Send Orders for Reprints to reprints@benthamscience.ae

The Open Automation and Control Systems Journal, 2014, *6*, 1875-1882 1875

Open Access

Process Capability Optimization in Multistage Manufacturing Processes Based on the Cost-Utility Ratio

Ning Wang*

Business school, Zhengzhou University, Zhengzhou 450001, P.R. China

Abstract: To solve the problem that process capability optimization in multistage manufacturing processes has not been studied so much. Firstly, a multistage manufacturing process quality variation model is built to analyze the impaction of each stage quality on process capability. Then, a multistage manufacturing process capability analysis method with "Cost-utility ratio" is proposed to prioritize process capability optimization efforts. At last, a two stage matching process is taken as an example to demonstrate it. The results show that this method ascertains the priorities and process capability optimization degree well.

Keywords: Multistage manufacturing process, quality improvement, process capability optimization, cost-utility ratio.

1. INTRODUCTION

Multistage manufacturing process capability refers to the actual processing ability of multistage manufacturing process under steady state making products to meet the design specification, which is usually affected by the specification limits, the process mean and process variance. Among them, the specification limit is assigned by the "customers", and the process mean and process variance affected by the manufacturing process. If process average is not deviated, then process capability can be improved by decreasing the process variance namely reducing the quality variation. However, as the production has become increasingly complex, the manufacturing process often involves more sub processes, in which the influence of the correlation exist, and the impact of the quality variation reduction on process capability is also more complex.

In recent years, Scholars at home and abroad have researched the subject that multistage manufacturing process capability optimization widely. Professor Zhang Gongxu presented two kinds of process capability index which is used to judge and evaluate the production process. Pearn, Chang and some scholars put forward the method of process capability analysis on the process with Multi-strip production line. Ding studied on the process capability sensitivity of the multistage manufacturing process. Liu Daoyu and Jiang Pingyu proposed a multistage process capability evaluation method based on the process variation trajectory chart to solve the problem that the single process and single quality characteristic evaluation method cannot be directly used in multistage process capability analysis. Linn, studied a multistage process capability analysis algorithm, and which is used to analyze the multistage process improvement effect. Sun Jing proposed a process capability analysis method with regard to the relevant data. Huang Wenzhen and Kong Zhenyu proposed sensitivity analysis method based on the qualification rate to evaluate the multistage assembly process capability. Fang Zhu and Xiongfei, Huang used the modified process capability indices to calculate the overall process capacity of complex product manufacturing processing, and further determined the improvement direction and scope of single process parameters based on the sensitivity analysis.

In conclusion, the current multistage manufacturing process optimization mainly through the sampling data of existing process to make "afterwards" evaluation, which is to use the experimental design method to reduce the sensitivity of the product performance to process parameter variation. The ultimate goal of these methods is to achieve the most optimal process capability. However, there is no way to effectively evaluate the direct influence of each sub processes quality variation on multistage manufacturing process capability. In addition, existing research only focuses on process variation reduction, but ignore the resource consumption with it, which would tend to cause excessive process control and ignore the fluctuations that tend to cause and form quality waste. Therefore, in this article, based on the Law less's multistage manufacturing process analysis model, the corresponding relationship between each sub process quality variation with each sub process capability, sub process transfer coefficient and total process capability is built, and the influence of each sub processes quality variation decrease and different transfer coefficient on the process capability. Then according to the "difficulty" and "cost-utility ratio" of variation reduction evaluating the quality improvement effect, so as to provide the basis for process optimization.

2. RESEARCH ASSUMPTIONS AND VARIABLE DEFINITIONS

Multistage manufacturing process capability optimization is mainly to identify each sub process capability in multistage manufacturing process, analyze the influence of each

1874-4443/14 2014 Bentham Open

sub processes quality variation on the total process capability, then, determine the priority of each sub processes quality variation reduction in process capability optimization and confirm the degree and number in need of improvement. Therefore, in order to facilitate analysis, the following notations are used in presenting the process capability analysis procedures.

2.1. Research Premise and Assumptions

The multistage manufacturing process capability optimization in this paper is created under the following premise assumptions:

Premise 1: Multistage manufacturing process is stable or statistical controlled, and the process output obeys normal distribution;

Premise 2: The total process and sub-processes have clearly output characteristic;

Premise 3: The process samples extracting only affected by random factors.

Assumptions 1: To facilitate discuss C_{pmokj}, two stage process is chosen to illustrate multistage manufacturing process capability optimization;

Assumptions2: The random error in the two stage is w_{X_1} and w_{X_2}, and both obey the standard normal distribution: $w_{X_1} \sim N(0,1)$, $w_{X_2} \sim N(0,1)$;

Assumptions 3: The mean of multistage manufacturing process have deviation, the mean deviate from specification center 1 unit;

Assumptions 4: The specification ranges of both processes are [-4，4], the target and specification centre are coincide, namely $T = m = 0$；

Assumptions5: In the first process, $\sigma_{s1} = \sigma_{o1}$. σ_{s1} reflects the specific variation, which remove the quality variation affection transmitted from previous process.

2.2. Variable Definitions

The following notations are used in presenting the process capability optimization procedures.

σ_{si}^2 : Specific variation in the process;

σ_{oi}^2 : Overall variation in the ith process, which is affected by the current and previous process;

σ_{sij}^2 : Specific variation in the ith ith process jth equipment;

σ_{oij}^2 : Overall variation in the ith process jth equipment, which is affected by the current and previous process;

β_i : The process transfer coefficient from stage $i-1$ to stage i ;

μ_{ij} : Overall mean in process which is affected by the current and previous processes;

USL, LSL : The process upper and lower specification limits;

C_{pksij} : Specific process capability in the ith process jth equipment,

$$C_{pksi} = \frac{\min(\mu_i - LSL, USL - \mu_i)}{3\sigma_{si}} \tag{1}$$

C_{pkoij} : Overall process capability in the process equipment,

$$C_{posi} = \frac{\min(\mu_i - LSL, USL - \mu_i)}{3\sigma_{oi}} \tag{2}$$

C_{pmsij} : Specific Taguchi process capability in the process equipment,

$$C_{pmsi} = \frac{USL - LSL}{6\sqrt{\sigma_{si}^2 + (\mu_i - T)^2}} \tag{3}$$

C_{pmoij} : Overall Taguchi process capability in the process equipment,

$$C_{pmoi} = \frac{USL - LSL}{6\sqrt{\sigma_{oi}^2 + (\mu_i - T)^2}} \tag{4}$$

C_{pkokj} : Overall process capability in the last kth process equipment.

C_{pmokj} : Overall Taguchi process capability in the last process equipment,

IC_{pksij} and IC_{pmsij} : Numerical increment of C_{pksij} and C_{pmsij} after the variation reduction in the process equipment.

IC_{pkokj} and IC_{pmokj} : Numerical increment of C_{pkoij} and C_{pmoij} after the variation reduction in the process equipment.

F_{dij} : Degree of difficulty to reduce variation in the process equipment. The degree of difficulty, F_{dij} is a normalized value among all stages. It is determined by the resource consumption on reducing the variation in each stage. The resource includes time, manpower, materials, and other overheads. The degree of difficulty for the stage l with least resource consumption, is set to 1, $F_{dl} = 1$. The degrees of difficulty for the rest stages, F_{dij} where $i \neq l$, are determined by the ratio of resource consumptions of process jth equipment, and the stage l.

ER: Effort ratio which is the ratio of effort spent to increase the C_{pksij} or C_{pmsij} with respect to the increment of the C_{pksij} or C_{pmsij},

$$ER = \frac{IC_{pkokj}}{IC_{pksij} \times F_{dij}} \tag{5}$$

3. MODELING ANALYSIS OF MULTISTAGE MANUFACTURING PROCESS

Multistage manufacturing process capability analysis is based on multistage process variation propagation model. A multistage manufacturing process variation propagation model will be built in this section referring to the AR (1) model proposed by Lawless (1999).

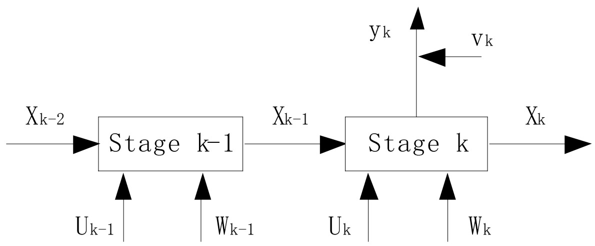

Fig. (1). Two sub processes tandem structure.

First of all, the two sub processes tandem structure is taken as an example to discuss the modeling of multistage manufacturing process variation transmission model, as shown in Fig. (**1**). On the basis of the AR (1) model propos©ed by Lawless (1999), the quality relationship of the adjacent two tandem structure sub processes in figure is formulized:

$$x_k = A_{k-1}x_{k-1} + B_k u_k + W_k$$
$$y_k = C_k x_k + v_k \tag{6}$$

Where $A_{k-1}x_{k-1}$ is the influence of the product quality characteristic on stage product quality, which is propagated from $k-1$ stage. is the influence of stage product quality characteristics on product quality, which is caused by this stage process failure. C_k maps the product quality status in the k_{th} process to the product quality measurement value, namely measure coefficient vector. To facilitate the understand, the measure coefficient vector is assumed to be the unit matrix and there is no measurement error in this paper. So the formula (6) can be simplified:

$$x_k = A_{k-1}x_{k-1} + B_k u_k + W_k \tag{7}$$

Before modeling variation propagation model, assume that the quality characteristics x_k and x_{k-1} in the k stage and the k-1 stage obey the normal distribution:

$$x_{k-1} \sim N(\mu_{k-1}, \sigma_{k-1}^2), \quad x_k \sim N(\mu_k, \sigma_k^2)$$

For convenience, defined $A_{k-1} = \beta_{k-1}, B_k u_k = \alpha_k$, substituting into the formula (7) to acquire:

$$x_k = \alpha_k + \beta_{k-1}x_{k-1} + w_k \tag{8}$$

In multistage manufacturing process, the quality variation in a sub process besides affected by this process, also includes the variation influence propagated from the last process. So the quality variation x_k can be formulized:

$$Var(x_k) = Var(E(x_k | x_{k-1})) + E(Var(x_k | x_{k-1})) \tag{9}$$

Defining $E(x_k) = \mu_k, Var(x_k) = \sigma_k^2$, the following formula can be got by formulas (8) and (9):

$$\mu_k = \beta_{k-1}\mu_{k-1} + \alpha_k \tag{10}$$

$$\sigma_k^2 = \beta_{k-1}^2\sigma_{k-1}^2 + \sigma_{kA}^2 \tag{11}$$

Formula (11) is the two stage process variation propagation model, the first item $\beta_{k-1}^2\sigma_{k-1}^2$ on the right side of the formula means the quality variation propagated from the $k-1$ stage to the k stage. The second item σ_{kA}^2 said the increased quality variation of the k stage itself in the manufacturing process, which include normal variation and the system noise.

Formulas (2) to (6) represents the two-stage quality characteristics variation propagation model, after recursion, the multistage manufacturing process variation propagation model can be got:

$$Var(x_k) = \sigma_k^2 = \sum_{i=1}^{k} \beta_k^2\beta_{k-1}^2, \cdots, \beta_i^2\sigma_{iA}^2 + \beta_k^2\beta_{k-1}^2, \cdots, \beta_1^2\sigma_{1A}^2 \tag{12}$$

Formula (7) is the multistage manufacturing process variation propagation model.

4. MULTISTAGE MANUFACTURING PROCESS CAPABILITY OPTIMIZATION

In multistage manufacturing process, there would be different effects and influence of each sub processes quality variation on the total process capability and the final product improvement. Richard J. Linn *et al.* (2002) present the relationship between the each sub process quality variation and process capability indexes, and then determine the priorities of quality improvement. In this article, the interrelation between each sub process quality variation σ^2, transfer coefficient β and C_{pk} are respectively established based on the Linn's study. Then, the different effects of each sub process quality variation reduction on the specific process capability and overall process capability. At last, two concepts, "difficulty" and "cost-utility Ratio" are introduced to be as the improvement basis of multistage manufacturing process capability optimization.

4.1. The Ideas of Multistage Manufacturing Process Capability Optimization

In this paper, The ideas of multistage manufacturing process capability optimization is keeping the other sub process quality variation invariable and improve the final process capability index by reducing one sub process quality variation. According to the above multistage manufacturing process modeling analysis. Two stage string manufacturing process variation propagation model is:

$$\mu_2 = \alpha_2 + \beta_1 \mu_1 \quad (13)$$

$$\sigma_{o2}^2 = \beta^2 \sigma_{o1}^2 + \sigma_{s2}^2 \quad (14)$$

Among them, β value can be obtained based on historical data using PLSR method. Therefore, for two stages manufacturing process, there are two ways to optimize the overall process capability:

Method 1: keep $\sigma_{s2} = 1$ unchanged, gradually reduce the first sub process quality variation.

Method 2: keep $\sigma_{s1} = 1$ unchanged, gradually reduce the second sub-process quality variation.

Detailed analysis of these two approaches as follows

According to the formula(12) , σ_{o2} could get different values by different correlation coefficients β and process capability index C_{pksi} $(i = 1, 2)$. The relationship between σ_{o2} , C_{pksi} , β and σ_{si} under two methods in Tables **1** and **2**.

The relationship diagram between overall process capability C_{pko2} and correlation coefficients β could be got through the data of the Table **1** and **2**, as shown in Figs. (**2**) and (**3**).

As seen in Fig. (**2**), according to the improved method 1 that improve the same degree of process capability index C_{pks1} , the bigger value of β, the greater increase of process capability index C_{pko2} ,and if the value of A is fixed, then the distance between the curves is not the same. Therefore, it can be concluded that the improvement of process capability

Table 1. The relationship table of σ_{o2} , C_{pksi} , β and σ_{si} in method 1.

		β								
C_{pks1}	$\hat{U}_{s1}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1.1	1.2121	1.007	1.029	1.064	1.111	1.169	1.236	1.311	1.393	1.48
1.2	1.1111	1.006	1.024	1.054	1.094	1.144	1.202	1.267	1.338	1.414
1.3	1.0256	1.005	1.021	1.046	1.081	1.124	1.174	1.231	1.294	1.361
1.4	0.9524	1.005	1.018	1.04	1.07	1.108	1.152	1.202	1.257	1.317
1.5	0.8889	1.004	1.016	1.035	1.061	1.094	1.133	1.178	1.227	1.281
1.6	0.8333	1.003	1.014	1.031	1.054	1.083	1.118	1.158	1.202	1.25
1.7	0.7843	1.003	1.012	1.027	1.048	1.074	1.105	1.141	1.181	1.224
1.8	0.7407	1.003	1.011	1.024	1.043	1.066	1.094	1.126	1.162	1.202
1.9	0.7018	1.003	1.01	1.022	1.039	1.06	1.085	1.114	1.147	1.183
2.0	0.6667	1.002	1.009	1.02	1.035	1.054	1.077	1.104	1.133	1.166

Table 2. The relationship table of σ_{o2} , C_{pks2} , β and σ_{s2} in method 2.

		β								
C_{pks2}	$\hat{U}_{s2}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1.1	1.2121	1.216	1.228	1.249	1.276	1.311	1.352	1.4	1.452	1.51
1.2	1.1111	1.116	1.129	1.151	1.181	1.218	1.263	1.313	1.369	1.43
1.3	1.0256	1.03	1.045	1.069	1.101	1.141	1.188	1.242	1.301	1.364
1.4	0.9524	0.958	0.973	0.999	1.033	1.076	1.126	1.182	1.244	1.31
1.5	0.8889	0.895	0.911	0.938	0.975	1.02	1.072	1.131	1.196	1.265
1.6	0.8333	0.839	0.857	0.886	0.924	0.972	1.027	1.088	1.155	1.227
1.7	0.7843	0.791	0.809	0.84	0.88	0.93	0.987	1.051	1.12	1.194
1.8	0.7407	0.747	0.767	0.799	0.842	0.894	0.953	1.019	1	1.166
1.9	0.7018	0.709	0.73	0.763	0.808	0.862	0.923	0.991	1.064	1.141
2.0	0.6667	0.674	0.696	0.731	0.777	0.833	0.897	0.967	1.041	1.12

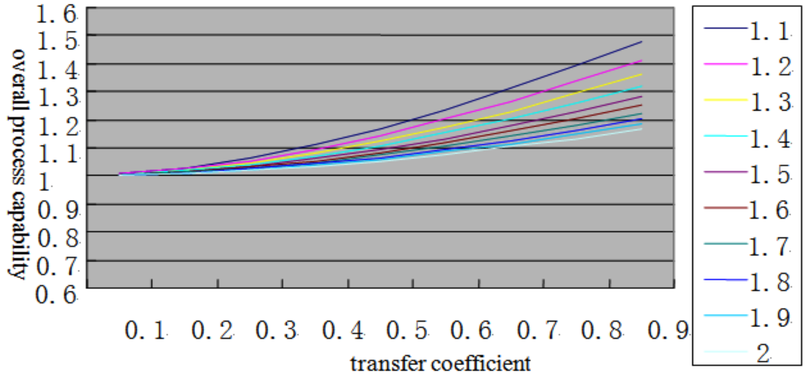

Fig. (2). The diagram of overall process capability and transfer coefficient in method 1.

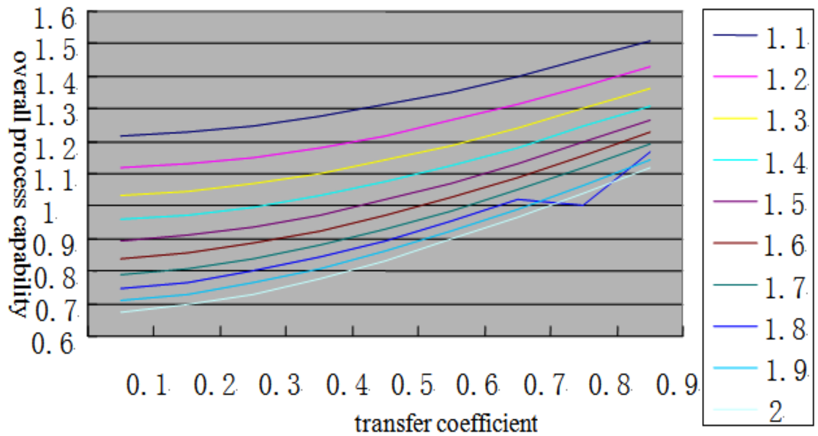

Fig. (3). The diagram of overall process capability and transfer coefficient in method 2.

index C_{pko2} and the improvement of process capability index C_{pks1} is not proportional if use method 1.If the initial value of C_{pks1} is relatively high, C_{pks1} need to be higher to increase the C_{pko2} with same extent.

In Fig. (**3**), increasing the same amount process capability index C_{pks2}, the larger value of β, the smaller increase of process capability index C_{pko2}, if the value of β is fixed, the distance between the two process capability curve are equal. Therefore, it can be concluded that the improvement of process capability index C_{pko2} and the improvement of process capability index C_{pks2} is proportional if use method 2. Because of the higher effect of sub-process, increasing the value of β will increase the second sub fluctuations. Therefore, raising the same amount of B need greater efforts.

4.2. Method of Multistage Manufacturing Process Capability Optimization based on "Cost-Utility Ratio"

The ultimate goal of multistage process capability optimization is clearly pointing out the relationship between different sub processes quality output and the process capability of the final output, enhancing the improvement effect of multistage manufacturing process capability. Therefore, based on the above analysis, multistage tandem process capability optimization method can be summarized as follows:

The first step: Through the historical data, the mean, variance and the transfer coefficient β of each process need to be calculated based on the quality relationship model and variation transmission model.

Step two: calculating the specific and overall process capability index of each sub process according to the formulas (1), (2), (3) and (4) ;

Step Three: Compare C_{pko2} and its target value, if it meet the target value, it do not need to be improved. Otherwise, the target value is set as improvement targets;

Step four: Based on the target of C_{pko2} and the value of β, calculating the needed degree of quality variation reduction to achieve the target value of C_{pko2} according to the two methods by the formula (12) and (13);

Step Five: According to the actual situation, calculate F_{di}, then calculate cost-utility ratio ER by the formul,

$$ER = \frac{IC_{pkokj}}{IC_{pksij} \times F_{dij}}.$$

According to the formula, the utility ratio is inversely proportional to the degree of difficulty in variation reduction, and proportional to the degree of improvement in overall process capacity. that is, the higher utility ratio indicating that the effect of improving process capacity by per unit of resource consumption is more excellent, so the best process ability optimized order could be determined.

5. EMPIRICAL STUDY

Now take mandrel drilling process as an example to verify the correctness and effectiveness of the method described above. This mandrel drilling process that mandrel after processing is carried fixture in the machine, then drilling by the tool, is a typical multi-stage manufacturing process, shown in Fig. (**4**).

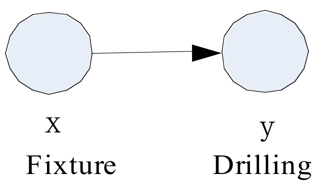

Fig. (4). Drilling mandrel manufacturing process diagram.

Among this, the key quality characteristics, fixture diameter, in the fixture process is x, y for the hole diameter, which is the drilling process key quality characteristics, fixture diameter has a direct impact on the hole diameter after drilling.

Within a certain time, random sample of 70 sets data are chosen and ensure that they are one to one, specific data could be shown in Tables **3** and **4**. Where, Table **3** is fixture diameter sample data and Table **4** is the hole diameter sample data.

Through the data statistical analysis, we can obtained that, during fixture process, the mean of fixture diameter x is 201.24, variance is 2.618524. In the drilling process, the mean of hole diameter y is 201.131, variance is 1.685. Specification limit of fixture diameter is set as [202.38, 218.1], specification limit of hole diameter is set as [194.91, 207.35]. Assuming that the random errors of the two process were ε_x and ε_y , and subject to normal distribution $\varepsilon_x \sim N(0,\sigma_x^2)$, $\varepsilon_y \sim N(0,\sigma_y^2)$, in accordance with the foregoing modeling method, the quality relationship mode could be got:

Table 3. Fixture diameter sample data (unit: 0.001mm).

202.0256	202.8422	200.3642	199.5749	202.9619	201.2187	199.7900
201.2319	201.5942	199.0821	201.6334	200.8429	200.3010	201.4587
200.7930	201.6634	202.9758	199.2066	198.7843	204.6969	201.0150
203.3055	203.2036	200.0877	200.6782	201.2558	200.8231	199.3574
204.2553	200.7955	201.2217	199.7167	201.3555	198.9591	203.1555
200.3944	201.0246	201.2387	199.3393	201.7522	204.1044	201.2150
201.4074	199.1841	200.8364	199.5876	202.0488	201.7668	202.1077
199.9331	198.5480	201.8817	200.5900	203.3082	199.4292	200.0807
202.3411	200.1015	200.8128	201.5210	200.3535	202.2438	200.1792
197.4137	201.6945	198.5473	201.0521	201.6620	203.2947	201.7487

Table 4. Hole diameter sample data (unit: 0.001mm).

201.2696	202.2174	202.1843	200.2812	201.7033	199.8574	203.3839
203.5300	200.1935	201.9570	199.7283	202.7937	200.2373	203.6458
200.7739	200.1945	202.8315	201.0690	200.4849	202.8696	203.2533
204.0029	200.8699	201.5556	201.6234	199.6789	199.9508	199.5008
203.0891	201.1044	200.2575	200.7022	202.1793	200.5951	200.8538
198.6063	201.4930	200.9372	200.4821	201.1845	200.4740	200.8728
198.9497	202.5047	197.9522	201.0843	200.1494	203.2334	201.5301
200.3866	201.9379	201.7453	200.9042	201.0153	201.2360	200.3881
200.8898	198.8587	201.2828	199.8885	198.5235	199.7278	199.8620
201.1426	202.0362	200.3637	202.8087	202.5379	199.6714	200.5510

Table 5. Variation and process capability of two stage process.

	$i=1$	$i=2$
σ_{si}	2.618524	1.685
C_{pksi}	1	1.23
σ_{oi}	2.618524	2.072036
C_{pkoi}	1	1

Table 6. Process capability analysis.

	Current value	**Method 1**	**Method 2**
σ_{s1}	2.618524	1.835 (↓29.9%)	2.618524
σ_{s2}	1.685	1.685	1.449 (↓14%)
σ_{o2}	2.072036	1.885 (↓9%)	1.885 (↓9%)
	1	1.428 (↑42.8%)	1
	1.23	1.23	1.431 (↑16.3%)
C_{pko2}	1	1.1 (↑10%)	1.1 (↑10%)
ER		0.2336	0.4975

$$x = 201.24 + \varepsilon_x \quad y = 104.325 + 0.460456x + \varepsilon_y$$

Because $\sigma_{s1} = \sigma_{o1}$, $C_{pks1} = C_{pko1}$, according to the formula (1) and (2), the specific process capability and overall process capability could be calculated, the results are shown in Table **5**.

From the table, this two stage manufacturing process capability is obviously insufficient, the current process capability index C_{pko2} is 1, for ease to analysis, set making increased by 10% as an improve target, means when $C_{pko2} = 1.1$, this process capability is acceptable.

Then using the above process capability analysis to reduce the quality variation of the two stage sub processes to improve process capability, the results are shown in Table **6**.

As shown in Table **6**, according to the formula (12), σ_{s1}, σ_{s2} and σ_{o2} is 2.618524, 1.685 and 2.072036 respectively. The current C_{pko2} is 1, In order to achieve the goal of $C_{pko2} = 1.1$.In the method 1, reducing the fixture diameter quality variation σ_{s1} to 1.835, correspondingly the C_{pks1} increased to 1.428, total process quality variation reduced to 1.885, and achieve the target of C_{pko2} = 1.1. Also in the method 2, reducing the drilling process quality variation σ_{s2} to 1.449, correspondingly the C_{pks2} increased 16.3 percent to1.431, also achieved the target of C_{pko2} = 1.1.

Two methods both achieve the goals of improving process capability, and therefore need to compare the cost-utility ratio in improving the process ability. Assumed the degree of difficulty $F_{d1} = F_{d2} = 1$, then according to the formula (5), the cost-utility ratio is 0.2336 in method 1, and 0.4975 in method 2. Obviously, you should choose method 2 as the priority measures to improve the process capability.

6. CONCLUSION

In this paper, according to modeling analysis of multistage manufacturing process, the corresponding relationship between the sub processes quality variation, each sub process capability、the sub process transfer coefficient and overall process capability could be built, and identifying the influence of each sub processes quality variation and different transfer coefficient on overall process capability. And the "difficulty" and "cost-utility ratio" are introduced into evaluating the effect of quality improvement, which could provide the basis for the process ability optimization.

There are some limitations of this paper: (1) Sensitivity analysis problem of the multistage manufacturing process capability; (2) Multistage manufacturing process modeling and process capability analysis problems under parallel structure; (3) the multistage process ability analysis considering the mean shift. All this will be the focus of author's future work.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant No.71272207) ,the Ministry of Education of Humanities and Social Science Foundation of China(Grant No.14YJC630126)and Science and technology research key project Foundation in Henan province department of education of China (No. 14A630053).

REFERENCES

[1] S. Kotz and N. L. Johnson, "Process capability indices-a review, 1992-2000/discussion", *Journal of Quality Technology*, vol. 34, no. 1, pp. 2-53, 2002.

[2] L. K. Chan, and S. W. Cheng, "Spring F A. A new measure of process capability index Cpm", *Journal of Quality Technology*, vol. 20, no. 3, pp. 162-175, 1988.

[3] C. W. Wu, W. L. Pearn, and S. Kotz, "An overview of theory and practice on process capability indices for quality assurance", *Int. J. Production Economics*, vol. 117, pp. 338-359, 2009.

[4] V. E. Kane, "Process capability indices", *Journal of Quality Technology*, vol. 18, pp. 41-52, 2009.

[5] B. H. Gunter, "The use and abuse of Cpk (Part 1-4)", *Quality Progress*, vol. 22, no. 1, pp. 72-73, 1989.

[6] R. A. Boyles, "The Taguchi capability index", *Journal of Quality Technology*, vol. 23, no. 1, pp. 107-126, 1991.

[7] S. Sardar and Y. H. Lee, "A Quantitative Model of Supply Chain Innovativeness as a Disruption Management Strategy in the Textile Industry", *Advances in Industrial Engineering and Management*, vol. 4, no. 1, pp. 9-28, 2015..

[8] W. L. Pearn and C. S. Chang, "Precision measures for processes with multiple manufacturing lines", *International Journal of Advanced Manufacturing Technology*, no. 30, pp. 1202-1210, 2006.

[9] Y. Ding, S. Zhou, and Y. Chen, "A comparison of process variation estimators for in-process dimensional measurements and control", *ASME Transactions, Journal of Dynamic Systems, Measurement and Control*, vol. 127, no. 1, pp. 69-79, 2005.

[10] R. J. Linn, E. Au, and F. Tsung, "Process Capability Improvement for Multistage Processes", *Quality Engineerig*, vol. 15, no. 2, pp. 281-292, 2002.

[11] N. Wang, "Identifying Method for Key Quality Characteristics in Series-Parallel Multistage Manufacturing Process", *The Open Automation and Control Systems Journal*, vol. 11, no. 6, pp. 203-207, 2014.

[12] N. Wang, "Identifying method of key quality characteristics in multistage manufacturing process", *Computer Integrated Manufacturing Systems*, no. 4, pp. 888-895, 2013.

[13] N. Wang, "Method of Identifying Key Quality Characteristics in Multistage Manufacturing Process Based on PLSR", *Operations Research and Management Science*, no. 5, pp. 227-232, 2013.

[14] J. Sun, S. X. Wang, and Z. H. Fu, "Process capability analysis and estimation scheme for auto correlated data", *Journal of Systems Science and Systems Engineering*, vol. 19, no. 1, pp. 105-127, 2010.

[15] W. Z. Huang and Z. Y. Kong, "Process Capability Sensitivity Analysis for Design Evaluation of Multistage Assembly Processes", *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 7, pp. 736-745, 2010.

Received: September 16, 2014 Revised: December 23, 2014 Accepted: December 31, 2014