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ORIGINAL ARTICLE

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Contract manufacturer selection by using the process incapability index C_{pp}

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Abstract In the competitive global business environment, enterprises should effectively respond to and satisfy customer needs. Outsourcing manufacturing is an effective method of adjusting the flexibility of production capability. To ensure final product quality, evaluating and selecting a contract manufacturer is essential. Process capability indices are extensively adopted in manufacturing to determine whether a process meets capability requirements. This study attempts to determine the score index R_i and then apply it to assess the process performance of contract manufacturer by using the process incapability index C_{pp}. The formulae for C_{pp} and R_i are simple to understand and to apply. The procedure developed in this paper is also an easy and convenient tool for practitioners to assess contract manufacturer quality performance and make more reliable decisions regarding contract manufacturer.

Keywords Contract manufacturer · Outsourcing manufacture · Process capability index

1 Introduction

In the competitive global business environment, customer-oriented economics is the major development trend in the 21st century. To satisfy changing customer demands, shorter product lifecycles and management challenges due to globalization, enterprises should apply supply chain management. The competitiveness of an enterprise can be increased by using strategic alliances to integrate supply chain parties and activities, including procurement, production, outsourcing and distribution. Lee and Billington [1] proposed that the supply chain is a network coordinating various chain participants in value creating activities ranging from raw material procurement, through to its transformation, and eventual distribution to customers. Accordingly, the major parties in the supply chain, including suppliers, manufacturers, contract manufacturers, distributors and retailers, should be integrated and managed effectively to respond to customer needs.

Companies must frequently adjust their manufacturing capacity to react to a fluctuating and uncertain market. Companies can expand their manufacturing capacity by: (1) expanding existing plants, (2) building new plants, (3) automation, and (4) outsourcing production to contract manufacturers [2]. Lee and Tang [3] suggested that contracting manufacturing should help companies form strategic alliances with other manufacturers with special expertise, enabling each company involved to focus on its core competence.

Outsourcing refers to a situation in which a company lets a contract manufacturer manufacture parts and components, then assemble these parts and components and deliver the final product to customers. Outsourcing boosts professionalism in areas of core competence and enhances logistics performance and market competitiveness. Moreover, outsourcing might help a company maintain a better competitive position in the industry as a whole. Kim et al. [4] demonstrated that manufacturers could reserve future capacity from contract manufacturers but delay specifying the actual parts to be outsourced. Restated, outsourcing is an effective method of adjusting organizational production flexibility.

Based on the above argument, selecting suppliers and contract manufacturer is an important task in supply chain management. Manufacturers purchase components from suppliers or hire contract manufacturers to produce necessary parts, then assemble these parts to deliver the finished products to customers. Kim et al. [4] treat contract manufacturers as another type of supplier, and outsourcing manufacturing to a contract manufacturer is similar to procuring from a supplier. The major considerations when choosing a contract manufacturer thus include quality, cost, goodwill, service, delivery, and so on. According to research conducted by Dickson [5], quality and delivery are two

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of the items most demanded by component suppliers. Twenty-five years after Dickson's research, Weber et al. [6] still consider quality of "extreme importance" and delivery of "considerable importance." According to Weber's research on the Just In Time (JIT) model, the importance of quality and delivery remains the same. Pearson [7] surveyed 210 members of the National Association of Purchasing Management (NAPM) who were randomly selected from the listings of electronic firms in the two-digit SIC code 38 and indicated that quality is the most important criterion in the selection and evaluation suppliers for both small and large electronic firms surveyed. Moreover, according the survey of current and potential outsourcing end-users by the Outsourcing Institute [8], the top 10 factors in vendor selection are commitment to quality, price, reference/reputation, flexible contract terms, scope of resources, additional value-added capability, cultural match, existing relationship, location and other. Quality still is the most important factor of all. Thus, this study considers quality in determining a procedure for assessing and selecting contract manufacturers.

Quality has long been essential to corporate policy. Good quality is essential to maintaining corporate competitiveness and customer loyalty. However, the emergence of a supply chain means that enhancing product quality is no longer just the responsibility of the manufacturer, but is also the responsibility of the contract manufacturers who produce the parts and components. The manufacturing capability and product quality of contract manufacturers determine the finished product quality, as well as customer satisfaction and loyalty. Therefore, manufacturing capability and product quality are the key considerations when choosing contract manufacturers. Among the quality assessment methods discussed in many previous investigations, the process capability index is an effective and convenient tool for evaluating process effectiveness and quality performance. Many statisticians and quality engineers have investigated this area, including Kane [9], Chan et al. [10], Choi [11], Boyles [12], Pearn et al. [13], Boyles [14] and Chen [15]. Though the use of the process capability index to measure process performance is already mature, it is generally limited to evaluating the production process of manufacturers, but not contract manufacturers. Chou [16] suggested using the C_p index to evaluate both production processes. However, in the real business environment, there are usually more than two contract manufacturers to choose from. Consequently, to assess contract manufacturers more accurately and reliably, this study applies the process incapability index C_{pp} introduced by Greenwich and Jahr-Schaffrath [17] to develop an evaluation model. The index C_{pp} is easy to apply, and provides more process information than other process indices, such as process inaccuracy and process impression. The index thus allows practitioners to select contract manufacturers more effectively and easily, and to better understand the process situations of the other partners involved in a strategic alliance. Finally, this study applies the novel evaluation process to the production of TFT-LCD, a segment of the high-tech industry with high contracting rates. Not surprisingly, decisions regarding contract manufacturer selection made using the novel procedure is more reliable than those made without the procedure.

2 Incapability index C_{pp}

Process capability indices are extensively adopted in manufacturing, and provide numerical and unitless measures of whether a process is capable of producing items that meet the quality requirements of the product designer. Various process capability indices and approaches for measuring process capability have been developed by statisticians and quality engineers. Kane [9] discussed five popular process capability indices, namely C_p, CPL, CPU, k and C_{pk}. Boyles [12] noted that C_p and C_{pk} are yield-based indices and independent of the target T, which fails to account for process centering. Moreover, Chan et al. [6] developed index C_{pm} to consider process entering (the departure of the process mean μ from the target T). Additionally, Pearn et al. [13] proposed index C_{pmk} to deal with asymmetric tolerances. Finally, Kotz and Johnson [18] surveyed and briefly interpreted and commented on some 170 publications on process capability indices, which appeared in various sources from 1992 to 2000, and also assessed the most widespread process capability indices.

Greenwich and Jahr-Schaffrath [17] introduced a new index, C_{pp}, which is simpler and more analytically convenient than existing indexes. Let $D = d/3$, then C_{pp} is defined as follows:

$$C_{pp} = \left(\frac{\mu - T}{D}\right)^2 + \left(\frac{\sigma}{D}\right)^2 ,$$

where T denotes the target value, $d = (USL - LSL)/2$, USL represents the upper specification limit, LSL is the lower specification limit, μ denotes the process mean, and σ represents the process standard deviation. A small value of C_{pp} indicates that a process is more capable of meeting the required specifications than a process with a larger value of C_{pp}. In fact, C_{pp} is a simple transformation of C_{pm} ($C_{pp} = (1/C_{pm})^2$) and provides an uncontaminated separation between information concerning process accuracy and process precision, something not available with C_{pm}. As observed by Greenwich and Jahr-Schaffrath [17], $(\mu - T)^2/D^2$ is denoted by C_{ia} (inaccuracy index) and σ^2/D^2 is denoted by C_{ip} (imprecision index). Thus, $C_{pp} = C_{ia} + C_{ip}$. Table 1 displays the application of the indices C_{ia} and C_{ip}.

For a process with $(LSL, T, USL) = (27, 30, 33)$, the different process means and standard deviation of the four processes A, B, C and D can be found, as listed in Table 1. However, the values of C_{pm} and C_{pp} are equal for each A, B, C and D, and thus C_{pm} and C_{pp} fail to distinguish among the four processes. How-

Table 1. A comparison of process A, B, C and D

Process	μ	σ	C_{pm}	C_{pp}	C_{ia}	C_{ip}
A	30.0	1.00	1.00	1.00	0.00	1.00
B	30.5	0.866	1.00	1.00	0.25	0.75
C	30.6	0.800	1.00	1.00	0.36	0.64
D	30.75	0.661	1.00	1.00	0.56	0.44

ever, from Table 1, the different values of C_{ia} and C_{ip} for the four processes help to simply and accurately distinguish and improve them.

In practice, the real process measurements μ and σ cannot be found; instead sample data must be collected to calculate the index value. If practitioners ignore the sampling errors and simply use the index value calculated from the sample data as the basis for deciding whether the given process meets the capability requirements, then the decision will be unreliable. Chen [19] proposed the uniformly minimum variance unbiased estimator (*UMVUE*) and the probability density function of C_{pp}. According to the same approximation method used by Boyles [12] in obtaining confidence intervals for C_{pm}, Greenwich and Jahr-Schaffrath [17] proposed that that $\hat{C}_{pp}/C_{pp}$ is approximately distributed as χ^2_v/v, where χ^2_v is a chi-square distribution with v degrees of freedom and $v = n\{1+[(\mu-T)/\sigma]^2\}^2 / \{1+2[(\mu-T)/\sigma]^2\}$, and developed the $100(1-\alpha)$ confidence interval of C_{pp}. The confidence interval is $[\hat{v}\hat{C}_{pp}/\chi^2_{\alpha/2;\hat{v}}, \hat{v}\hat{C}_{pp}/\chi^2_{1-\alpha/2;\hat{v}}]$, where α denotes the producer risk, $\chi^2_{(p,k)}$ represents the upper p percentage point of χ^2 distribution with k degrees of freedom and $\hat{v}$ is the maximum likelihood estimator (*MLE*) of v. Pearn et al. [20] also developed a statistical hypothesis testing method based on the incapability index C_{pp} to determine whether or not a given process meets quality requirements. Finally, Huang et al. [21] showed the relationship between process incapability index C_{pp} and process yield. All of the above statistical approaches can increase reliability in decision making.

3 Evaluation of contract manufacturers process capability

The process capability index C_{pp} is a reliable tool for determining whether a process meets capability requirements. In fact, using the C_{pp} index to evaluate the process capabilities of suppliers or contract manufacturers and help practitioners to select the best supplier or contract manufacturers is feasible. Importantly, C_{pp} is easy to apply and includes more process information than other process indices, for example process inaccuracy and process impression. If a company lacks its own facilities for producing particular components, then it must outsource the manufacturing of these components. Apparently, contract manufacturers are very closely linked to the company and outsourcing management is very important for practitioners, because process yield is closely correlated with the process quality level of the outsourcing manufacturer. Thus, objectively evaluating and selecting a suitable contract manufacturer is essential. Furthermore, C_{pp} can provide additional process information, thus helping better understand the process situation of contract manufacturers and facilitating mutual cooperation to improve quality performance. Chou [16] developed a procedure using estimators of C_p, C_{pu}, and C_{pl} to assess whether or not two processes are equally capable. In real-world applications, more than two candidates can be selected. Furthermore, C_p is independent of the target value with bilateral specifications and fails to measure the process yield. This study used C_{pp} to determine the score index R_i for evaluating the process performance of individual contract manufacturers. This approach can be used to evaluate more than two contract manufacturers and make more accurate selection decisions. Furthermore, the subindices C_{ia} and C_{ip} can be used to understand process inaccuracy and impression of contract manufacturers, respectively, because possible contract manufacturers will become our strategic alliance in the future.

Suppose that some components need to be outsourced to contract manufacturers for manufacturing and the evaluation and selection involves h candidates. Since direct observation of the entire processes is impossible, products must be sampled from contract manufacturers and the sample data used to select the contract manufacturers capable of providing better product quality. Let $X_{i1}, X_{i2}, \ldots, X_{in}$, $i = 1, 2, \ldots, h$, be h sets of random samples of size n from each contract manufacturer. Moreover, each product of the contract manufacturers has the same product specification and target value.

Each process capability of the contract manufacturers can be understood based on each value in index $\hat{C}_{pp}$, but we cannot make a conclusion on which contract manufacturer is better. Because sampling error can lead to inappropriate decisions if we just look at the index value calculated from the sample data. To avoid inappropriate decisions, the confidence interval approach is used here to enhance reliability. From the previous section, the confidence intervals of indices C_{ppi} and C_{ppj} are $[CL_i, CU_i]$ and $[CL_j, CU_j]$, respectively. Moreover, the confidence interval of the ith contract manufacturer is $[\hat{v}_i\hat{C}_{ppi}/\chi^2_{\alpha/2;\hat{v}_i}, \hat{v}\hat{C}_{ppi}/\chi^2_{1-\alpha/2;\hat{v}_i}]$, where α denotes the producer risk, $\chi^2_{(p,k)}$ represents the upper p percentage point of χ^2 distribution with k degrees of freedom and $\hat{v}_i$ is the maximum likelihood estimator (*MLE*) of v_i. Statistically, the comparison of these two indices can be represented as:

1. If $[CL_i, CU_i] \cap [CL_j, CU_j] \neq \phi$, then $C_{ppi} = C_{ppj}$. In other words, the process capabilities of contract manufacturers i and j are equivalent.
2. If $CL_j > CU_i$, then $C_{ppi} < C_{ppj}$. In other words, the process capabilities of contract manufacturer i are better than those of contract manufacturer j.
3. If $CU_j < CL_i$, then concluded that $C_{ppj} < C_{ppi}$. In other words, the process capabilities of contract manufacturer j are better than those of contract manufacturer i.

Nevertheless, the comparison is rather vague and indeterminate in rule one. In this rule, the indices are concluded to be equal regardless of the intersection size. For instance:

Illustration A: when $[CL_i, CU_i] = [0.5, 1]$ and $[CL_j, CU_j] = [0.9, 1.5]$ then $[CL_i, CU_i] \cap [CL_j, CU_j] = [0.9, 1]$. According to rule one, we concluded that $C_{ppi} = C_{ppj}$. Similarly, given $[CL_k, CU_k] = [0.7, 1.2]$ then $[CL_i, CU_i] \cap [CL_k, CU_k] = [0.7, 1]$, we concluded that $C_{ppi} = C_{ppk}$. Obviously, regardless of the intersection size, the conclusion in the above context will be the same. The grade of index C_{pp} (for i, j and k) cannot be distinguished based on rule one.

Illustration B: when $[CL_i, CU_i] = [0.5, 1]$ and $[CL_j, CU_j] = [0.9, 1.5]$ then $[CL_i, CU_i] \cap [CL_j, CU_j] = [0.9, 1]$. According to rule one, we concluded that $C_{ppi} = C_{ppj}$. Similarly, given $[CL_r, CU_r] = [1.1, 1.8]$ then $[CL_i, CU_i] \cap [CL_r, CU_r] = \phi$ and $CL_r > CU_i$, we concluded that $C_{ppi} < C_{ppr}$. However, given $[CL_j, CU_j] \cap [CL_r, CU_r] = [1.1, 1.5]$, we concluded that $C_{ppi} = C_{ppr}$. Apparently, the above conclusions are incompatible.

To avoid the ambiguous situations like illustrations A and B, we propose using score index R_i to evaluate the process performance of each contract manufacturer. R_i is expressed as follows:

$$R_i = 1 - \frac{m_i - m}{l + l_i},$$

where, $m_i = (CL_i + CU_i)/2$, $i = 1, 2, \ldots, h$, $l_i = (CU_i - CL_i)/2$, and $m = \min\{m_1, m_2, \ldots, m_h\}$. If the jth contract manufacturer has a minimum value of all m_i, then let $m = m_j$, $l = (CU_j - CL_j)/2$. Restated, l_i denotes the half length of the confidence interval for contract manufacturer i and l represents the half length of the confidence interval for the contract manufacturer with the lowest confidence interval centering value among all the contract manufacturers. Table 2 summarizes the average, standard deviation, estimator $\hat{C}_{pp}$ and score index R_i.

From the score index R_i, the following information can be obtained:

1. When $R_i = 1$, then $m_i = m$. Contract manufacturer i has the lowest value of m_i among all contract manufacturers, indicating that the process performance of contract manufacturer i is better than other contractors. Clearly, in terms of process capability, we can conclude that contract manufacturer i is the best and that products should be outsourced to this contract manufacturer.
2. When $R_i < 1$, then $m_i > m$. The m_i value of contract manufacturer i is not the lowest among all the contract manufacturers. Restated, some contract manufacturers definitely have better process performance than contract manufacturer i, and thus we can conclude that contract manufacturer i is not the best outsourcing manufacturer in terms of process capability.
3. The score index R_i can be used to set priorities for a number of contract manufacturers. The smaller the index R_i is, the less capable the process would be. The score index R_i can be calculated for all h contract manufacturers. If the R_j value of the jth contract manufacturer is one ($R_j = 1$), then the process performance of that contract manufacturer is better than other contract manufacturers. Furthermore, if the R_i value of the ith contract manufacturer is negative ($R_i < 0$), then the lower confidence limit of the ith contract manufacturer is larger than the upper confidence limit of the jth contract manufacturer ($CL_i > CU_j$). The confidence intervals of two contract manufacturers are completely disjoint and their intersection is empty. Restated, the process performance of contract manufacturer i is significantly worse than that of other contract manufacturers, and there is no need to waste further time in considering this contract manufacturer.

Evaluating a group of contract manufacturers and selecting one or more as contract manufacturers is a complex task. Besides quality, numerous other factors must also be considered, such as cost, delivery, goodwill, service, conformity and so on. This study suggests that practitioners should use R_i to sort the contract manufacturers in terms of quality, and then distinguish some contract manufacturers whose process capabilities meet our quality criteria. Secondly, cost, delivery, goodwill and other factors can be considered to select the better contract manufacturers for outsourcing from other candidates. For instance, the index R_i of 0.5 can be set as a minimum standard (critical value), and candidates with R_i below 0.5 can then be eliminated. This approach simplifies the task of contract manufacturer evaluation and also makes decision-making more reliable. Figure 1 displays the process of simplifying the task of contract manufacturer evaluation. In fact, using the score index R_i to assess contract manufacturers is more reliable than other approaches and avoids problems of the sort demonstrated in illustrations A and B.

The complete procedure using score index R_i to rank contract manufacturers is summarized as follows:

STEP 1 Determine the sample size n_i for each contract manufacturer process and determine the α-risk (normally set to 0.05).

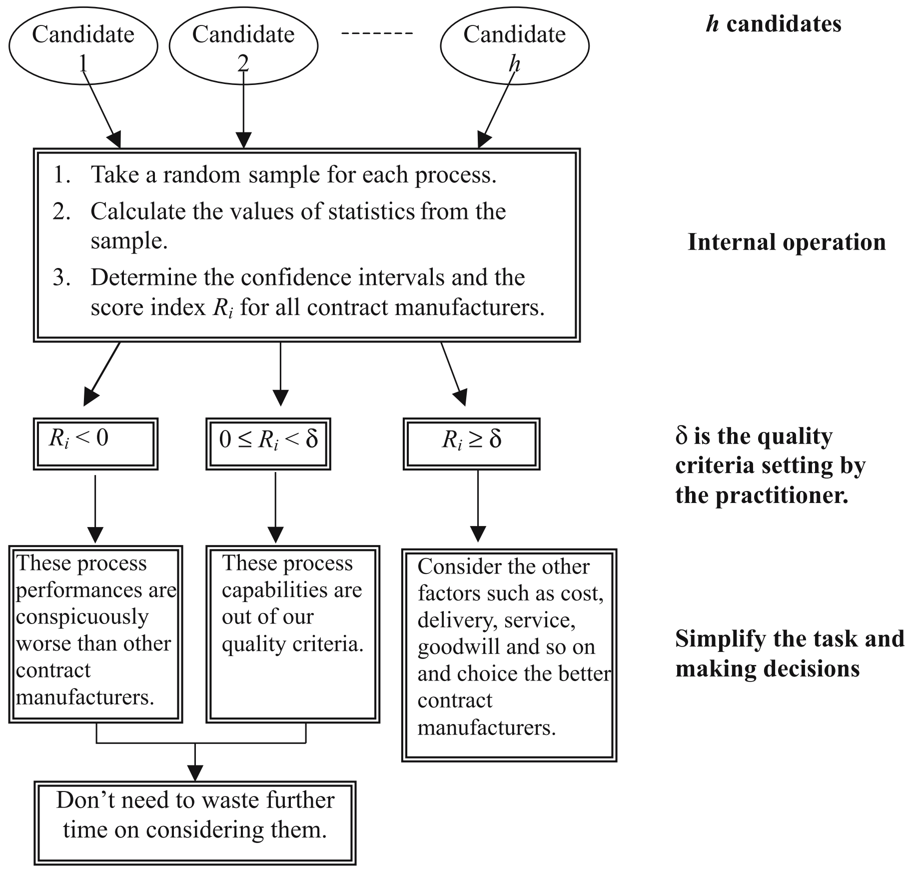
STEP 2 Take a random sample for each process and calculate the values $\overline{X}_i$, S_i, $\hat{v}_i$ and the estimator $\hat{C}_{pp}$ from the sample, for $i = 1, 2, \ldots, h$.

STEP 3 Calculate the values of confidence interval CL_i, CU_i, m_i and l_i for all contract manufacturers. Set $m = \min\{m_1, m_2, \ldots, m_h\}$ and calculate $l = (CU_j - CL_j)/2$ if the jth contract manufacturer have the minimum value of all m_i. Then, use m_i, l_i, m and l to determine the score index R_i for all contract manufacturers.

Table 2. Sample data mean, variance, estimator $\hat{C}_{pp}$ and score index R_i

Sample	Average	Standard deviation	Estimator	R_i
$X_{11}, \ldots, X_{1n_1}$	$\overline{X}_1 = \frac{\Sigma_{j=1}^{n_1} X_{1j}}{n_1}$	$S_1 = \sqrt{\frac{\Sigma_{j=1}^{n_1}(X_{1j}-\overline{X}_1)^2}{n_1}}$	$\hat{C}_{pp1} = \left(\frac{\overline{X}_1 - T}{D}\right)^2 + \left(\frac{S_1}{D}\right)^2$	$R_1 = 1 - \frac{m_1 - m}{l + l_1}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$X_{i1}, \ldots, X_{in_i}$	$\overline{X}_i = \frac{\Sigma_{j=1}^{n_i} X_{ij}}{n_i}$	$S_i = \sqrt{\frac{\Sigma_{j=1}^{n_i}(X_{ij}-\overline{X}_i)^2}{n_i}}$	$\hat{C}_{ppi} = \left(\frac{\overline{X}_i - T}{D}\right)^2 + \left(\frac{S_i}{D}\right)^2$	$R_i = 1 - \frac{m_i - m}{l + l_i}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$X_{h1}, \ldots, X_{hn_h}$	$\overline{X}_h = \frac{\Sigma_{j=1}^{n_h} X_{hj}}{n_h}$	$S_h = \sqrt{\frac{\Sigma_{j=1}^{n_h}(X_{hj}-\overline{X}_h)^2}{n_h}}$	$\hat{C}_{pph} = \left(\frac{\overline{X}_h - T}{D}\right)^2 + \left(\frac{S_h}{D}\right)^2$	$R_h = 1 - \frac{m_h - m}{l + l_h}$

Fig. 1. The process of simplifying the task of contract manufacturer evaluation



STEP 4 Setting the priorities for all contract manufacturers based on the value of R_i. Process capability decreases with R_i. Moreover, if $R_j = 1$ then the jth contract manufacturer is the best in terms of quality performance, while if $R_i < 0$ then the process performance of contract manufacturer i is conspicuously worse than other contract manufacturers and there is no need to waste further time on considering this contract manufacturer. Choices regarding contract manufacturers for outsourcing can then be made based on the priorities of contract manufacturers with a non-negative R_i index value, as well as cost, delivery, service, goodwill, conformity and so on.

4 Application for selecting better contract manufacturers

The TFT-LCD industry is another new leading industry after semiconductors. TFT-LCD is a flat, lightweight, low radiation appliance with lower electricity consumption than traditional monitors, and thus it is considered superior to CRT. In addition, TFT-LCD is increasing in size and therefore gradually replacing CRT. Notably, the TFT-LCD industry is capital and technology intensive and has a short sales cycle. The product must be assembled from many different parts. Therefore, vendors must respond quickly to changing market demand as well as providing good production technology, high quality yield and timely delivery to fulfill the needs of manufacturers.

Here, the contract manufacturer evaluation procedure described above is applied to a TFT-LCD manufacturer. The subject firm outsources the manufacturing of most of the parts required to build its TFT-LCD display to contract manufacturers. Thus the first step to ensuring product quality is to evaluate and choose a good contract manufacturer whose process quality level is superior. Backlight module is a key component of TFT-LCD display, since the TFT-LCD panel does not emit light by itself and requires a light source. Consequently, the backlight module is a crucial optical component in TFT-LCD displays called the "sun in the TFT-LCD panel."

Backlight module is composed of light guide panel, diffuser, reflection panel and illuminant. The manufacturing process of the backlight module is illustrated in Fig. 2. Notably, the major quality characteristics of backlight module include length, width, thickness, and brightness. Each of these quality characteristics has their own specification limits. Among these characteristics, width is crucial to subsequent assembly by the manufacturer. If component width deviates from the specifications, then final product assembly becomes very difficult.

Outsourcing the backlight module manufacturing to a contract manufacturer is the firm's policy. Considering the width of the backlight module, the specification limits are 294.95 ±

Fig. 2. The manufacturing process of the backlight module

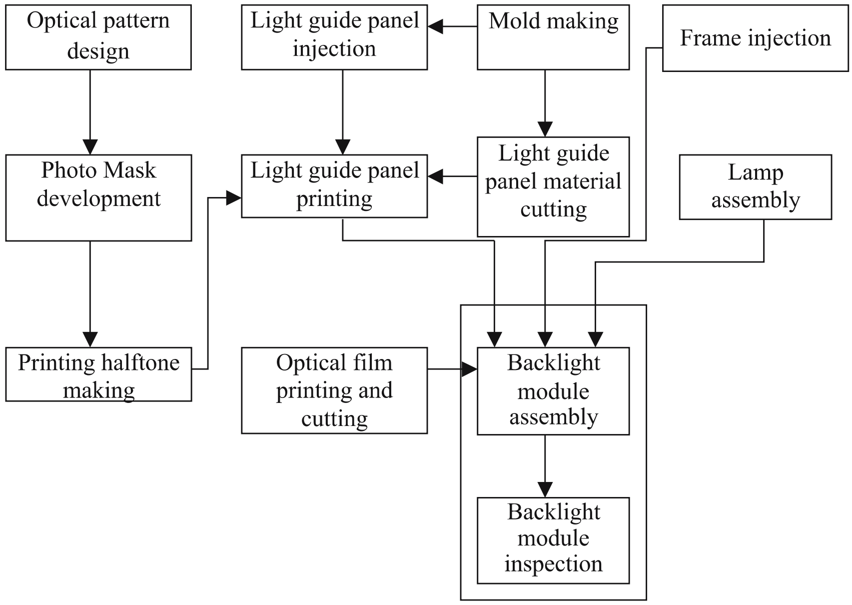


Table 3. The value $\overline{X}_i$, S_i, $\hat{v}_i$ and $\hat{C}_{pp}$ for five contract manufacturers

Contract manufacturers	A	B	C	D	E
$\overline{X}_i$	294.92	294.95	294.95	294.92	294.94
S_i	0.098	0.069	0.060	0.070	0.056
$\hat{v}_i$	50.54	50.00	50.001	50.80	50.06
$\hat{C}_{ppi}$	2.42	1.07	0.81	1.25	0.74

Table 4. The confidence interval and the score index R_i for five contract manufactureres

Contract manufacturers	A	B	C	D	E
CU_i	3.734	1.653	1.256	1.929	1.136
CL_i	1.699	0.749	0.569	0.880	0.515
m_i	2.717	1.201	0.913	1.405	0.826
l_i	1.017	0.452	0.344	0.525	0.311
R_i	-0.4236	0.5084	0.8672	0.3073	1.0000
Priority	5	3	2	4	1

0.2 mm, that is, the upper and lower specification limits are set to $USL = 295.15$ and $LSL = 294.75$, and the target value is set to $T = 294.95$. Apparently, this process is the nominal-the-best type. The process capability of contract manufacturers must be able to meet this quality level because of insoluble assembly problems if the backlight module width fails to fall within the tolerance (LSL, USL). The TFT-LCD producer considered here wants to re-evaluate their contract manufacturers. Five candidate contract manufacturers exist, two of which are old contract manufacturers that had previously cooperated and three of which are new. Moreover, 50 random samples are taken from the five candidates and the incapability index and score index R_i are used as measures to compare process capability. The full procedure used to assess the five candidates is as follows:

STEP 1 Determine the sample size $n_i = 50$, $i = 1, 2, 3, 4, 5$ for each contract manufacturers process as well as the α-risk (generally set to 0.05).

STEP 2 Take a random sample from each process and calculate the values $\overline{X}_i$, S_i, $\hat{v}_i$ and the estimator $\hat{C}_{pp}$ from the sample, for $i = 1, 2, 3, 4, 5$. Table 3 displays the values $\overline{X}_i$, S_i, $\hat{v}_i$ and $\hat{C}_{pp}$.

STEP 3 From Table 3, determine the confidence intervals CL_i, CU_i m_i and l_i for all five contract manufacturers. Moreover, set $m = \min\{m_1, m_2, \ldots, m_h\}$ and calculate $l = (CU_j - CL_j)/2$ if the jth contract manufacturer have the minimum value of all m_i. From the data, $m = 0.826$, $l = 0.311$. The m_i, l_i, m and l can then be used to determine the score index R_i. Table 4 lists the confidence interval, and the values of m_i, l_i and score index R_i.

STEP 4 From Table 4, we can understand the priorities for these five contract manufacturers. Since $R_E = 1$, contract manufacturer E has the best quality performance, making it the best choice in terms of quality. Moreover, contract manufacturer A can be set aside immediately because the value of R_A is negative. The negative R_A reveals that the process performance of contract manufacturer A is significantly lower than that of other contract manufacturers and there is no need to waste further time in considering this contract manufacturer. Notably, the manufacturer set the quality criteria at $R_i = 0.5$, meaning that quality performances of contract manufacturers E, C, B are satisfactory. While the quality performance of contract manufacturer E is better than other candidates, the outsourcing price of contract manufacturer E is also more expensive than the others. Besides quality, the second consideration of the manufacturer in evaluating contract manufacturers is cost. Outsourcing the parts or components for manufacturing to the contract manufacturer E involves the higher cost. Oppositely, not only the quality of contract manufacturer C satisfies the quality criteria, but also the outsourcing price of him is cheaper than contract manufacturer E. Furthermore, the outsourcing prices are not greatly different between the contract manufacturer B and C and according the index R_i, the quality performance of contract manufacturer C is better than contract manufacturer B. Thus, contract manufacturer C is selected for outsourcing in this example. Obviously, adopting the above procedure to assess contract manufacturers can facilitate managers in making reliable decisions.

5 Conclusions

Process capability indices provide single-number assessments of ability to meet the quality requirements preset by product designers, and are widely used in manufacturing. Among process capability indices the C_{pp} index developed by Greenwich and Jahr-Schaffrath [17] can not only evaluate the process capability, but also can easily distinguish different degrees of process inaccuracy and the process imprecision and provide additional process information. This study applies the C_{pp} index to determine the score index R_i and apply it to assess the process performance of contract manufacturers. Evaluating and selecting suitable contract manufacturers is a crucial task in supply chain management. The quality of parts and components that are outsourced to contract manufacturers is closely related to final product quality, and thus influences customer satisfaction and loyalty. The procedure presented here provides an easy and convenient tool for practitioners to use for assessing contract manufacturer quality performance. The proposed procedure can rank contract manufacturers in terms of quality, distinguish contract manufacturers whose process capabilities fail to meet the required quality criteria, simplify complex evaluation tasks and increase the reliability of decisions regarding contract manufacturers. Of course, the procedure is efficient and reliable, and hence its adoption by manufacturers should be encouraged.

References

1. Lee H, Billington C (1992) Managing supply chain inventory: pitfalls and opportunities. Sloan Manage Rev 33(3):65–73
2. De Kok TG (2000) Capacity allocation and outsourcing in a process industry. Int J Prod Econ 68:229–239
3. Lee H, Tang CS (1998) Managing supply chains with contract manufacturing, in global supply chain and technology management. In: Lee HL, Ng SM (eds) Production and operations management society, pp 141–151
4. Kim B, Leung JMY, Park KT, Zhang G, Lee S (2002) Configuring a manufacturing firm's supply network with multiple suppliers. IIE Trans 34:663–677
5. Dickson GW (1966) An analysis of vendor selection systems and decisions. J Purch 2(1):5–17
6. Weber CA, Current JR, Benton WC (1991) Vendor selection criteria and methods. Eur J Oper Res 50:2–18
7. Pearson JN, Ellram LM (1995) Supplier selection and evaluation in small versus large electronics firms. J Small Bus Manage 33(4):53–65
8. The Outsourcing Institute Membership (2003) Survey of current and potential outsourcing end-users, http://www.outsourcing.com
9. Kane VE (1986) Process capability indices. J Qual Technol 18(1): 41–52
10. Chan LK, Cheng SW, Spiring FA (1988) A new measure of process capability: C_{pm}. J Qual Technol 20:162–175
11. Choi BC, Owen DB (1990) A Study of a new Capability index. Commun Stat Theory Methods 19:1231–1245
12. Boyles RA (1991) The Taguchi capability index. J Qual Technol 23: 17–26
13. Pearn WL, Kotz S, Johnson NL (1992) Distributional and inferential properties of process capability indices. J Qual Technol 24:216–231
14. Boyles RA (1994) Process capability with asymmetric tolerances. Commun Stat Simul Comput 23:615–643
15. Chen KS (1997) Incapability index with asymmetric tolerances. Stat Sin 8(1):253–262
16. Chou YM (1994) Selecting a better supplier by testing process capability indices. Qual Eng 6(3):427–438
17. Greenwich M, Jahr-Schaffrath BL (1995) A process incapability index. Int J Qual Reliab Manage 12:58–71
18. Kotz S, Johnson NL (2002) Process capability indices–a review, 1992–2000. J Qual Technol 34(1):2–34
19. Chen KS (1998) Estimation of the process incapability index. Commun Stat Theory Methods 27(4):1263–1274
20. Pearn WL, Chen KL, Chen KS (2002) A practical implementation of the incapability index C_{pp}. Int J Ind Eng 9(4):372–383
21. Huang ML, Chen KS, Li RK (2002) Process capability evaluation for a PVC pipe product family. Asian J Qual, in press