$). Although C_{pk} guarantees the interval for the process yield, the specific value of the process yield is unknown. The one-to-one mathematical relationship between index C_{ps} and the process yield is $\%\mathrm{Yield} = 2\Phi(3C_{\mathrm{ps}}) - 1$. In assessing the process capabilities, index C_{ps} is better than C_{pk}. The process yield equals 99.73% when $C_{\mathrm{ps}} = 1.0$. Meanwhile, index C_{pk} is irrelevant to the process target (T), and may fail to account for process centering. C_{pk} cannot accurately reflect the specific process yield. This work selected index C_{ps} to replace C_{pk}. Meanwhile, indices C_{pu}, C_{pl}, and C_{ps} are used to assess the entire process capability for a multi-process product with smaller-the-better, larger-the-better, and nominal-the-best specifications, respectively. The integrated PCI for a backlight module is revised as

$$\mathrm{PCI} = \left(\frac{1}{3}\right)\Phi^{-1}\left(\left[\left(\prod_{i\in\omega}\prod_{j=1}^{n_i}\left[2\Phi(3C_{\mathrm{p}ij}) - 1\right]\right) + 1\right]\Big/ 2\right),$$
$$i \in \omega = \{l, s\},\ j = 1, 2, \ldots, n_i,\ n_l = 2 \text{ and } n_k = 3.$$

Additionally, Pearn et al. [13] designed an index for assessing the accuracy of the manufacturing process. The definition is $C_{\mathrm{a}} = 1 - ((|\mu - T|)/d)$, where T denotes the target value and $d = (\mathrm{USL} - \mathrm{LSL})/2$ is the half interval length.

Clearly, the value of C_{a} decreases as μ moves away from T. Conversely, the value of C_{a} increases when μ approaches T. $C_{\mathrm{a}} = 1$ when the process mean equals the preset target. Therefore, C_{a} is termed the accuracy index. In fact, C_{a} is the function of C_{pu} and C_{pl}, and they have the following relationship:

$$C_{\mathrm{a}} = C_{\mathrm{a}}(C_{\mathrm{pu}}, C_{\mathrm{pl}}) = 1 - \frac{|C_{\mathrm{pu}} - C_{\mathrm{pl}}|}{C_{\mathrm{pu}} + C_{\mathrm{pl}}}.$$

Meanwhile, C_{a} measures the relative distance of the shift from process mean to preset target. Equal relative distances result in the same values of C_{a}. Generally, C_{a} cannot be too small since a smaller C_{a} implies the process mean shifts further from the process target and causes significant process loss. The supplementary lines, denoting the values of C_{a}, are plotted on the multi-process capability analysis chart (MPCAC) to monitor the process loss of the backlight module. Fig. 3 displays a modified version of the MPCAC.

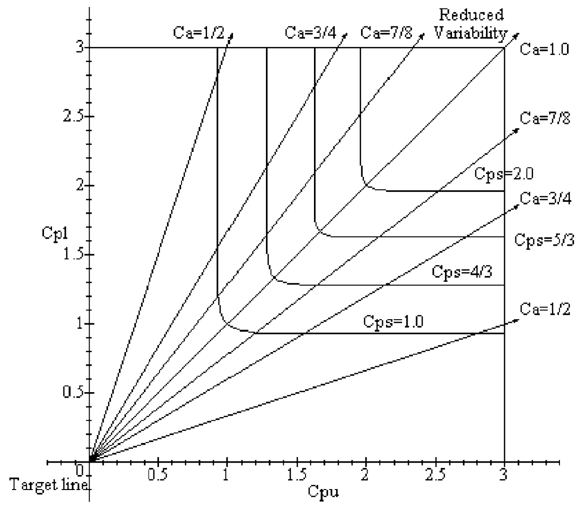

Fig. 3. Multi-process capability analysis chart.

3. Process capability zone

For a backlight module product, three nominal-the-best processes are evaluated by $C_{psj} (j = 1, 2, 3)$, and two larger-the-better processes were evaluated by $C_{plj} (j = 1, 2)$. Under normal assumptions the unilateral capability index C_{plj} has a one-to-one mathematical relationship with the process yield. Thus, the general form for unilateral characteristics can be written as: $p_{ij} = \Phi(3C_{plj})$, where Φ denotes the standard normal cumulative distribution function, $j = 1, 2$. Meanwhile, the one-to-one mathematical relationship between index C_{psi} and the process yield is $\%\text{Yield} = 2\Phi(3C_{psj}) - 1,\ j = 1, 2, 3$.

The formulas describing the relationship between C_{pij} and process yield p_{ij} are as follows:

$$p_{ij} = \begin{cases} \Phi(3C_{plj}), & j = 1, 2. \\ 2\Phi(3C_{psj}) - 1, & j = 1, 2, 3. \end{cases}$$

Process yield increases with process capability. Meanwhile, the relationship between process yield p_{ij} and the process capability index for a backlight module is:

$$p_{ij} \geqslant 2\Phi(3C_{pij}) - 1, \quad i \in \omega = \{l, s\},$$
$$j = 1, 2, \ldots, n_i,\ n_l = 2 \text{ and } n_s = 3.$$

Apparently, the above equation can be rewritten as $\prod_{i\in\omega}\prod_{j=1}^{n_i}(2\Phi(3C_{pij}) - 1) = 2\Phi(3k) - 1$ when $\text{PCI} = k$. Meanwhile, the integrated process yield (P^T) for the backlight module can be written as

$$P^T = \prod_{j=1}^{2}\Phi(3C_{plj})\prod_{j=1}^{3}[2\Phi(3C_{psj}) - 1].$$

When the unilateral process capabilities equal c_1, namely, $C_{pl1} = C_{pl2} = c_1$, and the bilateral process capability equals c_2, namely, $C_{ps1} = C_{ps2} = C_{ps3} = c_2$, the integrated process yield (P^T) can be expressed as

$$P^T = [\Phi(3c_1)]^2[2\Phi(3c_2) - 1]^3.$$

Generally, when assessing the process capability of a multi-process product, the integrated product yield (P^T) is lower than the individual process yields (p_{ij}), namely $P^T \leqslant p_{ij}$. For example, a product includes (1) process A, nominal-the-best specification, (2) process B, smaller-the-better specification, and (3) process C, larger-the-better specification. When the individual process capabilities for processes A, B and C all equal 1, the process yields for processes B and C are $p_{u1} = p_{l1} = 0.99865$, the process yield for process A is $p_{s1} = 0.9973$, and the integrated process yield for the backlight module is $P^T = 0.99461$. Obviously, the product yield is lower than the individual process yields ($p_{u1} = p_{l1} > p_{s1} > P^T$). When P^T is preset and the individual process yields are assumed to equal ($p_{uj} = p_{lj} = p_{sj} = p$), the individual process yield can be calculated as $p_{ij} = \sqrt[n]{P^T}$. Therefore, c_1 and c_2 are rewritten as

$$c_1 = \frac{1}{3}\Phi^{-1}(p) \text{ and } c_2 = \frac{1}{3}\Phi^{-1}\left(\frac{P+1}{2}\right).$$

When the product is designed exclusively with nominal-the-best specifications, namely $n_u = n_l = 0$, a one-to-one mathematical relationship $P^T = 2\Phi(3c_2) - 1$ exists between the process capability and the integrated process yield (P^T). The larger process capability clearly reveals the higher process yield. For example, the integrated process capability $\text{PCI} = k = 1.0$ guarantees $P^T \geqslant 99.73\%$.

Specifying the integrated PCI for the backlight module allows the corresponding integrated process yield (P^T) to be attained. Meanwhile, Table 2 lists the process yields and minimal process capabilities for each quality characteristics. In the current case, the integrated process capability required for the backlight module is preset to 1.33, while the corresponding values for c_1 and c_2 equal 1.4039 and 1.4552 respectively. Additionally, when the process loss is considered, e.g. $C_a \geqslant 0.875$, the process capability zone according to c_1, c_2 and C_a is marked as displayed in Fig. 4.

4. Illustrative example

The key quality characteristics of a backlight module include (1) length, width and thickness, which are nominal-the-best tolerances whose process capabilities are assessed with index C_{ps}, and (2) brightness and equalization, which are larger-the-better tolerances whose process capabilities are assessed with index C_{pl}.

Table 2
PCI and the corresponding process yields and individual process capabilities

PCI	P^T	P_{ij}	c_1	c_2
1.00	0.9973002039	0.9994594567	1.0895091815	1.1532722236
1.05	0.9983672954	0.9996732456	1.1361251948	1.1977033792
1.10	0.9990331517	0.9998065555	1.1829564547	1.2424757020
1.15	0.9994394134	0.9998878575	1.2299883289	1.2875653814
1.20	0.9996817828	0.9999363485	1.2772061383	1.3329493350
1.25	0.9998231654	0.9999646306	1.3245956626	1.3786056278
1.30	0.9999038073	0.9999807607	1.3721434462	1.4245137085
1.33	0.9999366575	0.9999873312	1.4039236620	1.4552495020
1.35	0.9999487824	0.9999897563	1.4198369592	1.4706545146
1.40	0.9999733085	0.9999946616	1.4676646584	1.5170104846
1.45	0.9999863862	0.9999972772	1.5156159830	1.5635655125
1.50	0.9999932047	0.9999986409	1.5636813119	1.6103048660
1.55	0.9999966806	0.9999993361	1.6118519000	1.6572150881
1.60	0.9999984133	0.9999996827	1.6601198056	1.7042838921
1.65	0.9999992579	0.9999998516	1.7084778157	1.7515000574
1.70	0.9999996603	0.9999999321	1.7569193750	1.7988533303
1.75	0.9999998479	0.9999999696	1.8054385195	1.8463343322
1.80	0.9999999334	0.9999999867	1.8540298153	1.8939344755
1.85	0.9999999714	0.9999999943	1.9026883050	1.9416458893
1.90	0.9999999880	0.9999999976	1.9514094596	1.9894613436
1.95	0.9999999951	0.9999999990	2.0001891356	2.0373742026
2.00	0.9999999980	0.9994594567	1.0895091815	1.1532722236

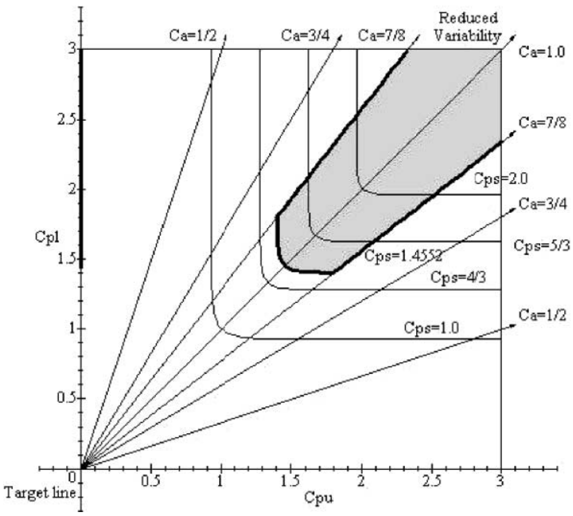

Fig. 4. Process capability zone.

As observed by Pearn and Chen [12], a process is considered "capable" if the PCI ranges from 1.00 and 1.33, which indicates that some process control is needed. Meanwhile, a process is termed "satisfactory" if the PCI ranges from 1.33 and 1.50, which indicates that process quality is satisfactory. As listed in Table 2, when the integrated process capability for the backlight module is preset to 1.33, the process capability for each larger-the-better process, including length, width, and thickness, is required to must be at least 1.4039, while the process capability for each nominal-the-best process including Brightness and equalization is required to be at least 1.4552. Table 3 displays the process capabilities of quality characteristics for the backlight module, while Fig. 5 analyzes the multi-process capabilities

(1) Characteristics 1–3 are nominal-the-best with bilateral specifications:
   (i) "Width" and "thickness", with process capabilities exceeding the minimum 1.4552 are located within the process capability zone, indicating that the process capabilities are satisfactory and stringent quality control is not required.
   (ii) "Length", which has a process capability value of 1.068, is not located within the process capability zone, indicating that its process capability is inadequate. Action must be taken to enhance the process quality. Specifically, process engineers should monitor the process to identify all assignable causes, and should reduce the process variation to boost process capability.
(2) "Brightness" and "equalization" are unilateral specifications, which are larger-the-better type and only have lower specification limits. The PCI of "brightness" is located within the process capability zone and the process capability is considered satisfactory. When the PCI of "equalization" is not located within the process capability zone, the process capability is inadequate. Enhancing the process quality

Table 3
Process capabilities of the characteristics of backlight module

Quality characteristic	Type	USL	T	LSL	μ	σ	C_{pl}	C_{ps}
(1) Length	Nominal-the-best	366.65	366.45	366.25	366.52	0.043	–	1.0684
(2) Width	Nominal-the-best	295.15	294.95	294.75	294.96	0.041	–	1.58642
(3) Thickness	Nominal-the-best	15.30	15.00	14.70	14.98	0.065	–	1.48261
(4) Brightness	Larger-the-better	–	–	4800	6013	151.4	2.6706	–
(5) Equalization	Larger-the-better	–	–	75%	79.6%	2.3%	0.6667	–

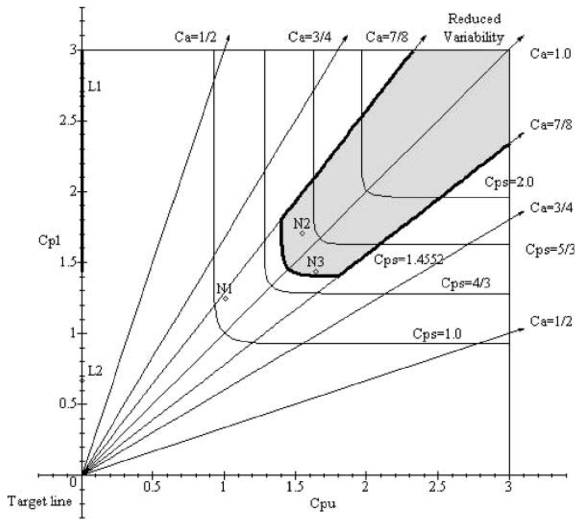

Fig. 5. MPCAC for a backlight module.

of "equalization" involves either reducing the process variation or shifting the process mean further from the lower specification limit.

5. Conclusions

A backlight module has three nominal-the-best quality characteristics and two larger-the-better quality characteristics. PCI are applied as effective and excellent means of measuring the process capabilities for a backlight module. This study employs indices C_{pl}, and C_{ps} to assess the integrated process capability for a backlight module product with larger-the-better and nominal-the-best specifications, respectively. The process capabilities for the key quality characteristics of the product must exceed specific values. Meanwhile, a MPCAC chart, that accurately presents the status of process capability for the backlight module is constructed for use in practical applications.

Acknowledgements

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