Int J Adv Manuf Technol (2004) 24: 425–432
DOI 10.1007/s00170-003-1784-x

ORIGINAL ARTICLE

Wen-Pei Sung · Kuen-Suan Chen

Evaluation model for multi-process capabilities of stranded wire

Received: 14 February 2003 / Accepted: 27 April 2003 / Published online: 11 May 2004
© Springer-Verlag London Limited 2004

Abstract Stranded wire is the most important component of familiar mechanical equipment such as elevators, cable cars, and cranes. The quality of these products that are used on a daily basis are mainly affected by the tensile strength of stranded wire. In order to attain the purpose of economical design and a long life span of stranded wire, a less relaxation property of strand type is suitable for manufactured tools. Thus, the manufacturing industries of stranded wire need to reach the goals of high tensile strength and low relaxation. To ensure the required quality of stranded wire, the strand pull test and the long period relaxation test are two important quality assurance tests. There are three specific items of the tensile strength test that belong to the larger-the-better quality type. The quality type of the smaller-the-better is for the long period relaxation test. However, many existing methods are able to measure process capability for the product with a single quality characteristic although it cannot be applied to most products with multiple properties. Thus, the indices of C_{pu} and C_{pl}, for the larger-the-better and the smaller-the-better quality type respectively proposed by Kane [5], are quoted and combined to propose a new index to evaluate the quality of multiple characteristics of stranded wire in this article. The principle of statistics is then used to derive the one-to-one mathematical relationship of this new index and ratio of satisfactory production process. Finally, the procedure and criteria to evaluate the quality of stranded wire is proposed. This integrated multi-quality property capability analysis model can be used to evaluate the multi-process capabilities and provide continuous improvements on the manufacturing process of stranded wire.

Keywords Index of multi-quality properties · Ratio of satisfactory production process · Entire product · Stranded wire

W.-P. Sung (✉)
Department of Landscape Design and Management,
National Chin-Yi Institute of Technology,
41111 Taichung, Taiwan, R.O.C.
E-mail: sung809@chinyi.ncit.edu.tw

K.-S. Chen
Department of Industrial Engineering and Management,
National Chin-Yi Institute of Technology,
41111 Taichung, Taiwan, R.O.C.

1 Introduction

Numerous manufactured tools and products are designed using the concept of pre-stressing, such as frame saw, and the spoke of a bicycle wheel. The old conventional way used rope to take the pretensioning forces for these manufactured tools. It is hard for rope to bear the long-term tensional forces; thus, the mechanical properties of high tensional strength, high elastic limit and high yield point of stranded wire are put to use in sophisticated equipment and structures such as elevators, cable cars, cranes, hoisting machines, wreckers, bridges, and buildings. In order to increase the use of a fixed number of years and lower manufacturing expenses, less relaxation of stranded wire types should be selected for manufacturing [1, 2, 3, 4]. Therefore, the goals of research and development works enhance the tensile strength and diminish relaxation to improve the capability of stranded wire [4]. The quality of production should achieve the stability and standardisation. The production process capability analysis and evaluation methods are quoted in this article to propose a production process capability index to evaluate the stranded wire quality and control capability of stranded wire manufacturing production processes. Simultaneously, the relationship between the proposed index and the ratio of a satisfactory production process is conferred. The objective method of statistical examination is proposed to judge if the quality of stranded wire meets the required specification.

The ratio of satisfactory production process, loss function of production process and index of production capability are methods for evaluating the production capability and achievements. Presently, many effective methods for evaluating the production process have been provided by well-known researchers [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. The purpose of this research is to provide accurate and convenient evaluation methods for the manufacturing industry. To promote the quality of these manufactured products, the tensile strength index of stranded wire is defined to evaluate whether the tensile strength of stranded wire will attain the minimum required tensile strength based on the production process capability analysis and evaluation method. At the same time, the relaxation index is defined to evaluate whether the relaxation of stranded wire is less than the subscribed value of the relaxation test. This proposed evaluation method ensures the suitability and safety of stranded wire in the manufacturing process.

2 The quality and evaluation index of stranded wire

Fine and delicate managerial system is described for the characteristics of management of each manufacturing process of stranded wire. The final purpose of inspection assures that the quality of stranded wire meets the required specifications. The wire pull test and the long time relaxation test are two important tests for the quality of stranded wire. The tensile force-elongation curve is obtained by the tensile test of stranded wire to measure the strength of stranded wire, which includes the tensile force of 0.2% permanent elongation, tensile strength and rate of elongation. These test values should be greater than the lower specification limit. The relaxation test is used to judge whether the relaxation value of stranded wire, subjected to a pull force for over 1,000 hours, is lower than the upper specification limit. There are two important quality properties of stranded wire:

1. The tensile strength of stranded wire.
2. The rate of relaxation of stranded wire after being pulled over 1,000 hours.

Obviously, the tensile strength characteristics of stranded wire are the larger-the-better quality type, and the rate of relaxation characteristics of stranded wire are the smaller-the-better quality type. Table 1 lists the lower specification limit (LSL) requirements of tensile strength and the upper specification limit (USL) requirements of a long time relaxation test for different types of stranded wire. They are classed as two-wire, seven-wire and nineteen-wire strands.

The indices of C_{pl} and C_{pu}, proposed by Kane [5], are used to evaluate the quality of stranded wire by virtue of the larger-the-better for each test item of tensile strength and the smaller-the-better for the relaxation test. To conveniently describe the quality properties of stranded wire , the larger-the-better and the smaller-the-better characteristics corresponded to the lower specification limit, upper specification limit and indices listed as follows:

For the larger-the-better quality type:

$$C_{pli} = \frac{\mu_i - LSL_i}{3\sigma_i},\ i = 1,\ 2,\ 3. \tag{1}$$

For the smaller-the-better quality type:

$$C_{pli} = \frac{\mu_i - LSL_i}{3\sigma_i},\ i = 1,\ 2,\ 3. \tag{2}$$

LSL_i is the lower specification limit, USL_i is the upper specification limit, μ_i is the process mean value, and σ_i is the process standard deviation.

Obviously C_{pli} and C_{puj} belong to indices of unilateral specification. The normal distribution is always assumed

Table 1 The required specification for the multiple properties of stranded wire

Type	Diameter	Pull test			Long time relaxation test
		The LSL of tensile force of 0.2% permanent elongation	The LSL of tensile strength	The LSL of elongation	The USL of Relaxation
	mm	kg	kg	%	%
Two-wire strand	2.9	2300	2600	3.5	3.0
Seven-wire strand (Type A)	9.3	7700	9050	3.5	3.0
	10.8	10400	12200	3.5	3.0
	12.4	13900	16300	3.5	3.0
	15.2	19700	23100	3.5	3.0
Seven-wire strand (Type B)	9.5	8850	10400	3.5	3.0
	11.1	12000	14100	3.5	3.0
	12.7	15900	18700	3.5	3.0
Nineteen-wire strand	17.8	33600	39500	3.5	3.0
	19.3	39500	46000	3.5	3.0
	20.3	43000	50500	3.5	3.0
	21.8	50500	58400	3.5	3.0

to be the quality characteristics of production as a result of actuality and most of the research. Therefore, the framework of this research is based on the assumption of normal distribution. The production process capability indices of C_{pli} and C_{puj} can be expressed as follows based on the different quality characteristics of a strand.

For the larger-the-better quality type:

$$\begin{aligned} p_i &= \mathrm{P}(X \geq LSL_i) \\ &= \mathrm{P}\left(Z \geq -\frac{\mu_i - LSL_i}{\sigma_i}\right) \\ &= \mathrm{P}\left(Z \leq 3C_{pli}\right) \\ &= \Phi\left(3C_{pli}\right),\ i = 1,\ 2,\ 3. \end{aligned} \tag{3}$$

For the smaller-the-better quality type:

$$\begin{aligned} p_4 &= \mathrm{P}(X \leqslant USL_4) \\ &= \mathrm{P}\left(Z \leqslant \frac{USL_4 - \mu_4}{\sigma_4}\right) \\ &= \mathrm{P}\left(Z \leqslant 3C_{pu4}\right) \\ &= \Phi\left(3C_{pu4}\right). \end{aligned} \tag{4}$$

LSL_{i} is the lower specification limit, $i = 1, 2, 3, USL_4$ is the upper specification limit, $Z = (X - \mu)/\sigma$ is standard normal distribution, and $\Phi(\cdot)$ is standard normal cumulative distribution function.

There is a one-to-one mathematical relationship of C_{pli}, $C_{puj,}$ and P_{ij}. The expression can be rearranged as follows:

$$p_i = \Phi\left(3C_{poi}\right) \tag{5}$$

where $C_{poi} = C_{pli}$ for $i=1, 2, 3$ and $C_{po4} = C_{pu4}$.

According to the analysis of the ratio of satisfactory production process and process capability, both of these different quality properties can be combined to subscribe the index C_T that reflects the production process capability of the whole product. The index C_T is expressed as follows:

$$C_T = \left(\frac{1}{3}\right)\Phi^{-1}\left(\prod_{i=1}^{4}\Phi\left(3C_{poi}\right)\right). \tag{6}$$

Assuming that the ratios of satisfactory production process of different quality characteristics are independent, the ratio of satisfactory production process p can be expressed as follows:

$$p = \prod_{i=1}^{4} p_i = \prod_{j=1}^{4}\Phi\left(3C_{poi}\right) = \Phi(3C_T). \tag{7}$$

When the production capability index C_T is large enough for each type of product, the ratio of satisfactory production process p is also high enough. For example, when the production capability index C_T is equal to 1.0, the ratio of satisfactory production process p is guaranteed to 99.73%.

A product is composed of four quality characteristics. Consequently, the ratio of satisfactory production process is less than the ratio of satisfactory production process of the individual quality property. Therefore, to meet the required standard of the production capability of the whole product, the ratio of satisfactory production process of each quality characteristic should be higher than the ratio of satisfactory production process of the whole product. If the required production capability index C_T is greater than c, then:

$$C_T = \left(\frac{1}{3}\right)\Phi^{-1}\left(\prod_{i=1}^{4}\Phi\left(3C_{poi}\right)\right) \geq c. \tag{8}$$

If the minimum requirement of the individual quality property is the same, then solving the above-mentioned an inequality, the production capability index of the whole product can be derived. When it is greater than c, the critical production capability index of the individual quality property is at least v ($C_{poi} \geq v$), where $v = \left(\frac{1}{3}\right)\Phi^{-1}\left(\sqrt[4]{\Phi(3c)}\right)$.

The five quality conditions, the corresponding values of the production capability index c and the production capability index of the individual quality property (v), proposed by Pearn and Chen [14], are listed in Table 2.

3 Quality evaluation index of stranded wire

The quality of a stranded wire product is composed of four quality properties. The ratio of satisfactory production process p is multiplied by these four quality characteristics. Consequently, when the ratio of satisfactory production process of stranded wire is p_0, it means that the ratio of satisfactory production process for each quality property should reach the specified requirement. The ratio of the satisfactory production process of the whole product can then be ensured to reach the requisition. Because of the one-to-one mathematical relationship between the production process capability indices C_{pl}, C_{pu} and the ratio of the satisfactory production process type of stranded wire, when the ratio of satisfactory production process of the whole product is c, then the production process capability for each quality characteristic cannot be assumed to be c.

As mentioned above, the ratio of the satisfactory production process of the whole product is lower than

Table 2 The five quality conditions

Quality condition	c values	v values
Inadequate	$c < 1.000$	$v < 1.133$
Capable	$1.000 \leq c < 1.333$	$1.133 \leq v < 1.436$
Satisfactory	$1.333 \leq c < 1.500$	$1.436 \leq v < 1.595$
Excellent	$1.500 \leq c < 2.000$	$1.595 \leq v < 2.074$
Super	$2.000 \leq c$	$2.074 \leq v$

the ratio of the satisfactory production process for the individual quality property p_i. Therefore, if the ratio of the satisfactory production process for each type of stranded wire is necessary to meet the specification, the individual quality characteristics of the pull and relaxation test should be higher than the ratio of the satisfactory production process for the whole product. If the required production process index of the whole product is $C_T = c$, then the production process index of each quality property should be $C_{poi} = v = \Phi^{-1}\left(\sqrt[4]{\Phi(3c)}\right)/3$. For example, if the required production process index is $C_T = 1.000$, then the production process index for each property of stranded wire is $C_{pij} = 1.133$ (see Table 2).

Chang [15] pointed out that the parameters of the production process are unknown. Therefore, the estimated value of the index is acquired by means of samples. Becuase of errors in sampling, the estimated values used to judge whether the production process capability meets the customers' requirements are biased. Consequently, the statistical inspection method is one of the objective methods to evaluate the production process capability. Therefore, the production process capability of each type of stranded wire meets the required specification based on the statistical inspection method. According to the above, the production capability index v of individual characteristics of stranded wire can be reached by the equation $v = \Phi^{-1}\left(\sqrt[4]{\Phi(3c)}\right)/3$. Then the production process index of each different quality property can be assured to be c. When the production process index of stranded wire is examined, whether it is greater than or equal to c, the production process capability index for each different quality characteristic should be inspected to determine if it is larger than or equal to v. The assumption of inspection can be expressed as follows:

$$\mathrm{H}_0: \; C_{poi} \geq v,$$
$$\mathrm{H}_a: \; C_{poi} < v.$$

The unbiased estimator $\hat{C}_{poi}$ of the index C_{poi} is used as the inspection statistical quantity to judge whether the value of production process capability index reaches the required specification. This inspection statistical quantity can be shown as follows:

$$\hat{C}_{poi} = (b_n) \times \left(\frac{\bar{X}_i - LSL_i}{3S_i}\right), \; i = 1, \; 2, \; 3; \quad (9)$$

$$\hat{C}_{poi} = (b_n) \times \left(\frac{USL_i - \bar{X}_i}{3S_i}\right), \; i = 4. \quad (10)$$

$\bar{X}_i = (n)^{-1}\left(\sum_{l=1}^{n} X_{il}\right)$ and $S_i = \left((n-1)^{-1}\sum_{l=1}^{n} (X_{il} - \bar{X}_i)^2\right)^{1/2}$ are mean values and standard deviation of random sample $X_{i1}, \ldots, X_{in}$ respectively. They are used to evaluate μ_i and σ_i, $i = 1, 2, 3, 4$. The constant item b_n can be expressed as follows:

$$b_n = \sqrt{\frac{2}{n-1}} \times \left(\frac{\Gamma[(n-1)/2]}{\Gamma[(n-2)/2]}\right), \; n > 2. \quad (11)$$

Pearn and Chen [16] pointed out that the unbiased estimator $\hat{C}_{poi}$ of the index C_{poi} is a function of complete enough statistical quantity $(\bar{X}_i, (S_i)^2)$. Thus, $\hat{C}_{poi}$ is the minimum variance unbiased estimator (UMVUE) of C_{poi} under the assumption of normal distribution. The quantity of $(3\sqrt{n}/b_n)\,\hat{C}_{pli}$ and $(3\sqrt{n}/b_n)\,\hat{C}_{pui}$ obeys a non-central t-distribution with $n-1$ degree of freedom and non-centrality parameter $\delta = 3\sqrt{n}\,C_{pli}$ and $\delta = 3\sqrt{n}\,C_{pui}$, denoted as $t'_{n-1}(\delta)$. In order to conveniently calculate the best estimators $\hat{C}_{pli}$ and $\hat{C}_{pui}$, various values of n correspond to values of b_n, listed in Table 3.

If the inspection statistical quantity $\hat{C}_{poi} = w_i$, acquired from the observed values of random samples, the *p-value* of each different quality property can be calculated from the following equation:

$$\begin{aligned} pv_j &= P\left\{\hat{C}_{poi} \leqslant w_i \mid C_{poi} = v\right\} \\ &= P\left\{\left(3\sqrt{n}/b_n\right)\hat{C}_{poi} \leqslant \left(3\sqrt{n}/b_n\right) w_i \mid C_{poi} = v\right\} \\ &= P\left\{t_{n-1}\left(\delta = 3\sqrt{n}\,v\right) \leqslant \left(3\sqrt{n}/b_n\right) w_i\right\}. \end{aligned} \quad (12)$$

In order to calculate the *p-value* conveniently, the program of SAS software is shown in the Appendix.

4 Evaluation procedure and criteria

In accordance with the inspection statistical quantity $\hat{C}_{poi} = w_i$, the *p-value* for each different quality charac-

Table 3 n values and corresponding values of b_n

n	b_n	n	b_n	n	b_n	n	b_n	n	b_n
6	0.8408	16	0.9490	26	0.9696	36	0.9784	46	0.9832
7	0.8687	17	0.9523	27	0.9708	37	0.9790	47	0.9836
8	0.8882	18	0.9551	28	0.9719	38	0.9796	48	0.9839
9	0.9027	19	0.9576	29	0.9729	39	0.9801	49	0.9843
10	0.9139	20	0.9599	30	0.9739	40	0.9806	50	0.9846
11	0.9227	21	0.9619	31	0.9748	41	0.9811	51	0.9849
12	0.9300	22	0.9638	32	0.9756	42	0.9816	52	0.9852
13	0.9359	23	0.9655	33	0.9763	43	0.9820	53	0.9855
14	0.9410	24	0.9670	34	0.9771	44	0.9824	54	0.9858
15	0.9453	25	0.9684	35	0.9778	45	0.9828	55	0.9860

Table 4 The evaluation table of production process capability for stranded wire

Item	Index value	*p-value*
Quality property 1: Loading of 0.2% permanent deformation	w_1	pv_1^{***}
Quality property 2: Tensile strength (kg)	w_2	pv_2
Quality property 3: Elongation (%)	w_3	pv_3
Quality property 4: Relaxation value (%)	w_4	pv_4

Marked with " *** " means that the production process capability of this quality property is unsatisfactory. The production process capability should be improved.

teristic can be calculated. The production process capability can then be evaluated whether it achieves the required specification based onα-risk. In order to get the most opportune moment of improved manufacture, a systematic evaluation method should be established for the manufacturer to judge the quality property of each product. Therefore, a simple evaluation procedure is provided in this article, based on the production process capability inspection of each different quality characteristic.

Step 1 Choose the required value of the production process capability c to calculate the production process capability index $r = \Phi^{-1}\left(\sqrt[4]{\Phi(3c)}\right)/3$ of each different quality property. The assigned alternative hypothesis and null hypothesis are:

$$\mathrm{H}_0 : C_{poi} \geq v,$$
$$\mathrm{H}_a : C_{poi} < v.$$

Step 2 Choose significance levelα (risks of manufacturer). The individual risk value can be assigned as $\alpha' = \alpha/4$ for each different quality property because there are four different quality characteristics of stranded wire.

Step 3 The sample mean value and standard deviation can be calculated according to observed values of random samples. The inspection statistical quantity $\hat{C}_{poi} = w_i$ can be attained in terms of sample size n value and corresponding value of b_n. The SAS program, provided in the Appendix, can then be used to obtain *p-value* $= pv_i$ for each quality property.

Step 4 The values of w_i and pv_j, gained from step 3, are filled in the evaluation table of production process capability, Table 4.

The following principles are used to judge whether the production process capability for each quality characteristic meets the required specification.

Table 5 The test results of Seven-wire strand-type A diameter = 10.8 mm, Seven-wire strand-type B diameter = 11.1 mm and nineteen-wire strand diameter = 20.3 mm

Type	Pull test			Long time relaxation test	Pull test			Long time relaxation test
Items	The tensile force of 0.2% permanent elongation	The tensile strength	The elongation	Relaxation	The tensile force of 0.2% permanent elongation	The tensile strength	The elongation	Relaxation
	kg	kg	%	%	kg	kg	%	%
Seven-wire strand-type A diameter = 10.8 mm	10440	12300	3.4	2.9	10300	12700	3.67	3.05
	11000	12100	3.5	3.1	10200	12030	3.5	3.2
	10000	12000	3.2	2.9	10600	14000	3.6	3.12
	10800	11900	3.3	2.85	10300	13000	3.8	2.89
	10700	13100	3.5	3.2	10500	13200	3.4	2.85
	11000	12280	3.7	2.83	10350	12300	3.6	2.98
	10900	12300	3.5	2.95	1500	13050	3.55	3.1
	10100	13000	3.7	3.1	10800	12900	3.45	3.07
Seven-wire strand-type B diameter = 11.1 mm	18800	18500	4.2	2.5	18890	18500	4.22	2.56
	19850	19000	4.11	2.6	18540	17000	4.13	2.679
	18850	18500	4.02	2.89	16980	18500	4.32	2.982
	19850	17850	3.99	2.44	16500	19850	3.98	2.34
	18540	17200	3.85	2.556	16580	18200	3.95	2.56
	19650	18505	4.21	2.67	18500	18500	4.15	2.63
	18850	18500	3.99	2.467	16850	19850	4.23	2.37
	16855	17800	4.01	2.89	17850	18950	4.00	2.67
Nineteen-wire strand diameter = 20.3 mm	54210	54500	3.78	2.51	54210	59870	3.85	2.51
	51300	58900	3.98	2.61	54620	57890	3.88	2.47
	51020	58940	3.76	2.59	52150	59870	3.77	2.75
	50450	60100	3.77	2.44	55400	56870	3.88	2.44
	54320	58400	3.8	2.56	55400	58900	3.89	2.46
	51200	58895	3.79	2.55	56500	57870	3.79	2.54
	52100	58840	3.87	2.45	54500	56980	3.82	2.40
	51050	57890	3.78	2.65	55000	59800	3.85	2.57

1. When $pv_j \leq \alpha'$, it means that the production process capability for this quality property is unqualified. The upper-right corner of *p-value* should be marked as " *** ".
2. When $pv_{ij} > \alpha'$, it means that the production process capability for this quality property is satisfactory.

If the upper right corner of *p-value* is marked as " *** ", the quality improved actions should be carried out. When the upper right corners of all *p-value* have no " *** " label, they mean that the production process capability of the product for each different quality characteristic attained the required specification. This means that the production process capability for this type of stranded wire meets the specified requirement.

5 Application of actual examples

Case studies demonstrated here reveal the applicability of this proposed evaluation procedure and criteria. These actual examples are samples from manufactured products to test the quality of strands. The manufacturer of strand products seven-wire strand-type A, diameter = 10.8 mm, seven-wire strand-type B, diameter = 11.1 mm and nineteen-wire strand, diameter = 20.3 mm for a pre-stressed concrete bridge of the high speed railroad system in Taiwan. Each batch of the product is sampled twice for the test. There are 16 samples for these three types of strands. The pull test and the long time relaxation test are listed in Table 5.

Step 1 Choose the required quality condition, "Satisfactory". Thus, the minimum required value of production process capability c is 1.333. Then the production process capability index is $r = v = 1.436$ for each different quality property(see Table 2). The assigned alternative hypothesis and null hypothesis are:

$$\mathrm{H}_0 : C_{poi} \geq v,$$
$$\mathrm{H}_\mathrm{a} : C_{poi} < v.$$

Step 2 Determine the significance level, the manufacturer's risks, $\alpha = 0.5$. The individual risk value can then be assigned as $\alpha' = \alpha/4 = 0.125$ for each different quality property.

Step 3 The sample size n value and corresponding value of b_n are equal to 16 and 0.9490 respectively.

The sample mean value, standard deviation and inspection statistical quantity $\hat{C}_{poi} = w_i$ of the three types of strands are listed in Table 6.

The SAS program, provided in the Appendix, can then be used to obtain *p-value* $= pv_i$ for each quality property.

Step 4 The values of $w_i$and pv_j, acquired from step 3, are filled in the evaluation table of the production process capability, (Table 7).

In accordance with the evaluation table of Table 7, all the quality properties of the seven-wire strand-type A, the quality property 4 of the seven-wire strand-type B are unsatisfactory. The " *** " marking the *p-values* in the upper-right corner of Table 7 means that the production process capability of the product for each different quality characteristic do not reach the required specification. Strand manufacturers should improve the quality of this type of strand quickly, otherwise the purchasing agency of a construction company may decided to return an order for the goods based on this evaluation procedure and criteria.

Table 6 The test statistical quantity of sample mean value, standard deviation and $\hat{C}_{poi} = w_i$ of three types of strands

Type of strand	Mean value	Standard deviation	$\hat{C}_{poi} = w_i$
Seven-wire strand-type A diameter = 10.8 mm			
Quality property 1: Loading of 0.2% permanent deformation (kg)	10530.6250	304.2505	0.1359
Quality property 2: Tensile strength (kg)	12635.0000	557.3490	0.2468
Quality property 3: Elongation (%)	3.5231	0.1511	0.0484
Quality property 4: Relaxation value (%)	3.0056	0.1225	–0.0145
Seven-wire strand-type B diameter = 11.1 mm			
Quality property 1: Loading of 0.2% permanent deformation (kg)	18245.9400	1125.6300	1.7553
Quality property 2: Tensile strength (kg)	18450.3100	750.0220	1.8348
Quality property 3: Elongation (%)	4.0850	0.1250	1.4810
Quality property 4: Relaxation value (%)	2.6128	0.1781	0.6879
Nineteen-wire strand diameter = 20.3 mm			
Quality property 1: Loading of 0.2% permanent deformation (kg)	53464.3800	2081.9600	1.5900
Quality property 2: Tensile strength (kg)	58375.9400	1477.1400	1.6867
Quality property 3: Elongation (%)	3.8288	0.0585	1.7774
Quality property 4: Relaxation value (%)	2.5313	0.0882	1.6805

Table 7 The evaluation table of production process capability for test samples

Item	Index value	*p-value*
Seven-wire strand-type A diameter = 10.8 mm		
Quality property 1: Loading of 0.2% permanent deformation (kg)	0.1359	0.0000***
Quality property 2: Tensile strength (kg)	0.2468	0.0000***
Quality property 3: Elongation (%)	0.0484	0.0000***
Quality property 4: Relaxation value (%)	–0.0145	0.0000***
Seven-wire strand-type B diameter = 11.1 mm		
Quality property 1: Loading of 0.2% permanent deformation (kg)	1.7553	0.8676
Quality property 2: Tensile strength (kg)	1.8348	0.9055
Quality property 3: Elongation (%)	1.4810	0.6213
Quality property 4: Relaxation value (%)	0.6879	0.0000***
Nineteen-wire strand diameter = 20.3 mm		
Quality property 1: Loading of 0.2% permanent deformation (kg)	1.5900	0.7438
Quality property 2: Tensile strength (kg)	1.6867	0.8245
Quality property 3: Elongation (%)	1.7774	0.8794
Quality property 4: Relaxation value (%)	1.6805	0.8201

6 Conclusion

The formulae for the proposed index and evaluation procedure and criteria are easy to understand and straightforward to apply. Generally, most products consist of numerous unilateral and bilateral specifications. The approach of this research is to develop one integrated process capability model that can precisely measure a product with the larger-the-better and the smaller-the-better multi-process characteristics. This integrated multi-quality property capability analysis model can be used to evaluate the multi-process capabilities. Actions of quality improvement are taken with respect to unsatisfactory processes to improve the entire quality of the strand in the manufacturing process. Therefore, this integrated multi-quality property capability analysis model can be used to evaluate the multi-process capabilities and provide continuous improvements on stranded wire manufacturing processes. This new procedure is also very useful for the customers to examine and compare the production capability and quality of stranded wire manufacturers. Therefore, the engineering unit can wisely purchase the high quality of strand.

7 Appendix

```
/*************************************************************/;
/* SAS PROGRAMING--p-value */;
/*************************************************************/;
/* H0:Cpoi>=1.436 (P-VALUE) */;
OPTIONS REPLACE PAGESIZE=58 LINE-
SIZE=78 NODATE;
DATA NCENT;
INPUT w @@;
n=16;v=1.436;bn=0.949;
D=3*SQRT(n)*v;
x=3*SQRT(n)*w/bn;
PV=PROBT(X,15,D);
FORMAT PV 6.4;
CARDS;
0.1359 0.2468 0.0484 –0.0145
1.7553 1.8348 1.4810 0.6879 1.5900
1.6867 1.7774 1.6805
;
PROC PRINT DATA=NCENT;
VAR W PV;
RUN;
```

References

1. American society for testing and materials committee (1998) ASTM A 416-98, Standard specification for uncoated seven-wire stress-relieved strand for prestressed concrete, p 416
2. Euronorm 138-78 (1978) Prestressing steels. European Normal
3. Doi A et al (1971) Japanese report on cases of spontaneous rupture and laboratory research. Federation Internationale de la Precontrainte (FIP) Symposium, Stress Corrosion, Delft
4. Doi A, Tomoika H et al (1975) Physical properties of prestressing steel at low and elevated temperatures. Report No DRG75–04, Shinko Wire Co Ltd, Amagasaki, Japan
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. Chou YM, Owen DB (1989) On the distribution of the estimated process capability indices. Commun Stat Theory Methods 18:4549–4560
8. Boyles RA (1991) The Taguchi capability index. J Qual Technol 23(1):17–26
9. Pearn WL, Kotz S, Johnson KL (1992) Distribution and inferential properties of process capability indices. J Qual Technol 24:216–231
10. Boyles RA (1994) Process capability with asymmetric tolerances. J Tolerances Commun Stat Simul Comput 23(3):615–643
11. Greenwich M, Jahr-Schaffrath BL (1995) A process incapability index. Int J Qual Reliab Manage 12(4):58–71.
12. Chen KS (1998) Incapability index with asymmetric tolerances. Stat Sinica 8:253–262
13. Vännman K, Deleryd M (1999) Process capability plots – a quality improvement tool. Qual Reliab Int 15:213–217

14. Pearn WL, Chen KS (1988) Multiprocess performance analysis: a case study. Qual Eng 10(1):1–8
15. Chang PL, Hwang SN, Cheng WY (1995) Using data envelopment analysis to measure the achievement and change of regional development in Taiwan. J Environl Manage 43:49–66
16. Pearn WL, Chen KS (2002) One-sided capability indices cpu and cpl: decision making with sample information. Int J Qual Reliab Manage 19(3):221–245