Int J Adv Manuf Technol (2005) 27: 345–350
DOI 10.1007/s00170-004-2173-9

ORIGINAL ARTICLE

Feng-Tsung Cheng · Kuen-Suan Chen · Wen-Pei Sung

Evaluation model for the performance of multi-manufacturing time schedule

Received: 28 October 2003 / Accepted: 5 March 2004 / Published online: 2 February 2005

Abstract The research of Dickson [1] and Weber et al. [2] about the performance evaluation of suppliers pointed out that quality and delivery are two important assessable items. Chen and Yung [3] indicated that the significance of delivery would only increase in the future. Obviously, customers value quality and delivery. Therefore, a superior quality of product and rapid manufacturing process are the major factors in obtaining orders. Much research has been carried out on quality assurance, but the research on delivery is rare. Thus, this paper uses the manufacturing process of optical glass as an example to propose a performance index for a manufacturing time schedule and related a suite of objective evaluation models used. This evaluation method is very convenient and efficient for management to monitor the multi-manufacturing performance of each stage of a manufacturing process for deliveries of high quality.

Keywords Multi-process time schedule analysis chart · Objective evaluation model · Performance index of manufacturing time schedule · Quality and delivery · Tolerance interval of manufacturing time schedule

1 Introduction

In Taiwan, the applications of optical glasses are becoming widespread in products such as: cameras, scanners, fax machines, Photostat and overhead projectors, which all need to use high precision optical glass. The fabrication of optical glass has shifted from small quantity production to mass production, and is usually for product glass of the "build to order" (BTO) type. A condition is that the demand for optical glass is generally unstable, and as there are close to one hundred types of optical glass, the quantities of products are hard to estimate.

Chen et al. [4] pointed out that "faster and better" is a developing tendency of modern manufacturing industry. The quality requirement of an optical glass manufacturer has been raised in accordance with the development of information technology. The precision requirements of optical glasses are incessant, which encourages manufacturers to give consideration to the demands of quality and speed. The manufacturing time for optical glass must be effectively shortened to meet customer requirements. The manufacturing time schedule and quality of optical glass for a batch of an order must be controlled carefully to truly promote the competitive predominance at each stage of a received order: disconnection, weigh, grind, extrusion molding, thermal treatment and inspection.

Quality, cost and delivery are three important factors for a manufacturing schedule. Dickson [1] collected and analyzed more than 50 papers, concerned with the performance evaluation of suppliers, to produce 23 performance evaluation items for a supplier. Quality and delivery are the two most important features demanded by suppliers. Weber et al. [2] used Dickson's research results for reference and also concluded the extreme importance of quality and the considerable importance of delivery. Obviously, customers value quality and delivery; thus, quality and delivery are the major factors in obtaining orders. Chen and Yung [3] pointed out that numerous research focused on the evaluation methods of quality performance such as process yield, loss function and index of process capability that are investigated in many references. Simultaneously, many statistical experts and quality engineers presented research in this field, found in Kane [5], Chan et al. [6], Boyles [7, 8], Pearn et al. [9], Chen [10], Vännman and Delery [11], Chen and Pearn [12], and Chen et al. [13, 14]. There have been many studies that focus on evaluation methods for quality per-

F.-T. Cheng
Department of Industrial Engineering,
Feng Chia University,
Taichung, Taiwan 407, R.O.C.

K.-S. Chen
Department of Industrial Engineering and Management,
National Chin-Yi Institute of Technology,
Taichung, Taiwan 411, R.O.C.

W.-P. Sung (✉)
Department of Landscape Design and Management,
National Chin-Yi Institute of Technology,
Taichung, Taiwan 411, R.O.C.
E-mail: sung809@chinyi.ncit.edu.tw
Fax: +886-4-23930737

formance. This research that evaluates the quality was already very mature, whereas few papers were concerned with delivery. Chen and Yung [3] conferred on the delivery performance of a supplier from the standpoint of a customer. Chen et al. [4] proposed an analytical chart of the delivery performance of a supplier. Suppliers invest heavily to achieve a high delivery performance, for example in manpower and machinery equipment. Sometimes, when a supplier receives only a few orders, they can be delivered on time, although the manufacturing efficiency of the supplier is not good. Customers are concerned with delivery on schedule regardless of the supplier's problems. Both manufacturing quality and efficiency should be improved to improve the delivery performance of the supplier. It ought not to put on an additional shift or put more resources into production to maintain delivery performance. On the other hand, Pearn and Chen [15] indicate that the quality has something to do with the manufacturing time schedule. For example, when required quality condition as the capability, the scope of its manufacturing time schedule inside this quality requirement for conforming to the standard request, as shown in Fig. 1. But quality after promoting to go to certain degree, if the qualities want to promoted, it will need the very big price in cost.

The essentinal cost is established in the fix cost plus the fluctuation cost to develop the manufacturing time. Manufacturing time is longer when the cost is higher. Therefore, the cost is related to the manufacturing time schedule. Although the manufacturing time schedule is quicker and can spare cost, it affects the quality. Therefore, according to the above-mentioned reasons, the required quality and reasonable cost are considered in the scope of this research to make the manufacturing time schedule of various manufacturing procedure in the optimum state. This paper uses the manufacturing process of optical glass as an example to propose a performance index for a manufacturing time schedule and an associated suite of objective evaluation models. This evaluation method is convenient and efficient for management to use to monitor the manufacturing performance of each stage of the manufacturing process, and to achieve fine delivery performance under the good quality requirement.

2 Procedures analysis of optical glass manufacturing

There are several processing steps in each manufacturing procedure. Usually, the operator will shorten the required timing of each manufacturing step to reach the condition of required quality. However, the fundamental production timing that the step usually needs to be certain, can make the quality of the product reach the standard request. Therefore, the length of the whole manufacturing time schedule is affected by the efficiency of the manufacturing time schedule of each manufacturing step. Chen et al. [4] pointed out that when the manufacturing time schedule of each manufacturing procedure is too fast, it causes a loss because of the lower quality of the product or the increase of storage requirement. On the other hand, if the delivery to a customer is delayed, the supplier could be asked to pay a penalty and his reputation is affected to a certain degree. Therefore, the manufacturing time schedule is part of a nominal-the-better quality property with a bilateral specification. Assuming T represents the minimum expected schedule, and d is a tolerable error period. The tolerable interval of the manufacturing time schedule of each manufacturing procedure is $(T-d, T+d)$. A loss may result in the tolerable interval, but it is still acceptable. Once the specification is located outside of $T-d$ or $T+d$, it indicates that the manufacturing time schedule is too slow or too fast resulting in inducing the retardation of product delivery or the poor quality of a product, so manufacturers or customers may be subjected to considerable loss. Firstly, the standard schedule T should be established prior to developing a performance index for the manufacturing time schedule in accordance with the manufacturing procedure of optical glass. The manufacturing procedure of optical glass is shown in Fig. 2.

The raw material of a glass plate has to be passed through the stages of disconnection, grind and weight to meet the requirements of an order. The step of extrusion molding produces the glass to the requested shape, which is followed by a thermal treatment. This operation takes from 30 hours to 300 hours that is determined by the material property and the ratio of inflection. Finally, the product must pass an examination by ultraviolet rays to test for poor products, and then packing and delivery for loss.

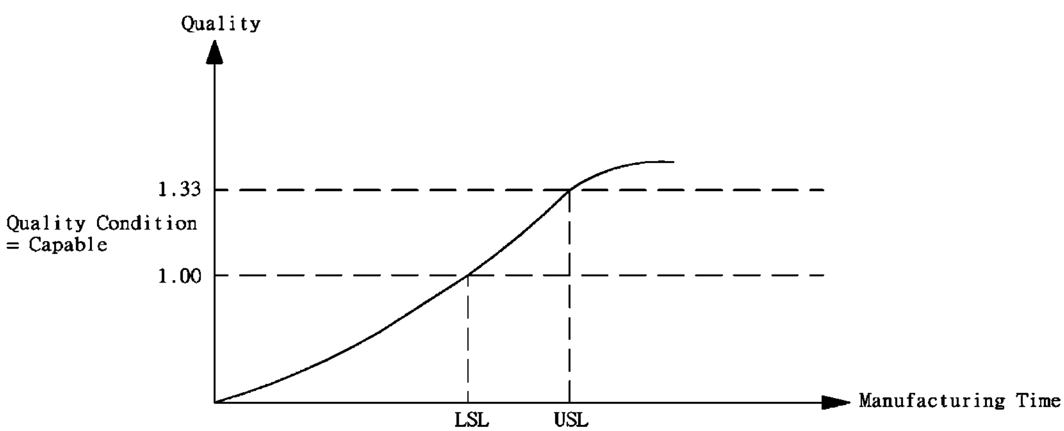

Fig. 1. Relation between process quality and manufacturing time

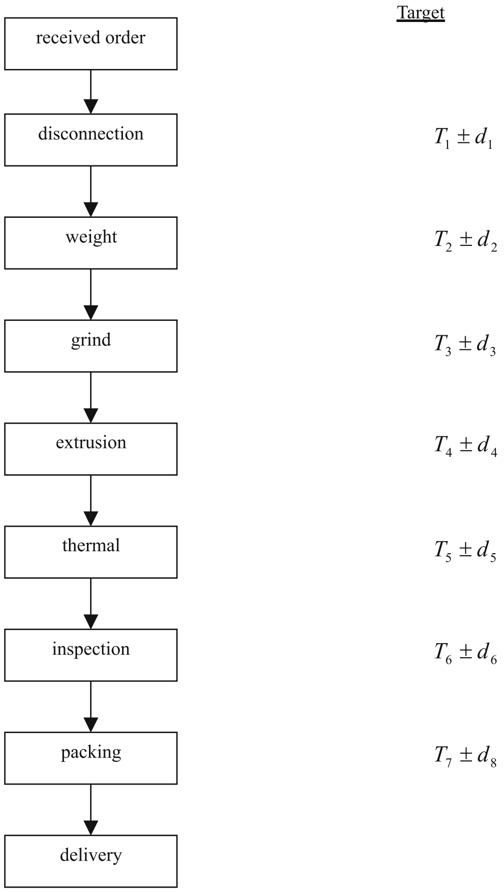

Fig. 2. The analysis chart of manufacturing procedure of optical glass

There are numerous factors that can affect the manufacturing time schedule of optical glass. Furthermore, the complexity of each manufacturing procedure is different; thus, the processing time varies. After analyzing the whole procedure of manufacturing optical glass, an analytical chart of the manufacturing flow path is drawn and on it is listed some important influencing factors of processing rate. These factors are (a) quantity, (b) material property and, (c) weight.

If the manufacturing efficacy is too slow, it will seriously affect the delivery. But, if the manufacturing efficacy is too fast, it will affect the quality of the product. Therefore, each processing manufacturing step should be reviewed and ascribed a reasonable manufacturing time schedule T_i, which is a function of these three main factors. If a, b, and c are the quantity, material property, and weight, respectively, then T_i can be defined as follows:

$$T_i = f_i(a, b, c), \quad i = 1, 2, \ldots, 7 \tag{1}$$

The time to finish its work is T, in accordance with the flow path.

$$T = \sum_{i=1}^{7} T_i \tag{2}$$

The reasonable manufacturing time schedule for each processing procedure can be easily calculated by summing the times of each step. The performance index of a manufacturing time schedule evaluates the performance of each processing manufacturing step to see if it meets the standard requirement or not. If the performance of each processing manufacturing procedure meets the demand, then it must be decided how much manpower and time is needed for delivery. If some of the performances in the manufacturing procedure do not meet the requirements, the procedure should be improved to shorten the manufacturing time schedule and increase the competitiveness.

3 Performance index of manufacturing time schedule

Making manufacturing time schedules of each manufacturing procedure can meet the request. Therefore, according to the definition of lower specific limit (LSL) and upper specific limit (USL) on Fig. 1, the manufacturing time schedule of each manufacturing procedure can be defined as follows. Assuming X_i is the actual processing time of the ith processing manufacturing procedure, the complexity of each manufacturing flow path is different, thus a demand of tolerable interval (LSL_i, USL_i) of manufacturing time schedule is obtainable. Where $LSL_i = T_i - d_i$ and $USL_i = T_i + d_i$. In order to conveniently evaluate the performance of the manufacturing time schedule, let a random variable $Y_i = (X_i - T_i)/d_i$ be a conversion value of the manufacturing time schedule. The tolerable interval of manufacturing time schedule of each process in the manufacturing procedure can be converted to (LSL_i, USL_i)=(-1,1). Similarly, the minimum target schedule, inducing loss, can be converted to $T_i = 0$, and the tolerable error schedule can be converted to $d_i = 1$. Table 1 shows a comparison table of X_i and Y_i before and after transformation, using four processing steps as an example.

As shown in Table 1, where $Y_1 = 1.25 > 1.00$, indicates that the manufacturing efficiency is too slow: delivery can be seriously affected. Manpower and work overtime need to be introduced to catch up with production scheduled progress. The manufacturing process of this procedure should be reviewed and modified. $Y_2 = -1.00$, indicates that the manufacturing efficiency is too high so the quality of product might be affected. The manufacturing process of this procedure should be reviewed. If this manufacturing process does not affect the quality of product, it shows that the manufacturing capability of this workstation can be increased. This workstation is not only satisfactory, but can attract premium wages. Both Y_3 and Y_4 approach 0, which reveals that the average manufacturing time schedule is

Table 1. A comparison table of X_i and Y_i before and after transformation for using four processing steps as example

Processing steps	T_i	d_i	LSL_i	USL_i	X_i	Y_i
1	40	4	36	44	45	1.25
2	45	2	43	47	43	−1.00
3	60	10	50	70	59	−0.10
4	85	5	80	90	86	0.20

satisfactory and can produce the required quality of the product and the delivery. The efficiency of the manufacturing time schedule of each workstation can be examined in accordance with the value of Y_i, which can be consulted for evaluation and improvement of the manufacturing time schedule.

Pearn et al. [9] proposed an index to reflect process yield and loss in a manufacturing process. This index is modified and a new index is improved to evaluate the performance of a manufacturing time schedule based on the above-mentioned concepts. The index for the performance of a manufacturing time schedule is defined as follows:

$$MTI_i = \frac{1-|\mu_{Y_i}|}{\sqrt{\sigma_{Y_i}^2+\mu_{Y_i}^2}}\,, \tag{3}$$

where μ_{Y_i} and σ_{Y_i} are the mean value and standard deviation, respectively.

When $MTI_i \geq c$, then

$$\begin{aligned}
&\frac{1-|\mu_{Y_i}|}{\sqrt{\sigma_{Y_i}^2+\mu_{Y_i}^2}} \geq c\\
\Rightarrow\quad & 1-|\mu_{Y_i}| \geq c\sqrt{\sigma_{Y_i}^2+\mu_{Y_i}^2} \geq c|\mu_{Y_i}|\\
\Rightarrow\quad & (1+c)|\mu_{Y_i}| \leq 1\\
\Rightarrow\quad & |\mu_{Y_i}| \leq 1/(1+c)\,.
\end{aligned}$$

When the value of MTI_i becomes larger, the absolute value of μ_{Y_i} approaches 0. This indicates that the average manufacturing time schedule is well situated and meets both the quality of the product and delivery. Let p_i be the ratio of finished work in the tolerable interval $(LSL_i,\ USL_i)$ of the actual processing time of the ith processing procedure, then

$$\begin{aligned}
p_i &= P\,(LSL_i \leq X_i \leq USL_i)\\
&= P\,(-1 \leq Y_i \leq 1)\\
&= P\left(\frac{-1-\mu_{Y_i}}{\sigma_{Y_i}} \leq Z \leq \frac{1-\mu_{Y_i}}{\sigma_{Y_i}}\right)\\
&= \Phi\left(\frac{1-\mu_{Y_i}}{\sigma_{Y_i}}\right) - \Phi\left(-\frac{1+\mu_{Y_i}}{\sigma_{Y_i}}\right)\\
&\geq 2\Phi\left(\frac{1-|\mu_{Y_i}|}{\sigma_{Y_i}}\right) - 1\\
&\geq 2\Phi\left(\frac{1-|\mu_{Y_i}|}{\sqrt{\sigma_{Y_i}^2+\mu_{Y_i}^2}}\right) - 1\\
&= 2\Phi(MTI_i) - 1\,,
\end{aligned} \tag{4}$$

where $\Phi(x)$ is a cumulative function of the standard normal distribution.

The larger the index of MTI_i, the higher is the ratio of finished work in the tolerable interval p_i. The relationship between the index value of MTI_i and the lower limit value of p_i is shown in Table 2.

Table 2. MTI_i and corresponding to the lower limit value of p_i

MTI_i	p_i	MTI_i	p_i	MTI_i	p_i	MTI_i	p_i
0.0	0.0000	1.0	0.6827	2.0	0.9545	3.0	0.9973
0.1	0.0797	1.1	0.7287	2.1	0.9643	3.1	0.9981
0.2	0.1585	1.2	0.7699	2.2	0.9722	3.2	0.9986
0.3	0.2358	1.3	0.8064	2.3	0.9786	3.3	0.9990
0.4	0.3108	1.4	0.8385	2.4	0.9836	3.4	0.9993
0.5	0.3829	1.5	0.8664	2.5	0.9876	3.5	0.9995
0.6	0.4515	1.6	0.8904	2.6	0.9907	3.6	0.9997
0.7	0.5161	1.7	0.9109	2.7	0.9931	3.7	0.9998
0.8	0.5763	1.8	0.9281	2.8	0.9949	3.8	0.9999
0.9	0.6319	1.9	0.9426	2.9	0.9963	3.9	0.9999

4 Analysis chart of the performance of multi-manufacturing time schedule

This research uses the methods of Vännman [11] and Chen et al. [4] for proposing an analysis chart for the performance evaluation of the manufacturing time schedule in order to accurately evaluate the performance of the manufacturing time schedule of each processing procedure. Firstly, the relationship between the index value of performance of manufacturing time schedule MTI_i and the ratio of finished work in the tolerable interval p_i should be considered when establishing the required value of performance index of the manufacturing time schedule in accordance with the staged target or working methods of the company. Table 3 illustrates different performance index values of manufacturing time schedule and the relevant job conditions and suggestions. The value of t_1 and t_2 involves industrial background, condition of competitors, manufacturer expectations, etc. to decide ($t_1 < t_2$).

μ_{Y_i} is the abscissa and σ_{Y_i} is the ordinate, and the contour lines of MTI_i are drawn. The position of μ_{Y_i} in the abscissa shows the speed of the manufacturing time schedule (shift degree) and the position of σ_{Y_i} in the ordinate reveals the stability degree of the manufacturing time schedule. The lower position of σ_{Y_i} indicates that the degree of stability is high. After the variable transformation of $Y_i = (X_i - T_i)/d_i$, the target value becomes 0 and the upper and lower limit specification converts to 1 and -1. In this figure, block black lines from top to bottom represent the contour lines of $MTI_i = t_1$ and $MTI_i = t_2$, respectively. The contour lines enclose three manufacturing time schedule performance blocks that form "the analysis chart of evaluation index of operation performance." The larger the area enclosed in the contour line says that the largest value of MTI_i is larger; it indicates that the manufacturing time schedule is more moderate than the ratios of finished work in the tolerable interval p_i. Hence, the performance coordinate of $(\mu_{Y_i}, \sigma_{Y_i})$ created by the average value and standard deviation of all the procedures of the manufacturing processes can be drawn on the analysis chart of multi-manufacturing time schedule performance. The condition of each manufacturing process can be easily and accurately understood from this figure to judge whether the manufacturing time schedule meets the demand or not. Unsatisfactory work-

Table 3. The required performance index value of manufacturing time schedule and suggestions

Performance block	Condition of the performance	The performance index value of manufacturing time schedule	Suggestions
I	Good	$MTI_i > t_2$	Reward
II	Fair	$t_1 \leq MTI_i \leq t_2$	Maintain/review
III	Poor	$MTI_i < t_1$	Improve/review

stations should be reviewed to improve the manufacturing time schedule performance.

5 Case study

In this section, an optical glass manufacturer is used as an example to illustrate the use of the analysis chart of multi-manufacturing time schedule performance. Many factors influence optical glass manufacturing. The required time of each process is different as a result of various complexities. The manufacturing flow path drawing is shown in Fig. 2. The main manufacturing procedure of optical glass can be classified as (1) disconnection, (2) grind, (3) weight, (4) extrusion molding, (5) thermal treatment, (6) inspection and (7) packing. The reasonable time for each manufacturing step T_i is the tolerable interval of the required manufacturing time schedule, listed in Table 4, in accordance with (a) quantity (b) material property and (c) weight. The average value μ_{X_i}, standard deviation σ_{X_i}, after transformation of average value μ_{Y_i} and standard deviation σ_{Y_i} of the actual process step are recorded quarterly in Table 4.

According to the above-mentioned information, the contour lines of μ_{Y_i} and σ_{Y_i} are drawn in Figs. 3 and 4.

According to the target of working mission and the conditions of competitors, the optical glass manufacturer concludes so that $t_1 = 3$ and $t_2 = 4$. The contour lines of $MTI = 3$ and $MTI = 4$ are dawn in the analysis chart of the optical glass manufacturing time schedule. The contour lines enclose three manufacturing time schedule performance blocks II, III, and I. Figure 3 is used to assess the performance of the manufacturing time schedule of the seven main processing steps of optical glass manufacturing. The manufacturing time schedule performance of these steps is as follows:

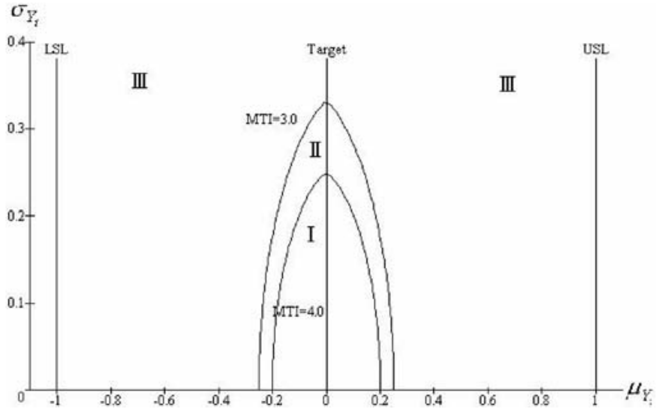

Fig. 3. The analysis chart of manufacturing time schedule capability

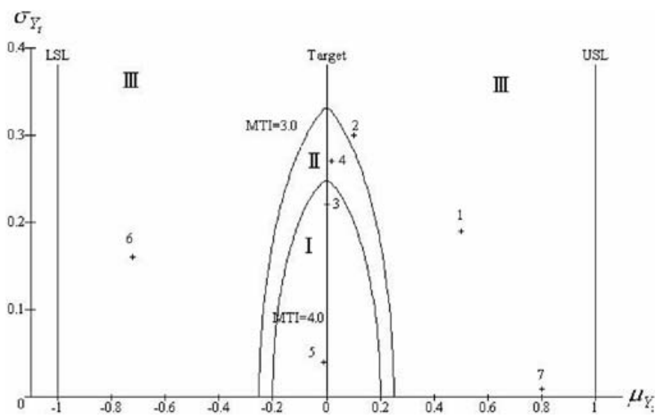

Fig. 4. The analysis chart of optical glass manufacturing time schedule

Step 1: The coordinate point is located outside the contour line of $MTI = 3$, and $\mu_{Y_1} = 0.50$. This indicates that the average manufacturing time schedule tends to be slow. The reasons should be found. The manufacturing time schedule $T = 0$ is used as an objective.

Step 2: The coordinate point is located outside the contour line of $MTI = 3$, the variation of manufacturing time sched-

Table 4. The recorded data for seven main process steps

Process Step	Flow path	T_i	LSL_i	USL_i	d_i	μ_{X_i}	σ_{X_i}	μ_{Y_i}	σ_{Y_i}
1	Disconnection	3	1.50	4.50	1.50	3.75	0.29	0.50	0.19
2	Grind	3	1.50	4.50	1.50	3.15	0.46	0.10	0.30
3	Weight	3	1.50	4.50	1.50	3.00	0.33	0.00	0.22
4	Extrusion molding	4	2.00	6.00	2.00	4.04	0.55	0.02	0.27
5	Thermal treatment	8	4.00	12.0	4.00	7.96	0.16	−0.01	0.04
6	Inspection	1	0.50	1.50	0.50	0.72	0.08	−0.72	0.16
7	Packing	1	0.50	1.50	0.50	1.40	0.05	0.80	0.01

ule $\sigma_{Y_2} = 0.30$ tends to be large. It reveals that the speed of manufacturing time schedule is unstable. The manufacturing process should be reviewed and improved immediately.

Step 3: The coordinate point is located inside the contour line of $MTI = 4$, and $\mu_{Y_3} = 0.0$ shows that the average manufacturing time schedule is very satisfactory. The rapid manufacturing time schedule achieves the required quality of production process, it represents that the performance of the manufacturing time schedule reaches the required specification. The manufacturing time schedule is equal to the target value T. It is a certificated process and should be maintained. The workers should be rewarded.

Step 4: The coordinate point is located between contour lines of $MTI = 3$ and $MTI = 4$, the average manufacturing time schedule is almost the same value as in Step 3. Although this step is a qualified process, the variation of this process is larger than in Step 3. Thus, it should be investigated and improved.

Step 5: The coordinate point is located inside the contour line of $MTI = 4$, and μ_{Y_5} is close to target value, which indicates that the average manufacturing time schedule is very rapid. This step is a certificated process. Figure 3 shows that the variation of this process is very small and the time of manufacturing process is nearly situated on $T = 0$. This shows that not only does the process capability meet the requirement but it also exceeds the requirement. So, a lower cost process to replace the current production process or specification for the available process should be considered and discussed.

Step 6: The situation of this step is located outside the contour line of $MTI = 3$. The manufacturing time schedule is much less than target value T. Although this step is a superior process, a new process should be found to lower the cost of the process.

Step 7: The condition of this step is analogous to Step 1. The coordinate point is located outside the contour line of $MTI_1 = 3$, and $\mu_{Y_i} = 0.80$ shows that the average manufacturing time schedule tends to be slow. Consequently, the reasons should be found and manufacturing time schedule $T = 0$ should be used as an improvable target.

A survey of the above-mentioned points shows Step 1, 2 and 7 need improvement. The manufacturing time schedule of Step 7 deviates from the target value and the variation of process is very large, which means that the management of this step has a problem. These processes may be a choke point of the whole process. Consider adding manpower, purchasing additional equipment, improving the schedule or adopting contract work to solve the defects. Although the performance of the manufacturing time schedule is fair, the deviation is large and should be improved. Figure 3 shows that the performance of Step 3 and 5 are satisfactory and the performance should be continuously maintained. The performance of Step 6 is very good, but resources such as labor or facilities should be examined to see if the cost could be reduced to improve the performance.

6 Conclusions

A performance index of a manufacturing time schedule proposed by this paper is a convenient and effective analytical tool for an optical glass manufacturer to objectively measure the quality and the delivery of the product. This paper uses Vännman's [11] and Chen et al. [4] method as basis to plot the coordinate that is generated by the actual average value of manufacturing time schedule and standard deviation on "the analysis chart of multi-manufacturing time schedule performance." Managements can judge and supervise the actual multi-manufacturing time schedule performance from this chart to achieve a high quality product. In addition, managements can immediately recognize the problems that may exist in a manufacturing process and use this information for improving the manufacturing process.

Acknowledgement This work has been supported by the National Science Council of Taiwan, R.O.C. through grant No. Nsc-92-2213-e-167-001. This support is gratefully acknowledged. The authors would also like to thank anonymous referees for their careful reading of the paper and several suggestions, which have helped to improve the paper.

References

1. Dickson GW (1966) An analysis of vendor selection systems and decisions. J Purchasing 2(1):5–17
2. Weber CA, Current JR, Benton WC (1991) Vendor selection criteria and methods. Eur J Oper Res 50:2–18
3. Chen KS, Yung HH (1999) Evaluate supplier delivery performance. J Chin Inst Ind Eng 16(6):681–688
4. Chen KS, Chen SC, Li RK (2002) Process capability analysis of capacitors. Int J Adv Manuf Technol 19:623–628
5. Kane VE (1986) Process capability indices. J Qual Technol 18(1): 41–52
6. Chan LK, Cheng SW, Spiring FA (1988) A new measure of process capability: C_{pm}. J Qual Technol 20:162–175
7. Boyles RA (1991) The Taguchi capability index. J Qual Technol 23(1):17–26
8. Boyles RA (1994) Process capability with asymmetric tolerances. J Tolerances Commun Stat Simul Comput 23(3):615–643
9. Pearn WL, Kotz S, Johnson KL (1992) Distribution and inferential properties of process capability indices. J Qual Technol 24:216–231
10. Chen KS (1998) Incapability index with asymmetric tolerances. Stat Sin 8:253–262
11. Vännman K, Delery M (1999) Process capability plots – a quality improvement tool. Qual Reliab Int 15:213–217
12. Chen KS, Pearn WL (2001) Capability indices for processes with asymmetric tolerance. J Chin Inst Eng 24(5):559–568
13. Chen KS, Huang ML, Li RK (2001) Process capability analysis for an entire product. Int J Prod Res 39(17):4077–4087
14. Chen KS, Sung WP, Tsai YY (2002) The evaluation for the performance of supplier. Int J Agile Manuf 5(1):9–15
15. Pearn WL, Chen KS (1997) A practical implementation of the process capability index C_{pk}. Qual Eng 7(2):721–737