Applied Product Capability Analysis Chart in Measure Step of Six Sigma

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Abstract. This paper will apply product capability analysis chart PCAC in Measure step of Six Sigma. Because the test model is sampling, sampling error must be consider. Thus minimum value will be used to evaluate process capability. Besides the paper used minimum value to evaluate process capability, we also applied the concept of Six Sigma in PCAC and construct PCAC of Six Sigma standard. Finally, PCAC of Six Sigma standard will apply in Six Sigma project of Offset Ratchet Wrenches which manufactured by Y company.

Key words: Six Sigma, process capability index, product capability analysis chart.

1. Introduction

In the 1980s and early 1990s, Motorola was one of many US and European corporations whose lunch (along with all other meals and snacks) was being eaten by Japanese competitors. Motorola's top leaders conceded that the quality of its products was awful. They were, to quote one Motorola Six Sigma veteran, "In a word of hurt." Like many companies at the time, Motorola didn't have one "quality" program, it had several. But in in 1987, a new approach came out of Motorola's Communications Sector – at the time headed by George Fisher, later top exec at Kodak. The innovative improvement concept was called "Six Sigma" (Pande et al., 2000). Six Sigma is named after the process that has six standard deviations on each side of the specification window. Such a process produces 3.4 defects per one million opportunities in the long term (Wyper and Harrison, 2000). Based on Tong et al. (2004), six sigma has been initiated using statistical tools and techniques in business, transactional, and manufacturing process.

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It has been proven to be successful in reducing costs, improving cycle times, eliminating defects, raising customer satisfaction, and significantly increasing profitability. In the first 5 years of Six Sigma implementation, Motorola achieved saving of $US 2.2 billion. Other companies followed, e.g. GE, ABB, Bombardier and Allied Signal. (Wyper and Harrison, 2000)

According to Roger (2001), the weeks correspond roughly to the Measure, Analyze, Improve, and Control (MAIC). (GE and others have added a "Define" phase at the beginning, to assure that the right projects are selected.) We will follow the improvement model is MAIC:

Measure: Gather data to establish the "current state," what is actually going on in the workplace with the process as it works today.
Analyze: Interpret the data to establish cause-and-effect relationships.
Improve: Develop solutions targeted at the confirmed causes.
Control: Implement procedures to make sure the improvements/gains can be sustained.

Because many companies of achievements of Six Sigma implementation are positive, we want to apply Six Sigma in process capability improvement. Based on Chen et al. (2001), the process capability indices (PCIs) can be viewed as an effective and excellent means of measuring product quality and performance. Thus, we want to use PCIs to measure process capability in Measure step of Six Sigma. But Huang et al. (2002) indicated that a product usually hold many quality characteristics. For example, the key quality characteristics of a backlight module include: (1) length, (2) width, (3) thickness, (4) brightness, (5) equalization. Besides, (1)–(3) are nominal-the-best characteristics, and (4) and (5) are larger-the-best characteristics among the characteristics. In fact, customers will accept products whenever all process capabilities of each characteristic satisfy preset specifications, so to measure process capability for a product must consider many quality characteristics. Obviously, univariate process capability indices cannot meet the requirements stated as above. Thus, Chen et al. (2001) develop a Product Capability Analysis Chart (PCAC) model to evaluate process capability for a product consists of smaller-the-better unilateral specifications, larger-the-better unilateral specifications, and nominal-the-best bilateral specifications. Based on the above analysis, we will apply PCAC in Measure step of Six Sigma. Not only the PCAC model can evaluate process capability for a product which holds many quality characteristics but also it can judge the process of precision and accuracy soon according to the points of fall. If the process of accuracy is not enough, you can comprehend the average specification which slanting large or small on the PCAC model. Following on the above analysis, the worker on the line and the manager can comprehend whether the process of precision and accuracy is enough on the PCAC model. If the process of accuracy is not enough, they can

analyze the reasons on the PCAC model. Thus, PCAC model is not only a measure tool but also a preliminary analysis tool.

The PCAC, proposed by Chen et al. (2001), did not consider the sampling error. Chen et al. (2001) used point estimation to evaluate process capability, even though the method agrees with 100% tests. If the check is sampling, the process capability must consider sampling error. Hence, we will mark the process capability zone according to minimum value. The finally, PCAC will be applied in the case which is Six Sigma implementation of Offset Ratchet Wrengches.

2. Product Capability Analysis Char

Process mean (μ), Process variance (σ^2) and product specification are basic elements to evaluate process capability. However, the specifications are different in different products. Manager of process can't evaluate process performance from μ and σ right away. For the above reason, Juran (1974) combined process parameters with product specifications to bring up the idea of Process Capability Indices. Since Kane (1986) defined the first Process Capability Index C_p, Process Capability Indices (*PCIs*) is a convenient tool to evaluate process capability and performance today. As noted by Bothe (1992) and Chen et al. (2001), most products with multiple characteristics could consist of numerous unilateral specifications and bilateral specifications. In fact, customers will accept products whenever all process capabilities of each characteristic satisfy preset specifications. Thus, Chen et al. (2001) develop a Product Capability Analysis Char (*PCAC*) model to evaluate process capability for a product consists of smaller-the-better unilateral specifications, larger-the-better unilateral specifications, and nominal-the-best bilateral specifications.

In *PCAC*, indices C_{pu}, and C_{pl} represent axes X and Y respectively to evaluate the smaller-the-better and larger-the-better unilateral specifications, respectively. Index C_{pk} assesses nominal-the-best specification, and the relationship between XY plane. Where indices C_{pu}, C_{Pl} and C_{pk} are defined as (see Kane, 1986):

$$C_{pu} = \frac{USL - \mu}{3\sigma},$$
$$C_{pl} = \frac{\mu - LSL}{3\sigma},$$
$$C_{pk} = \min\{C_{pu}, C_{pl}\} = \frac{d - |\mu - T|}{3\sigma},$$

where *USL* is the upper specification limit, *LSL* is the lower specification limit, μ is the process mean, and σ is the process standard deviation, and T is the process target.

Based on the above analysis, most products with multiple characteristics could consist of numerous unilateral specifications and bilateral specifications. The integrated process capability index must consider that a product usually hold many quality characteristics. Based on Huang et al. (2002), Chen et al. (2001), and Chen et al. (2004), we defined an integrated process capability index C_T which consider that a product usually hold many quality characteristics. The integrated process capability index C_T can be defined as follows:

$$C_T = \left(\frac{1}{3}\right) \Phi^{-1} \left\{ \left[\left(\prod_{i \in S} \prod_{j=1}^{t_i} [2\Phi(3C_{pij}) - 1] \right) + 1 \right] \Big/ 2 \right\}, \quad S = \{u, l, k\},$$

$$C_{pij} = \begin{cases} \dfrac{USL_{uj} - \mu_{uj}}{3\sigma_{uj}}, & i = u, \quad j = 1, 2, \ldots, t_u, \\[3mm] \dfrac{\mu_{lj} - LSL_{lj}}{3\sigma_{lj}}, & i = l, \quad j = 1, 2, \ldots, t_l, \\[3mm] \min\left\{ \dfrac{USL_{nj} - \mu_{nj}}{3\sigma_{nj}}, \dfrac{\mu_{nj} - LSL_{nj}}{3\sigma_{nj}} \right\}, & i = k, \quad j = 1, 2, \ldots, t_k° \end{cases}$$

The yield of a multi-process product is lower than individual process capability of each characteristic. Similarly, when process yield is set to meet required level, then process capability of each characteristic should be greater than the preset standard for entire product. The minimum process capability indices C_0 of each individual process characteristic, $C_0 = \Phi^{-1}[(\sqrt{2\Phi(3c) - 1} + 1)/2]/3)$ (see Chen et al. 2001). Where $t = t_k + t_s + t_l$, t is the total number of quality characteristics, t_l is the number of larger-the-better quality characteristics, t_s is the number of smaller-the-better quality characteristics, and t_k is the number of nominal-the-best quality characteristics for a multi-process product. The critical values $C_0(C_{pij} \geq C_0)$ for individual process capability can be attained by solving the previous inequality when the integrated process yield exceed $c(C_T \geq c)$. For example, one single product consists of 5 processes (N1, N2, N3, L1 and S1). N1, N2 and N3 are nominal-the-best quality characteristics, L1 is larger-the-better quality characteristics and S1 is smaller-the-better quality characteristics. Let the entire produce yield is preset to be greater than $1.5 (C_T \geq c = 1.5)$, and could also be verified by $C_0 = \Phi^{-1}[(\sqrt[5]{2\Phi(3 \times 1.5) - 1} + 1)/2]/3) = 1.610$. The process capability zone is the grey zone which is $C_{pu} \geq 1.610, C_{pl} \geq 1.610$, or $C_{pk} \geq 1.610$ in Figure 1. Process N1, N2, L1 and S1 are located within the process capability zone, but process N3 is not. Thus, the process of N3 must be improved.
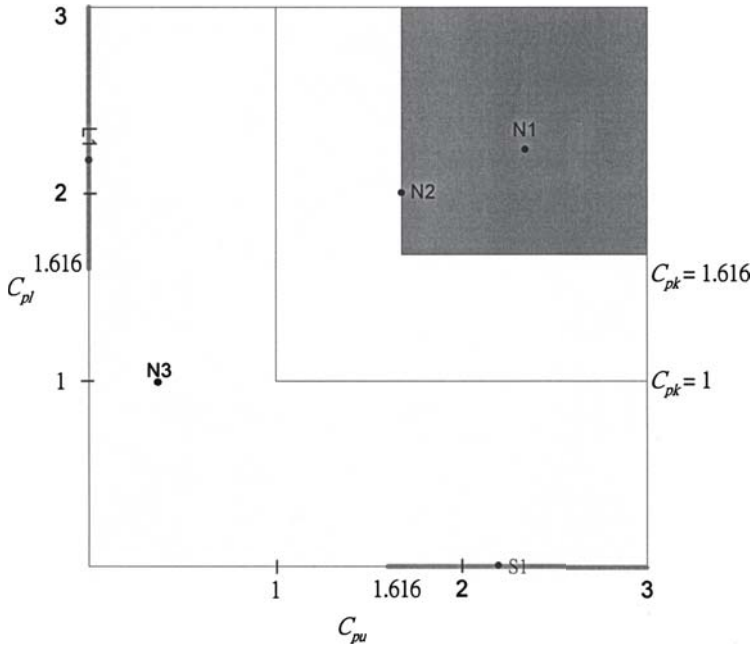
Figure 1. Product capability analysis chart.

3. PCAC of Considering Sampling Error

As a general rule, Process mean (μ) and Process variance (σ^2) unknown, so the values which are C_{pu}, C_p and C_{pk} can't be computed. Based on Chou et al. (1990), if Process mean (μ) and Process variance (σ^2) unknown, you can use sample mean ($\overline{X}$) and sample variance (S^2) to estimate them. Thus, the estimators of C_{pu}, C_{pl} and C_{pk} as follows:

$$\hat{C}_{pu} = \frac{USL - \bar{X}}{3S},$$

$$\hat{C}_{pl} = \frac{\bar{X} - LSL}{3S},$$

$$\hat{C}_{pk} = \min\{\hat{C}_{pu}, \hat{C}_{pl}\} = \frac{d - |\bar{X} - T|}{3S}.$$

Chen et al. (2001) proposed PCAC model which used point estimation to evaluate process capability. The method didn't consider sampling error. It agrees with 100% tests. However, 100% tests are not suitable for use all manufacture. Contrarily, there are many cases which are suitable fore use sampling. According to Chen et al. (2003), Sampling is most likely to be useful when the testing is destructive, the testing cost is extremely high, the vendor's past quality history is excellent, and the potential product

liability risks are serious, etc. If the testing is sampling, the process capability must consider sampling error. For the trouble, Chou et al. (1990) calculated the minimum value of C_{pu} and C_{pl}, and they used the minimum value to evaluate process capability. Based on the above analysis, we will conduct the minimum value to PCAC, and the method can make the industry to evaluate process capability more accurately when the testing is sampling. Suppose that a process is considered capability if $C_{pu} \geq 1.2$. Since C_{pu} is unknown, we take a random sample of size n and calculate $\hat{C}_{pu} = (USL - \overline{X})/3$. For a random sample of size $n = 20$, if the minimum value of C_{pu} is $\hat{C}_{pu} \geq 1.67$, then we claim that the process is capable at least 95% of the time. For a random sample of size $n = 100$, if the minimum value of C_{pu} is $\hat{C}_{pu} \geq 1.37$, then we claim that the process is capable at least 95% of the time. (Chou et al., 1990); the minimum value which is C of C_{pi} can be written as:

$$\Pr[C_{pi} \geq C] = r, \quad i = \{u, l\}$$
$$\Pr[T_{n-1}(\delta = 3\sqrt{n}\hat{C}_{pi}) \geq 3\sqrt{n}C] = r$$

Obviously, process capability can be evaluated by minimum value. The rule of judgment are as follows: process is good when $\hat{C}_{pi} \geq \mathrm{MV}$ (minimum value); Oppositely, process is bad when $\hat{C}_{pi} < \mathrm{MV}$. Because $\hat{C}_{pk} = \min\{\hat{C}_{pu}, \hat{C}_{pl}\}$ evaluates nominal-the-best specification, process is good when $\hat{C}_{pu} \geq \mathrm{MV}$ and $\hat{C}_{pl} \geq \mathrm{MV}$. If the sampling error is considered, the minimum value of C_{pu}, C_{pl} and C_{pk} must be calculated when the value of C_0 was decided already in PCAC that Chen et al. (2001) proposed it. Thus, the process capability is qualified when the process capability index of sampling is greater than the minimum value of C_{pu}, C_{pl} and C_{pk} which were already calculated. For example, one single product consists of 5 processes (N1, N2, N3, L1 and S1) and assume the entire produce yield preseting to be greater than $1.5 (C_T \geq c = 1.5)$, and verified by $C_0 = (1/3)\Phi^{-1}[(\sqrt[5]{2\Phi(3 \times 1.5) - 1} + 1)/2] = 1.610$. Following above, the minimum value of C_{pu}, C_{pl} and C_{pk} is 1.714 when considering sampling error and sampling 400 samples. Thus the qualified zone is the grey zone when $\hat{C}_{pu} \geq 1.714, \hat{C}_{pl} \geq 1.714$, or $\hat{C}_{pk} \geq 1.714$ in Figure 2. Process N1, L1 and S1 are located within the process capability zone, but process N2 and N3 are not. Therefore the process N2 and N3 must be improved when the PCAC considered sampling error.

4. PCAC of Six Sigma standard

Based on Linderman et al. (2002), Motorola set this goal so that process variability is $\pm 6\sigma$ from the mean. They further assumed that the process was subject to disturbances that could cause the process mean to shift
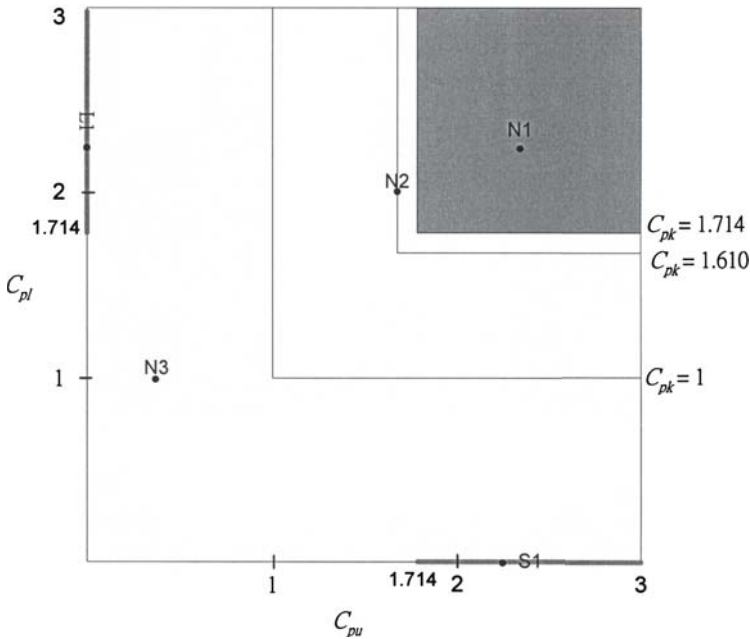
Figure 2. PCAC of considering sampling error.

by as much as 1.5σ off the target. Based on the above account, the Six Sigma values of C_{pu}, C_{pl} and C_{pk} which shift by as much as 1.5σ can be computed. The values follow as:

$$C_{pu} = \frac{USL - \mu}{3\sigma} = \frac{6\sigma - 1.5\sigma}{3\sigma} = 1.5,$$

$$C_{pl} = \frac{\mu - LSL}{3\sigma} = \frac{6\sigma - 1.5\sigma}{3\sigma} = 1.5,$$

$$C_{pk} = \frac{d - |\mu - T|}{3\sigma} = \frac{6\sigma - 1.5\sigma}{3\sigma} = 1.5$$

If the values of C_{pu}, C_{pl} and C_{pk} can be greater than 1.5 when the process mean shifts by as much as 1.5σ off the target, the process still reach the standard of Six Sigma. So we can acquire the Table I which is the minimum value compared table in Six Sigma standard. Table I considers numbers of quality characteristics and numbers of sampling. Because C_{pu}, C_{pl} and C_{pk} must be greater than 1.5 in Six Sigma standard, we can acquire the value which the minimum process capability indices C_0 of each individual process characteristic by $C_0 = (1/3)\Phi^{-1}[(\sqrt{2\Phi(3c) - 1} + 1)/2]$ in 100% tests. If the test model is sampling, the minimum value can be aquired by the above chapter. This paper lists the minimum value of 3–7 quality characteristics (N) and 100, 200, 300 and 400 samples (n) in Table I After the minimum value is acquired, the zone which considers sampling error and

Table I. The minimum value of 3–7 quality characteristics and 100, 200, 300 and 400 samples

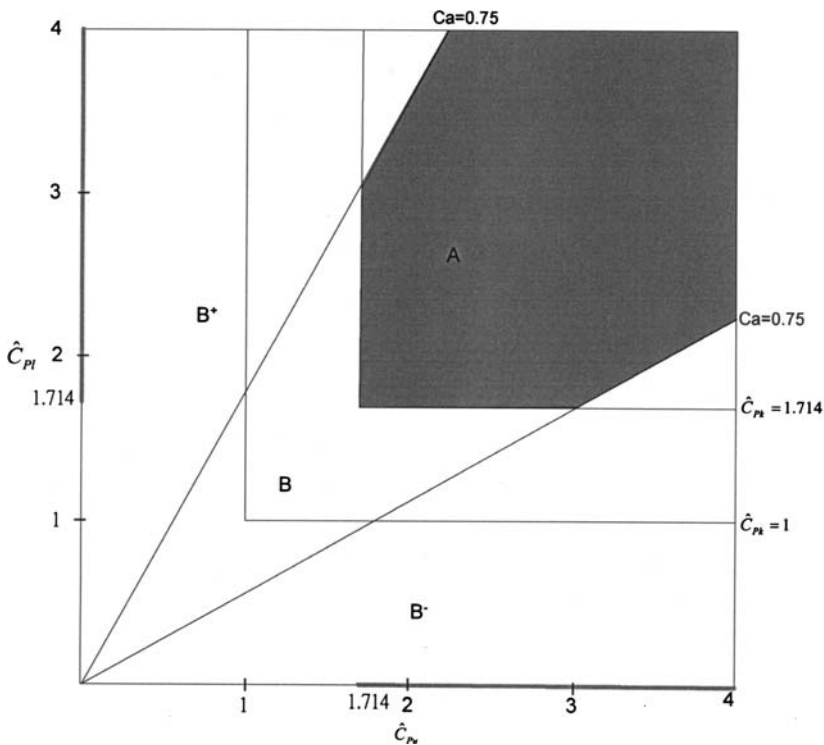|	$C_{pu}(C_{pl})$	$n=100$	$n=200$	$n=300$	$n=400$
$N=3$	1.576	1.795	1.724	1.695	1.678
$N=4$	1.595	1.816	1.745	1.715	1.698
$N=5$	1.61	1.833	1.761	1.731	1.714
$N=6$	1.622	1.847	1.774	1.744	1.727
$N=7$	1.632	1.858	1.785	1.755	1.737

Figure 3. PCAC of Six Sigma standard.

Six Sigma standard can be built. Figure 3 is the zone of 4 quality characteristics and 400 samples, and the zone arrives at Six Sigma standard.

Huang et al. (2002) designed an index which is C_a for assesing the accuracy of the manufacturing process. The definition is $C_a = 1 - (|\mu - T|/d)$, where T denotes the target value and $d = (\text{USL} - \text{LSL})/2$ is the half interval length. The value of C_a decreases as μ moves away from T. On the other hand, the value of C_a increases when, μ approaches T. $C_a = 1$ when

the process mean equals the target. In fact, C_a is the function of C_{pu} and C_{pl}, and they have the following relationship:

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

Because the process mean can shift by as much as 1.5σ off the target in Six Sigma, the value of C_a is 0.75. The function of C_{pu} and C_{pl} can be written as:

$$C_a = 1 - \frac{|C_{pu} - C_{pl}|}{C_{pu} + C_{pl}} = 0.75$$

$$3C_{pu} - 5C_{pl} = 0, \quad \text{when } C_{pu} > C_{pl},$$

$$5C_{pu} - 3C_{pl} = 0, \quad \text{when } C_{pu} < C_{pl}.$$

To draw $3C_{pu} - 5C_{pl} = 0$ and $5C_{pu} - 3C_{pl} = 0$ in Figure 3 which considering sampling error and the process capability indices reach the standard of Six Sigma, and then the district which the process mean shifted by as much as 1.5σ off the target in Six Sigma can be acquired (Figure 3).

The PCAC of Six Sigma standard separated A part and B part. The process capability arrived at Six Sigma standard already when the process capability index fell into A part. Thus the process can be accepted in A part. If the process capability index fell into B part, the process capability doesn't arrive at Six Sigma standard. Also, B part can be separated three zones which are B$^+$, B, and B$^-$. B$^+$ zone is that the process mean shifts right. The average specifications of productions shift so small when the process capability index fell into B$^+$ zone, and process mean shifts greater than 1.5σ which Six Sigma standard can tolerate the maximum of greatest. B$^-$ zone is that the process mean shifts left. The average specifications of productions shift so small when the process capability index fell into B$^-$ zone, and process mean shifts greater than 1.5σ which Six Sigma standard can tolerate the maximum of greatest as well. B zone is that the process capability is inadequate, but the process mean shifts less than 1.5σ. The process variation so larger is the principal reason to make the above problem. To bring about the process capability indices to fall into B part, and provide the reasons as in Table II.

5. Real Example-Offset Ratchet Wrenches

Offset Ratchet Wrenches are produced by Y company in Taiwan. Wrench is one of common tools in manufacture. Many components need to fasten by the screw and the nut. The immovable degree of components depends on the compact degree of the screw and the nut. Wrench is the tool which

Table II. Reasons of *PCIs* falling into B part

Zone	Resons
B⁺ and B⁻	1. The parameter of machine is not adapted (e.g., rotational speed, twist strength, temperature, etc.).
	2. The specifications of working cutting tools are not adapted.
B	1. The quality of raw materials is unsettled.
	2. Stuff of staff is different.
	3. Maintenance and upkeep are not certainty.

regulates the compact degree of the screw and the nut. The types of wrenches are variety, and their functions are different. The principal purpose of Offset Ratchet Wrenches is to use in hard-exerting-strength space. Basic structures on the Offset Ratchet Wrenches are divided into three parts which are head, handle, and tail (Figure 1). The head rise 25°. Both of head and tail can be used to regulate the compact degree of the screw and the nut. Because the head rise 25°, Offset Ratchet Wrenches can be used in hard-exerting-strength space more quickly (Figure 4).

The key quality characteristics of Offset Ratchet Wrenches includes: first, length, height, length of ID in head, length of ID in tail and width are nominal-the-best specifications. Secondly, Variation of width is smaller-the-better specifications. The below two reasons make Y company to apply Six Sigma: one reason is that, Y company will want to woo advance quality; the other reason is many international companies acquired good
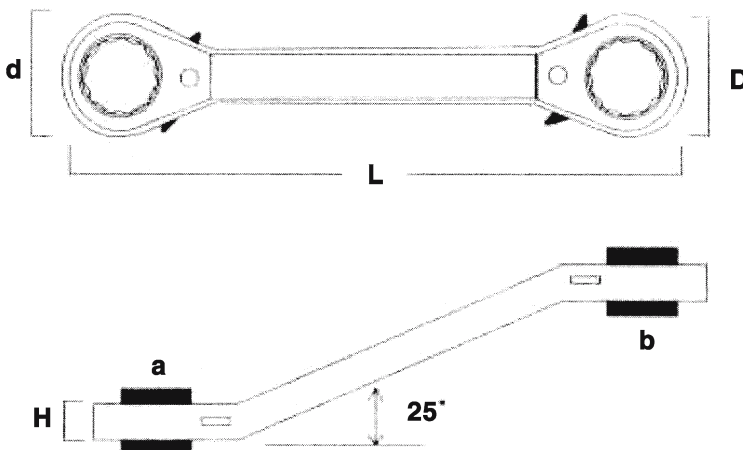

Figure 4. Profile of Offset Ratchet Wrenches.

achievement to applied Six Sigma. Thus Y company decided to apply Six Sigma to improve quality of Offset Ratchet Wrenches.

A lot of tools can be chosen in every step of Six Sigma, and their goals are equal. In Measure step, the goals of tools are focus on measurement of the present situation of enterprises. In Analysis step, the goals of tools are to analyze the unqualified reasons. The research will apply PCAP, which proposed by Chen et al. (2001), to measure present process capability of Offset Ratchet Wrenches. The major function of PCAC model is to measure the process capability of multi-process product. Besides, PCAC model can evaluate process capability of a product consists of smaller-the-better unilateral specifications, larger-the-better unilateral specifications, and nominal-the-best bilateral specifications at the same time. Because there are 6 quality characteristics which are 5 nominal-the-best quality characteristics and 1 smaller-the-better quality characteristic in the example of the research, PCAC agrees with measuring the example.

Because Offset Ratchet Wrenches are manufactured very much by Y company, the model of test is sampling. Thus sampling error must be considered. Two hundreds samples are collected in respective quality characteristic in the paper. Process capability indices of respective quality characteristics are computed in Table III. If the quality characteristic of Offset Ratchet Wrenches arrived at Six Sigma standard, the process capability indices must be greater than 1.774 according to Table I. Based on the above, the PCAC considers the concept of Six Sigma can be built in Figure 5. Let process capability indices of Table III point at Figure 5. Weight which is one of quality characteristics fell B zone, and the other quality characteristics fell A zone. Thus Weight did not arrive at Six Sigma standard, and it must be improved.

Based on the above measure, Weight which is one of the quality characteristics in Offset Ratchet Wrenches does not fall into A zone. Besides PCAC model can measure whether the process capability arrived at Six

Table III. Process capability of the characteristic of Offset Ratchet Wrengches

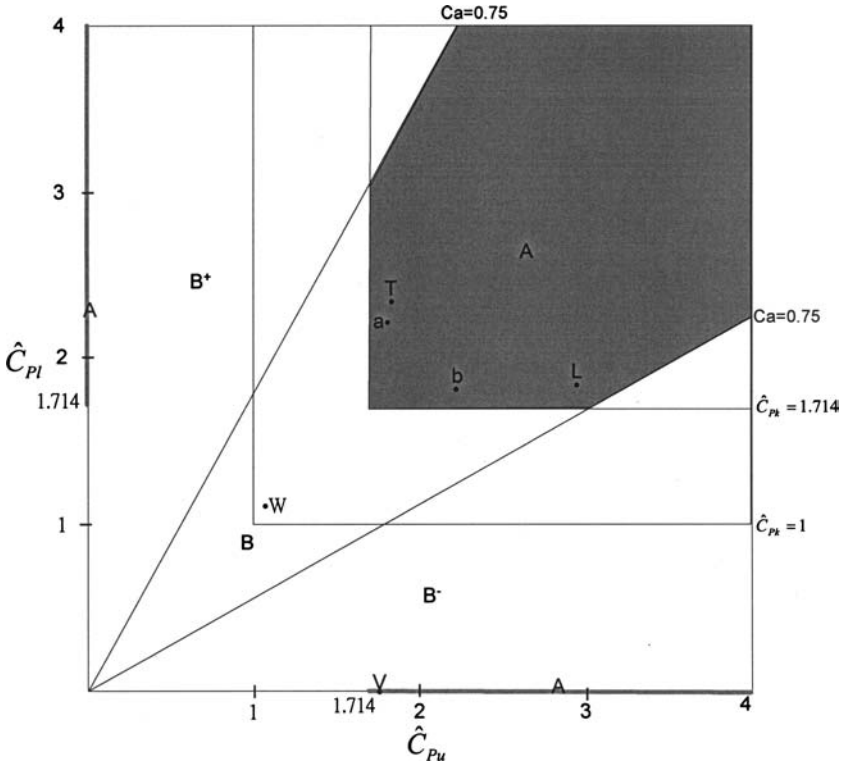| Quality characteristic	Type	USL	T	LSL	μ		C_{pu}	C_{pk}
(1) Length (L)	N	112.3	112	111.7	111.928	0.042		1.810
(2) Height (H)	N	8.05	8	7.95	8.006	0.008		1.833
(3) Length of ID in head (b)	N	8.03	8	7.97	7.997	0.005		1.800
(4) Length of ID in tail (a)	N	6.03	6	5.97	6.003	0.005		1.800
(5) Weigh (W)	N	8.05	8	7.95	8.001	0.015		1.089
(6) Variation of width (V)	S	0.03			0.009	0.004	1.750	

When N: Nominal-the-best, S: Smaller-the-better

Figure 5. PCAC of Offset Ratchet Wrenches.

Sigma standard. And it is also a preliminary analysis tool. Therefore we can approximately analyze the reason which the process capability is not qualified based on a point of fall in PCAC. After observing Figure 5, we can find that the quality characteristic which is Weight fell into B zone. In other words, the process capability of Weight is inadequate, but the process mean of Weight shifted by less than 1.5σ. Maybe the reasons make the above problem, and the reasons follow as: the quality of raw materials are unsettled, stuff of staff is different, etc. After deeper analysis, we found the cause of the above problems. The raw materials of Offset Ratchet Wrenches are shortage, so Y Company must purchase them from five major suppliers. Because the process capability is different in the 5 suppliers, the quality of raw materials is divergence. The above reason influences quality of the finished products. Hence Y company decides to request the unqualified suppliers to improve the process capability. If the unqualified suppliers do not improve the process capability, the order will be transferred to other qualified suppliers. Besides Y company will check the raw materials more strictly. Based on this example, PCAC can be applied in Measure step of MAIC, and it is also a preliminary analysis tool.

6. Conclusion

The objective of this paper is to apply PCAC model in Six Sigma. PCAC model can be applied in Measure step of MAIC, and it is also a preliminary analysis tool. However, PCAC model which proposed by Chen et al. (2001) who did not consider sampling error. Chen et al. (2001) used point estimation to evaluate process capability, but point estimation is suitable for 100% tests. If the test model was sampling, sampling error must be consider. Thus this paper used minimum value to evaluate process capability according to Chou et al. (1990). Besides this paper used minimum value to evaluate process capability, we also applied the concept of Six Sigma in PCAC model. The PCAC model was separated A zone and B zone. A zone is a qualified zone, but B zone is a unqualified zone. Also, three zones, B^+, B, and B^-, are separated from B zone. Finally, we applied the above methods in Six Sigma project of Offset Ratchet Wrenches which manufactured by Y company. After the above measure, Weight which is one of the quality characteristics in Offset Ratchet Wrenches did not arrive at Six Sigma standard. Perhaps some reasons make Weight can not arrive at Six Sigma standard, and the reasons follow as: the quality of raw materials are unsettled, stuff of staff is different, etc. After deeper analysis, we found Y company must purchase the raw materials of Offset Ratchet Wrenches from five major suppliers. The above reason influences quality of the finished products. Thus Y company decides to request the unqualified suppliers to improve the process capability. Based on the case of Y company, we can identify that PCAC model can be applied in Measure step of MAIC, and it is also a preliminary analysis tool.

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