

MIT Open Access Articles

A Systematic Study of the Prediction Model for Operator-Induced Assembly Defects Based on Assembly Complexity Factors

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Qiang Su, Lei Liu, and Daniel E. Whitney. "A Systematic Study of the Prediction Model for Operator-Induced Assembly Defects Based on Assembly Complexity Factors." *Systems, Man and Cybernetics, Part A: Systems and Humans*, IEEE Transactions on 40.1 (2010): 107-120. © 2009 Institute of Electrical and Electronics Engineers.

As Published: <http://dx.doi.org/10.1109/tsmca.2009.2033030>

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: <http://hdl.handle.net/1721.1/53551>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



A Systematic Study of the Prediction Model for Operator-Induced Assembly Defects Based on Assembly Complexity Factors

Qiang Su, *Member, IEEE*, Lei Liu, and Daniel E. Whitney, *Fellow, IEEE*

Abstract—It is a common view that the assembly process heavily affects a product's final quality and cost. The continuously shortening product life cycle requires a faster response speed as well as a lower defect rate in assembly production. In this situation, assembly quality control is becoming one of the most demanding problems in the modern manufacturing environment. The main causes of assembly defects can be classified into four categories, i.e., improper design, defective part, variance in assembly system, and operator error. The first three categories have been studied for many decades. However, elements of the operator error have not been fully explored. In this paper, using a copier assembly as an example, the problem of assembly defects caused by mistakes of operators is investigated systematically. A novel defect-rate prediction model is derived from the study of two complexity factors, namely, the design-based assembly complexity factor and the process-based assembly complexity factor, which are defined according to the structure and production characteristics of the copier. Several case studies consistently demonstrate that the new prediction model is accurate and stable for evaluating the copier assembly quality. Moreover, another case study offered in this paper demonstrates that the prediction model can provide effective assistance in the improvement of assembly quality.

Index Terms—Assembly, design for assembly (DFA), quality control.

I. INTRODUCTION

ASSEMBLY, the process of putting together of manufactured parts to make a completed product, is crucial to the cost and quality performance. Taking a copier as an example, according to the field statistics, the first-time pass rate in assembly production is only about 50% or less. Usually, three months are needed before the pass rate can reach a stable level of 95% or above. During this period, a huge number of defective products are generated and have to be reworked, repaired, or scrapped. This results in unbearable loss to the company. In this circumstance, a lower assembly defect rate is needed to

Manuscript received March 25, 2008. First published November 6, 2009; current version published December 16, 2009. This work was supported by the National Natural Science Foundation of China under Grant 70672077. This paper was recommended by Associate Editor R. Qui.

Q. Su is with the Department of Industrial Engineering and Logistics Management, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: suq@sjtu.edu.cn).

L. Liu was with Fuji Xerox of Shanghai Limited, Shanghai 200240, China. He is now with Arizona State University, Tempe, AZ 85287 USA.

D. E. Whitney is with the Center for Technology, Policy, and Industrial Development, Massachusetts Institute of Technology, Cambridge, MA 02139-4307 USA.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>

Digital Object Identifier 10.1109/TSMCA.2009.2033030

ensure a proper profit margin. Unfortunately, real situations are usually very different from our expectations. Frequently changing products are boosting the assembly defect rate to new records.

Through a detailed investigation at Fuji Xerox China, the main copier assembly defects are identified and illustrated in a Pareto chart (see Fig. 1). Ranking from tallest to shortest, these bars represent various types of assembly defects caused by part defect, operator error, part mishandling, design mistake, fixture, tooling, etc. The root causes of these assembly defects can be classified into four categories: improper design, defective part, variance in assembly system (induced by the changes of plan/schedule/arrangement of machine, fixture, tooling, etc.), and operator mistake. Previous research has focused on the first three root causes. Some useful assembly quality control technologies and management approaches have been developed. For instance, design failure modes and effects analysis, design of experiments, design for assembly (DFA), etc., can be employed for evaluating and improving the assembly design quality. Data mining, sensor-based monitoring, statistic process control, etc., can be utilized to control assembly system variance [41], [43], [44]. In addition, some supplier management standards and quality inspection strategies have been developed for controlling the quality of the purchased parts or modules.

In terms of the fourth root cause, many investigations disclose that human errors have significant influence on assembly system performance, sometimes more than the technological ones [29]. As shown in Fig. 1, our field study demonstrates that the operator errors account for 20% of the total defects in copier assembly. Shibata [28] studied the assembly errors of the compact disk/mini disk dual-deck players and found that 25% of the total assembly errors were induced by human mistakes. Vineyard *et al.* [34] reported that, in U.S. manufacturing plants, human failures caused by improper human action on the average accounted for 40% of all the failures. These high percentages suggest that diminishing the fourth root cause is very important for assembly quality control and more attention should be paid to the assembly defects caused by operator error.

However, in existing research, the operator-induced assembly defects have not been fully addressed. As stated in Booker *et al.* [4], efforts have been focused on predicting component quality levels through variability and process capability measures at the design stage, but the variability associated with assembly operations is rarely considered in the context of quality. Under these considerations, taking the copier as an example, the mechanisms of the operator mistake-induced assembly defect are explored systematically in this paper.

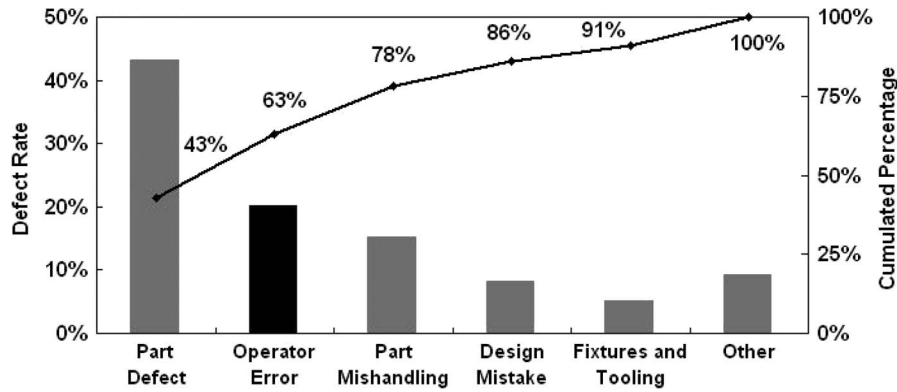


Fig. 1. Pareto chart for the defect sources.

Referring to previous literature, two assembly complexity factors are proposed and formulated to match the characteristics of copier assembly. Then, a novel mathematical model is developed for predicting and evaluating the operator-induced defect rate. Moreover, several case studies are conducted to demonstrate the effectiveness of the prediction model.

The arrangement of this paper is as follows. First, the related research works are reviewed and two prediction models, i.e., Hinckley model and Shibata model, are introduced in Section II. In Section III, a copier and its assembly system are investigated and evaluated using Shibata model. Then, in Sections IV and V, respectively, the calculation approaches for the design-based assembly complexity and the process-based assembly complexity are constructed according to the characteristics of the copier. Thereafter, a new assembly defect prediction model is constructed in Section VI. Then, three more cases are studied and some important issues are discussed in Section VII. Finally, Section VIII summarizes this paper.

II. LITERATURE REVIEW AND PREVIOUS MODELS

A. Literature Review

Assembly-related issues have been explored by industrial engineers and academic scholars for several decades. Most of the previous works are focused on the following three areas: assembly structure design and optimization, e.g., DFA [5], [24], [32], [33]; assembly process planning, e.g., assembly sequence planning [6], [8], [9], [12], [13], [15], [30], [31]; and assembly production scheduling [16], [37], [39], [42].

In the 1990s, some scholars started to pay attention to the geometrical tolerance control in car body assembly [2], [7], [10], [18]. Liu and Hu [20] analyzed the deforming problem in the sheet metal welding. Mantripragada and Whitney [21] proposed an algorithm to propagate and control variation in mechanical assemblies using the State Transition Model approach. Huang and Shi [17] applied the state space approach to analyze the stream of variation between assembly stations. Wang and Ceglarek [35], and Zhang and Ni [40] emphasized that car body assembly tolerances were closely related to the assembly sequence. Aguilar *et al.* [1] studied the error sources and their influence on measurement results by means of simulation and experimental tests. Prabhakaran *et al.* [26] introduced a concurrent tolerance approach that could determine optimal product tolerances and minimize combined manufacturing and quality-related costs in the early stages of design.

In order to find the reason for human failures, some ergonomic studies have been conducted [22], [27]. Park [25] remarked that humans generally had similar performance limitations that caused people to make more mistakes in more complex tasks. Capacity limitations in short-term memory and recall problems in long-term memory strongly affected human performance reliability. Complex task sequences in a specific order overstrained human memory. Eklund [11] evaluated the relationships between a number of ergonomic conditions and product quality in car assembly. The results showed that the quality deficiencies were three times as common for the work tasks with ergonomics problems, compared with the other tasks. Lin *et al.* [19] measured relationships between workstation ergonomics and product quality. The study found that two ergonomic variables, i.e., the time required for the task and the postural deficiencies, were together able to predict over 50% of the quality variance on an assembly line. Wartenberga *et al.* [36] stated that assembly task characteristics such as visual and manual demands influenced the postures employed and the muscular load during task execution. Tasks with high precision demands required a significantly longer completion time. In summary, these ergonomic studies directly or indirectly indicate that assembly complexity has a close relationship with human mistakes. Based on this viewpoint, the following two prediction models of the operator-induced assembly defect rate were proposed for semiconductor products.

B. Hinckley Model

Based on defect data of semiconductor products, Hinckley [14] found that defect per unit (DPU) was positively correlated with total assembly time and negatively correlated with number of assembly operations. He defined the assembly complexity factor (Cf) as follows:

$$Cf = TAT - t_0 \times TOP \quad (1)$$

where

TAT total assembly time for the entire product;
 TOP total number of assembly operations;
 t_0 threshold assembly time.

In order to calibrate the correlations between these parameters, he incorporated the threshold assembly time (t_0) which was defined as the time required to perform the simplest assembly operation. With this complexity index, Hinckley found that when plotting on a log-log scale, the complexity and the

corresponding defect rate showed a positive linear correlation with each other, as in the following two equivalent equations:

$$\log \text{DPU} = k \cdot \log Cf - \log C \quad (2)$$

$$\text{DPU} = \frac{(Cf)^K}{C} \quad (3)$$

where C and K are constants.

C. Shibata Model

Shibata [28] remarked that the Hinckley model did not take the assembly design factors into consideration and could not evaluate the defect rate for a specific workstation. Therefore, Shibata proposed a prediction model for a workstation based on two assembly complexity factors: the process-based complexity factor (Cf_{Pi}) and the design-based complexity factor (Cf_{Di}). In Shibata [28], home audio products, a combination of CD player and MiniDisc recorder/player, were utilized as assembly cases. For assembling these semiconductor products, about 300 job elements were included and the total time was around 10 min.

In Shibata model, the process-based complexity factor of workstation i is defined as

$$Cf_{Pi} = \sum_{j=1}^{N_{ai}} \text{SST}_{ij} - t_0 \cdot N_{ai} \quad (4)$$

where

- N_{ai} number of job elements in workstation i ;
- SST_{ij} time spent on job element j in workstation i ;
- t_0 threshold assembly time.

It should be noted that, in (4), the assembly time SST_{ij} is determined by Sony standard time (SST), a commonly used time estimation tool for electronic products. SST is a powerful tool to estimate the operation time for every kind of assembly operation of semiconductor products. It comes from long-time real field investigations and statistics. Usually, it is used to set the standard process time and estimate the required labor cost. All operators need to follow this standard time in their daily work. Therefore, the Shibata prediction model is built on the SST time instead of actual times of some specific operators.

Similar to (2) and (3), Shibata derived the following correlation relationships between the process-based assembly complexity factor and DPU:

$$\log \text{DPU}_i = K \cdot \log Cf_{Pi} - \log C \quad (5)$$

$$\text{DPU}_i = \frac{(Cf_{Pi})^K}{C} \quad (6)$$

where C and K are constants.

In addition, Shibata defined the design-based assembly complexity factor as

$$Cf_{Di} = \frac{K_D}{D_i} \quad (7)$$

where K_D is an arbitrary coefficient for calibration with process-based complexity; D_i is called the ease of assembly (EOA) of workstation i , evaluated based on the method of design for assembly/disassembly cost-effectiveness (DAC) developed in Sony Corporation.

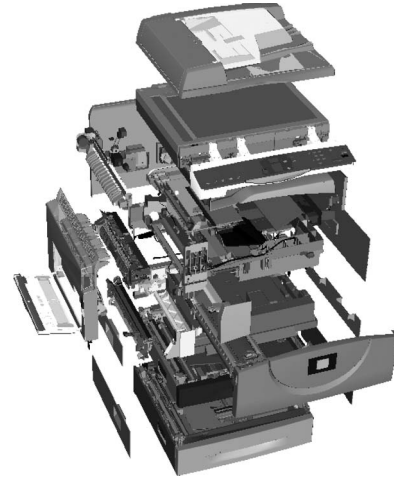


Fig. 2. Architecture of the multifunctional copier (DocuWorks).

Shibata found that the correlation between the design-based complexity and DPU can be expressed as follows:

$$\text{DPU}_i = a \cdot (Cf_{Di})^b \quad (8)$$

$$\log(\text{DPU}_i) = b \cdot \log(Cf_{Di}) + \log a \quad (9)$$

where a and b are constants.

According to Mendenhall and Sincich [23], more independent variables can improve the accuracy and stability of the regression function. Inspired by this point, Shibata [28] derived a bivariate prediction model by combining (5) and (9)

$$\log(\text{DPU}_i) = k_1 \cdot \log(Cf_{Pi}) + k_2 \cdot \log(Cf_{Di}) + C. \quad (10)$$

III. APPLYING THE SHIBATA MODEL IN COPIER ASSEMBLY

In this section, a case study is conducted to determine if Shibata's model is applicable in the copier industry. It is a type of multifunctional copier, entitled *DocuWorks*. It consists of 600 parts. In reality, these 600 parts are only buy-level parts, and some buy-level parts consist of 5–15 component-level parts. For this product, more than 1000 operations are included in the assembly production and most of the operations are performed manually at Fuji Xerox China. The total assembling time is about 1 h.

A. DocuWorks and Its Assembly System

Fig. 2 shows the configuration of *DocuWorks*. The copier is made of 14 subsystems: the duplex automatic document feeder, image input terminal, fuser, transfer, registration, exit, door, multiple sheet inserter (MSI), main controller unit, high/low voltage power supply, NOHAD (system of noise, ozone, heat, air flow, and dust), frame, tray, and customer replaceable unit.

Fig. 3 shows the layout of the workshop in which *DocuWorks* are assembled. In this system, 17 workstations are assigned for subassembly, 7 workstations are designated for main assembly, and the remaining 19 are for adjustment and inspection.

First, subsystems of door, MSI, fuser, tray frame, tray, and registration are built in subassembly workstations. Then, the subsystems and some components are all directed to the main

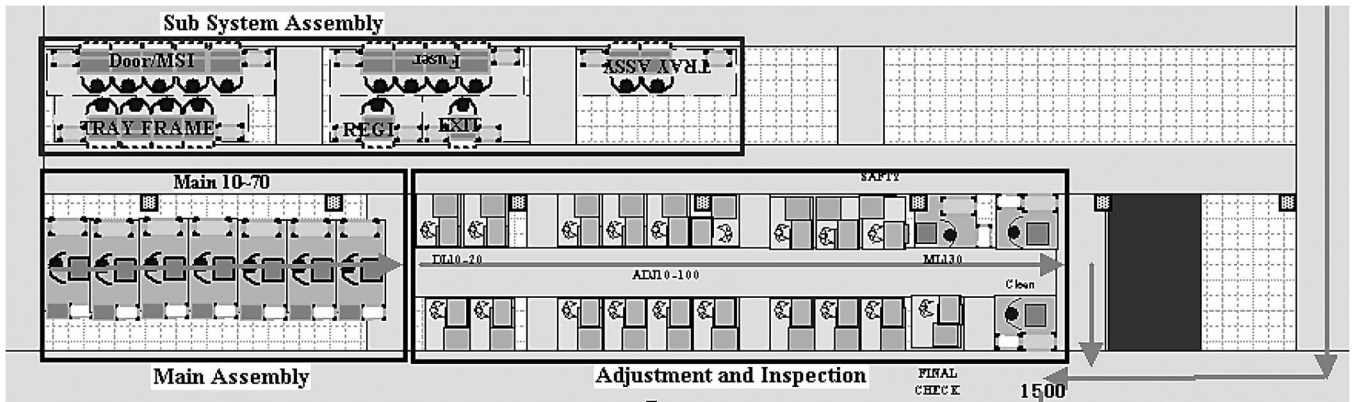


Fig. 3. Layout of the assembly line.

assembly line. After the assembly jobs in the main line are finished, copy machines are sent to the adjustment and inspection area for adjustment, inspection, and a safety test. If everything is OK, the machines are packaged and shipped to Fuji Xerox sales centers all around the world.

B. Data Collection

The authors experienced remarkable challenges in collecting data. For *DocuWorks*, a 100% inspection was executed at the inspection area. Additionally, approximately 10% of the machines were spot checked before delivering. Every problem was documented in detail, including the description, root cause, allocation, short-term action, etc. During the four-month investigation period, a total of 10036 copiers were assembled and 977 quality problems were recorded. Among them, 172 were determined to be operator-induced assembly defects.

Theoretically, all of the assembly defects should be recorded. However, sometimes, the downstream operator might directly send the defective product back to the upstream operator for correction. In this situation, the corresponding defect would not appear in quality records. To ensure the data quality, authors talked with operators and guaranteed that the collected data would only be used for research. In this way, 17 more defects were added according to operators' recall. Thus, a total of 199 operator-induced assembly defects were obtained.

C. Prediction Using Shibata Model

Using SPSS 13.0, case data were analyzed using the Shibata method and the following prediction model was derived:

$$\log(\text{DPU}_i) = 1.525 \log(Cf_{pi}) + 1.935 \log(Cf_{Di}) + 3.432. \quad (11)$$

Shibata [28] reported that the R square of his model can reach 0.7 for audio equipment assemblies. However, Table I shows that the value of R square is only 0.257 when used in the copier assembly. This finding implies that the Shibata model is not appropriate for electromechanical products like copiers.

Furthermore, the correlations between the individual assembly complexity factor and DPU are statistically analyzed as below

$$\text{DPU}_i = 0.642Cf_{pi}^{2.51} \quad (12)$$

$$\text{DPU}_i = 785.059Cf_{Di}^{3.534}. \quad (13)$$

TABLE I
STATISTIC SUMMARY OF ANALYSIS USING SHIBATA METHOD

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.507(a)	0.257	0.187	2.35486

The values of R square in Tables II or III are even smaller than that in Table I. Fig. 4 shows the fitting curve and residue analysis of Cf_{pi} versus DPU. Fig. 5 shows the fitting curve and residue analysis of Cf_{Di} versus DPU. One can see that, in the residue charts, the average deviates from zero and outliers appear. In the tenth workstation, a number of screws should be assembled to different faces of a frame. Many times, some of the screws located in rear face or corners are missed. That is why an extreme point occurs in this workstation. These findings suggest that Shibata's method is not suitable for the copier assembly defect prediction.

The aforementioned analysis results can be explained by the following three facts.

- 1) The Shibata model was developed by studying electronic products. All case data came from small size electronic products, e.g., mini stereo or MiniDisc player. Most of the assembly operations are something like inserting and soldering of small electronic components and electric wires on the printed circuit board. However, the multifunctional copier is a complicated electromechanical product. In addition, to some extent, a copier is more like a mechanical product from the view of assembly production. In addition, compared with the electronic products, copiers are 10 to 100 times larger in terms of size, weight or parts quantity. Moreover, different work mechanisms result in significant differences in parts, materials, and mating methods. These differences determine that the Shibata model cannot be directly used in analyzing copier products.
- 2) The DAC method used in the design-based assembly complexity factor evaluation in the Shibata model is not suitable for copier products, since DAC was developed for evaluating the EOA of Sony electronic products such as CD players or notebook computers. The criteria used in this method were developed based on electronic products other than mechanical or electromechanical products.
- 3) In the Shibata model, the process-based assembly complexity factor is evaluated based on the SST which is

TABLE II
MODEL SUMMARY OF Cf_{P_i} VERSUS DPU

Model Summary						Parameter Estimates	
Equation	R Square	F	df1	df2	Sig.	Constant	b1
Power	0.169	4.486	1	22	0.046	0.642	2.501

TABLE III
MODEL SUMMARY OF Cf_{D_i} VERSUS DPU

Model Summary						Parameter Estimates	
Equation	R Square	F	df1	df2	Sig.	Constant	b1
Power	0.153	3.979	1	22	0.059	785.059	3.534

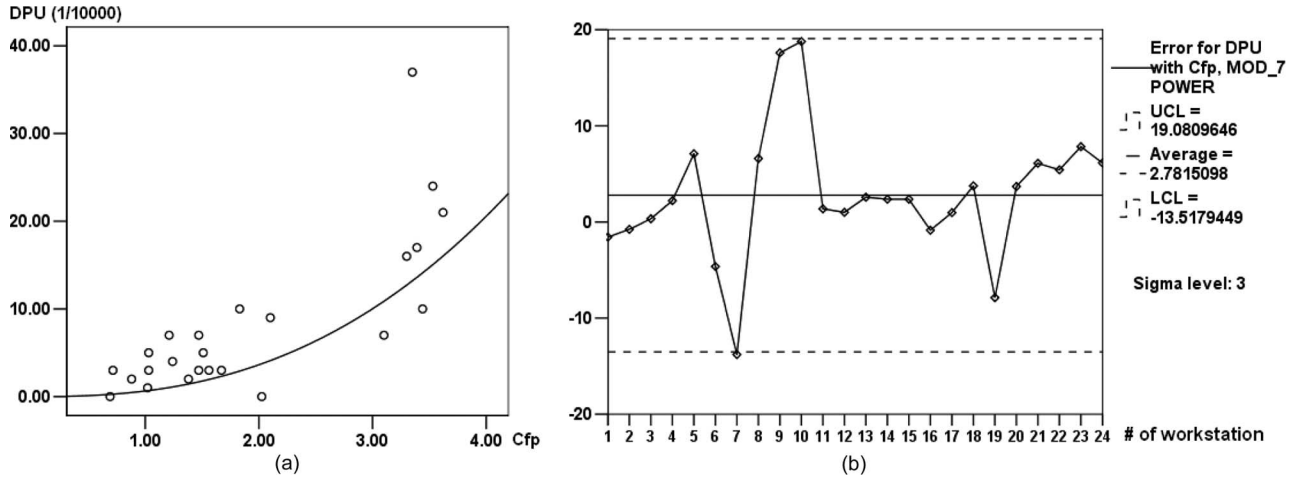


Fig. 4. Curve fit and residue analysis for Cf_{P_i} . (a) Fitting curve. (b) Residue analysis.

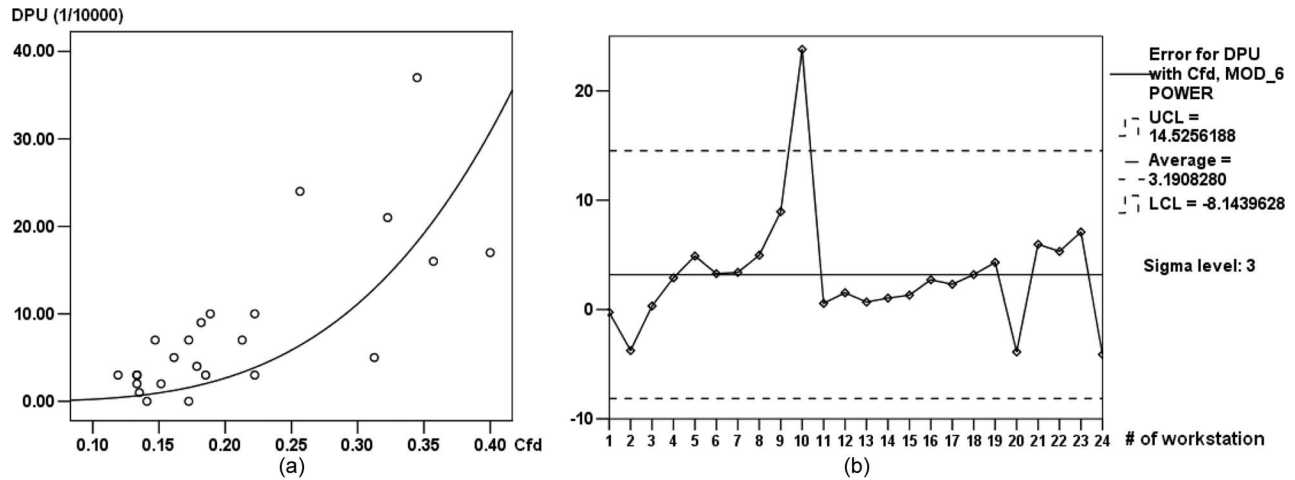


Fig. 5. Curve fit and residue analysis for Cf_{D_i} . (a) Fitting curve. (b) Residue analysis.

designed specifically for electronic component assembly operations. This time database is absolutely not suitable for analyzing the copier production. For instance, in SST, the threshold assembly time t_0 is 2 s. However, in copier assembling, the shortest adjustment action can be finished in 0.01 min (or 0.6 s) according to the time standard in Fuji Xerox.

For these reasons, the evaluation methods of the assembly complexity factors should be redesigned to better match the characteristics of a copier. In addition, a new prediction model should be developed accordingly.

IV. NEW DESIGN-BASED ASSEMBLY COMPLEXITY EVALUATION METHOD

A. Redesign of the Evaluation Method

As mentioned previously, DAC is not suitable for copiers. Therefore, the evaluation method of the design-based complexity factor should be redesigned. In addition, the possible substitute should be more suitable for mechanical or electro-mechanical products. With this concern in mind, the method developed in Ben-Arieh [3] is considered since it is simple and has been successfully applied to more than 150 different mechanical products. According to the characteristics in a

TABLE IV
PAIRED COMPARISON MATRIX

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
P1	1	2	2	3	7	5	6	3	3	2	1
P2	1/2	1	1	2	3	2	3	1	2	1	1/2
P3	1/2	1	1	1	2	3	3	2	1	1/2	1/3
P4	1/3	1/2	1	1	3	2	3	1/2	1/2	1/2	1/3
P5	1/7	1/3	1/2	1/3	1	1/2	1	1/3	1/2	1/4	1/6
P6	1/5	1/2	1/3	1/2	2	1	2	1/3	1/2	1/3	1/4
P7	1/6	1/3	1/3	1/3	1	1/2	1	1/3	1/2	1/4	1/5
P8	1/3	1	1/2	2	3	3	3	1	2	1	1/2
P9	1/3	1/2	1	2	2	2	2	1/2	1	1	1/2
P10	1/2	1	2	2	4	3	4	1	1	1	1/2
P11	1	2	3	3	6	4	5	2	2	2	1

copier assembly, 11 parameters are selected as the criteria for evaluating the design-based assembly complexity. These parameters are part shape(P1), force required(P2), mating direction(P3), alignment of components(P4), mating component's length(P5), length of components intersection(P6), ratio of length to width (diameter) (P7), ratio of the mating component's weight to the mated one(P8), stability(P9), support required(P10), and interference(P11).

To obtain an integrated index, the weights of the 11 criteria are allocated using the analytic hierarchy process (AHP) approach [38]. Six assembly engineers in Fuji Xerox were trained and involved in the AHP analysis. These engineers were asked to compare the relative importance of each parameter in determining the difficulty of putting a part into a product. According to the evaluation by the six assembly engineers, the paired comparison matrix between the 11 parameters is derived, as shown in Table IV. Here, the relative importance between two parameters is scored as integers from one to nine, where one indicates the same importance and nine indicates a dominant importance.

With the comparison matrix, the weights of the 11 parameters can be derived as follows:

$$w_i = \left(\prod_{j=1}^N a_{ij} \right)^{1/N} / \sum_{i=1}^N \left(\prod_{j=1}^N a_{ij} \right)^{1/N} \quad (14)$$

where

a_{ij} relative importance of parameter i over parameter j in Table IV;

N number of parameters, here $N = 11$;

w_i weight of parameter i ; as listed in Table V.

We define A_{kpi} as the evaluation of parameter p in workstation i estimated by engineer k . Using the weights in Table V, we can then calculate the new design-based complexity factor as follows:

$$Cf'_{Di} = \sum_{p=1}^{11} \left(w_p \cdot \frac{1}{6} \left(\sum_{k=1}^6 A_{kpi} \right) \right) \quad (15)$$

where

w_p weight of the parameter p ;

Cf'_{Di} new design-based complexity factor of the workstation i .

TABLE V
WEIGHTS OF PARAMETERS

Parameter	Weight
Shape	0.199
Force required	0.097
Mating direction	0.083
Alignment	0.085
Length	0.029
Intersection length	0.040
Ratio L/D	0.028
Weight ration	0.080
Stability	0.072
Support required	0.107
Interference	0.181

B. Correlation Analysis of Cf'_{Di} Versus DPU

Next, we analyze the correlation between the new design-based complexity Cf'_{Di} and DPU for the copier *DocuWorks*. To find the most suitable equation to describe the correlation, 11 different equations were tested in SPSS 13.0, as listed in Table VI.

Compared with the correlation analysis result shown in Table III, one can see that the value of R square is increased from 0.153 to 0.432 for the power fitting function. Furthermore, among the 11 equations, the cubic is the best fitting equation with the highest R square of 0.663. These figures suggest that the new design-based complexity Cf'_{Di} performs much better than the original design-based complexity Cf_{Di} defined in the Shibata model

$$DPU_i = -8.095 + 9.296Cf'_{Di} - 2.119(Cf'_{Di})^2 + 0.193(Cf'_{Di})^3. \quad (16)$$

Equation (16) is the derived cubic fitting function for the copier. Fig. 6 shows the fitting curve and the corresponding residue analysis of this function. In the residue chart, there is no cyclical behavior and no outlier. More importantly, the average is equal to zero. Therefore, it is safe to say that this predicting model is appropriate for a copier assembly.

V. NEW PROCESS-BASED ASSEMBLY COMPLEXITY EVALUATION METHOD

A. Fuji Xerox Standard Time

Instead of using SST, the new process-based assembly complexity factor is evaluated based on Fuji Xerox Standard Time, which is more suitable for copier production. To express this, (4) is changed to

$$Cf'_{Pi} = \sum_{j=1}^{N_{ai}} \text{FXT}_{ij} - t_0 \cdot N_{ai} \quad (17)$$

Cf'_{Pi} new process-based assembly complexity factor;

N_{ai} number of job elements in workstation i ;

FXT_{ij} time spent on job element j in workstation i ; this time is estimated using Fuji Xerox Standard Time.

t_0 threshold assembly time, it should be 0.6 s according to time standard in Fuji Xerox.

TABLE VI
MODEL SUMMARY AND PARAMETER ESTIMATION (Cf'_{Di} VERSUS DPU)

Model Summary					Parameter Estimates				
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	0.590	31.680	1	22	0.00001	-3.937	3.218		
Logarithmic	0.504	22.398	1	22	0.00010	-3.693	10.280		
Inverse	0.390	14.061	1	22	0.00111	17.244	-23.955		
Quadratic	0.633	18.142	2	21	0.00003	2.590	-0.906	0.487	
Cubic	0.663	13.089	3	20	0.00006	-8.095	9.296	-2.119	0.193
Compound	0.315	10.097	1	22	0.00436	0.095	2.342		
Power	0.432	16.717	1	22	0.00049	0.043	3.445		
S	0.553	27.247	1	22	0.00003	4.744	-10.338		
Growth	0.315	10.097	1	22	0.00436	-2.354	0.851		
Exponential	0.315	10.097	1	22	0.00436	0.095	0.851		
Logistic	0.315	10.097	1	22	0.00436	10.524	0.427		

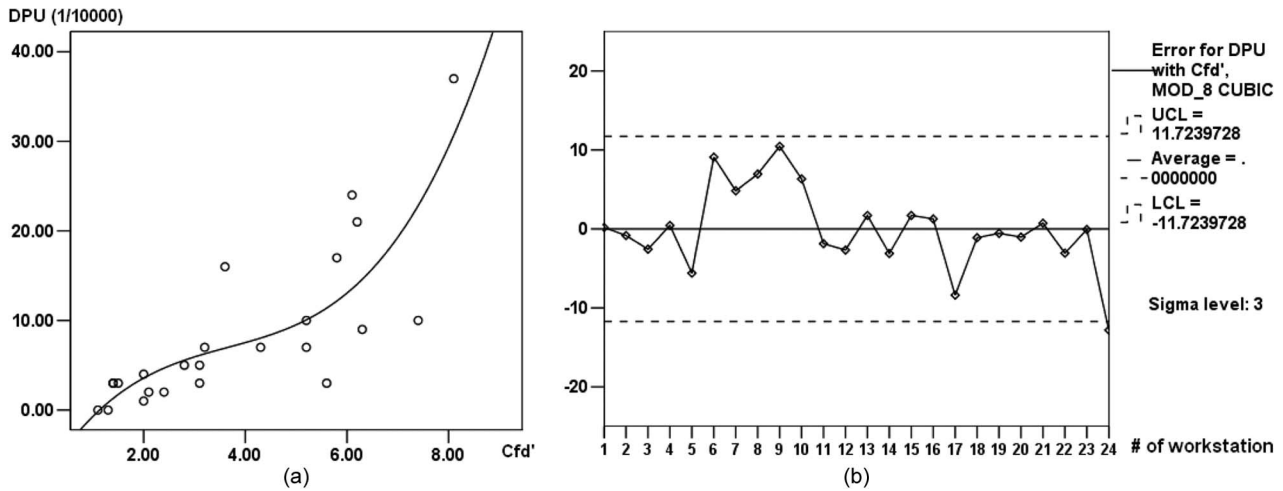


Fig. 6. Curve fit and residue analysis for Cf'_{Di} . (a) Fitting curve. (b) Residue analysis.

The correlation of the new process-based complexity Cf'_{Pi} and DPU are explored using the 11 equations as listed in Table VII. The best regression function is again the cubic fitting equation. Fig. 7 shows the fitting curve and the corresponding residue analysis of this function. Equation (18) is the resulting model

$$DPU_i = -6.29 + 16.546Cf'_{Pi} - 9.033(Cf'_{Pi})^2 + 1.866(Cf'_{Pi})^3. \quad (18)$$

Compared with the original process-based complexity Cf_{Pi} defined in the Shibata model, the value of R square is increased from 0.169 (see Table II) to 0.656 (see Table VII). This significant improvement demonstrates that the Fuji Xerox Standard Time-based process-based complexity factor is far more suitable for the copier DPU analysis.

B. Time Variation

In our investigation, an interesting phenomenon was encountered. As shown in Fig. 8(a), a workstation was blamed for its high defect rate. As a generally used approach, assembly engineers developed a fixture for this workstation.

When the fixture was installed, two more operations were added, as shown in Fig. 8(b). By (17), the process-based assembly complexity Cf'_{Pi} would be increased from 0.19 to 0.22. Thus, the defect rate should be increased a little bit according to (18). Ironically, the fact was totally different from this expectation. The defect rate was dramatically decreased when the fixture was installed. This phenomenon implies that, in the process-based complexity evaluation, only taking the operation time into consideration is not enough.

Comparing Fig. 8(a) and (b), we can see that the time variations of the two curves are significantly different from each other. As we know, variation is one of the most important causes of quality problems. Thus, we may hypothesize that the defect rate reduction is due at least in part to the significant decline of the time variance from 0.0026 to 0.00053.

This hypothesis can be verified with the following case data. As shown in Fig. 9, the operation times in five workstations, i.e., A, B, C, D, E, are given. About 30 to 60 operations are included in each workstation. The circles denote that at least one defect has occurred in this operation. For each workstation, the process-based complexity, time variance, and total defects are given at the upper-right corner of the corresponding curve.

TABLE VII
MODEL SUMMARY AND PARAMETER ESTIMATION (Cf'_{pi} VERSUS DPU)

Model Summary					Parameter Estimates				
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	0.615	35.181	1	22	5.720E-06	-5.048	6.876		
Logarithmic	0.540	25.861	1	22	4.286E-05	1.767	12.328		
Inverse	0.414	15.566	1	22	6.889E-04	19.433	-16.596		
Quadratic	0.648	19.310	2	21	1.745E-05	4.149	-3.683	2.374	
Cubic	0.656	12.732	3	20	7.048E-05	-6.290	16.546	-9.033	1.866
Compound	0.152	3.958	1	22	5.921E-02	0.218	3.456		
Power	0.169	4.486	1	22	4.571E-02	0.642	2.501		
S	0.194	5.288	1	22	3.134E-02	3.641	-4.112		
Growth	0.152	3.958	1	22	5.921E-02	-1.525	1.240		
Exponential	0.152	3.958	1	22	5.921E-02	0.218	1.240		
Logistic	0.152	3.958	1	22	5.921E-02	4.595	0.289		

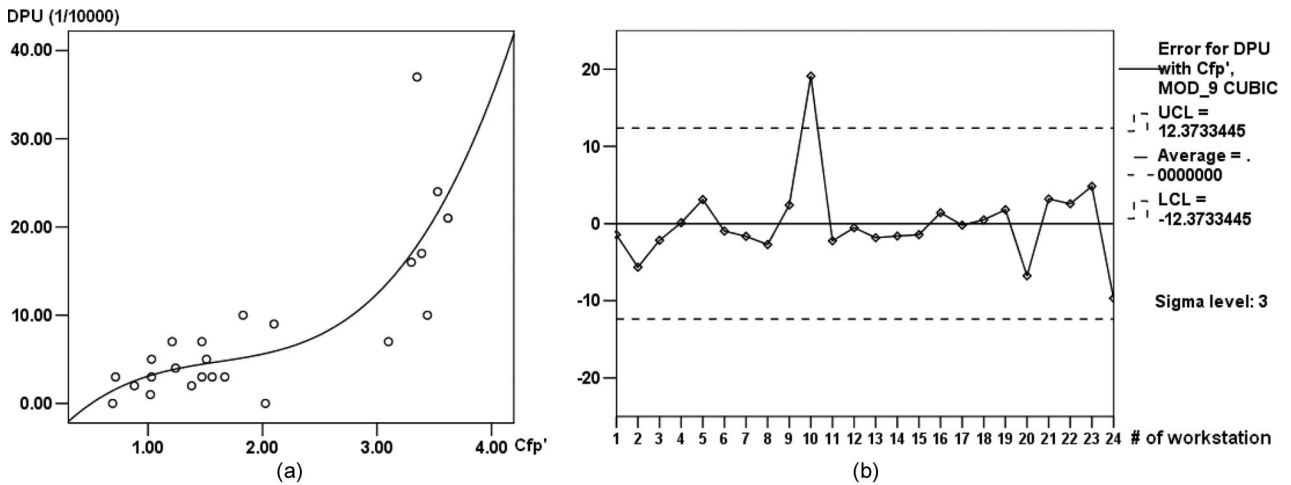


Fig. 7. Curve fit and residue analysis of Cf'_{pi} . (a) Curve fitting. (b) Residue analysis.

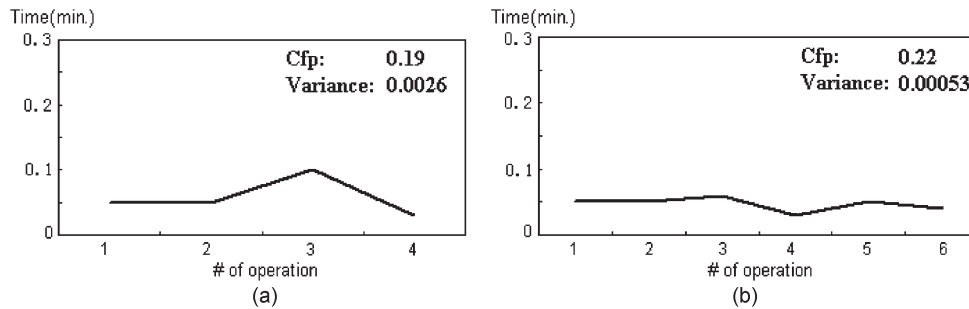


Fig. 8. Variance of assembly time before and after cut-in fixture. (a) Before fixture is used. (b) After fixture is used.

One can see that the highest defect rate appears neither in workstation B, which has the largest complexity, nor in workstation A, which possesses the biggest number of operations. In fact, the workstation D, which has the largest time variation, has the highest defect rate.

C. Redesign of the Process-Based Assembly Complexity Evaluation Method

The aforementioned analysis demonstrates that the workstation with the largest variation of assembly time is likely to

induce a high defect rate. This finding suggests that the time variation should be considered in the new defined process-based assembly complexity. Therefore, the new process-based assembly complexity is revised as follows:

$$Cf''_{pi} = Cf'_{pi} + k \cdot \sigma_i \tag{19}$$

where

Cf''_{pi} new defined process-based assembly complexity;
 Cf'_{pi} process-based assembly complexity defined in (17);

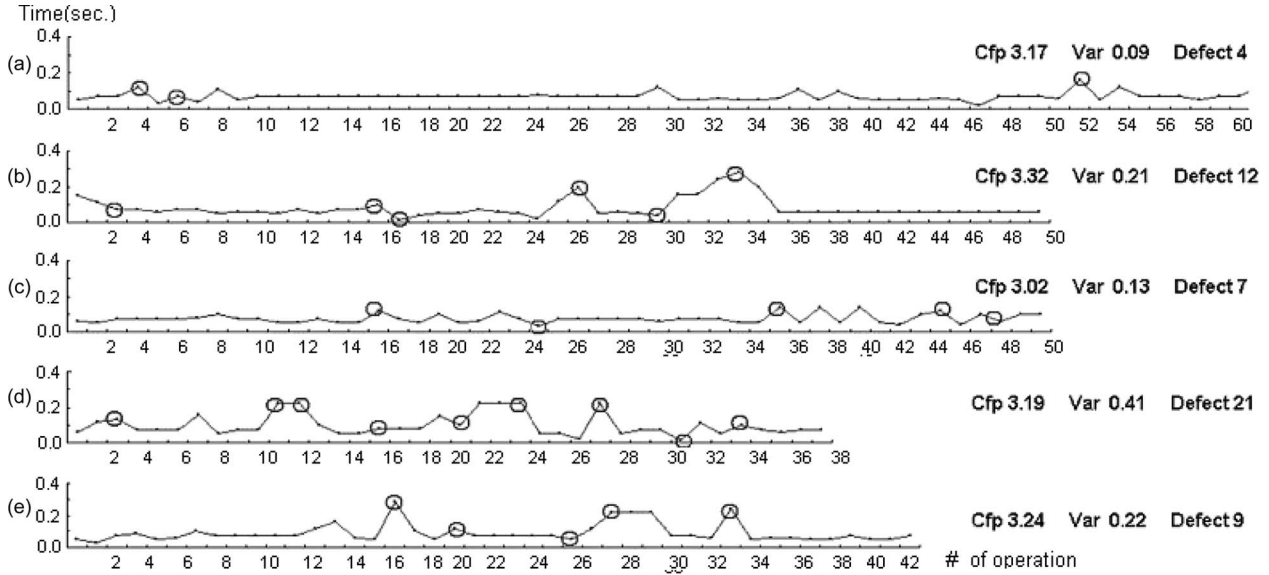
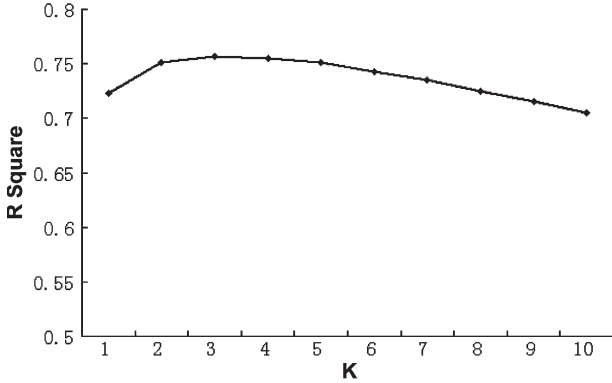


Fig. 9. Assembly time fluctuation.


 Fig. 10. Relationship between K and R square.

k calibration coefficient;
 σ_i variation in work time at station i , which can be predicted from Fuji Xerox data.

To find the proper value of k , a series of numerical experiments are conducted. As shown in Fig. 10, one can see that the R square of Cf''_{pi} versus DPU will reach to its maximal value when k is three or four. Here, k is set to four in the following analysis.

As shown in Table VIII, the correlation of Cf''_{pi} versus DPU is statistically computed for the 11 equations.

Compared with the R squares in Table VII, the inclusion of time variation can enhance the R squares considerably. The maximal R square of 0.755 is achieved when the cubic fitting equation is applied. Fig. 11 shows the cubic fitting and the corresponding residue analysis of the new process-based complexities Cf''_{pi} versus DPU.

One can conclude that Cf''_{pi} is better in both the curve fitting and the residue analysis. In addition, the corresponding prediction model can be derived as follows:

$$\begin{aligned}
 \text{DPU}_i = & -2.503 + 6.26Cf''_{pi} \\
 & - 2.512 (Cf''_{pi})^2 + 0.506 (Cf''_{pi})^3. \quad (20)
 \end{aligned}$$

VI. NEW PREDICTION MODEL

In this section, the new design-based complexity Cf'_{Di} and the new process-based complexity Cf''_{pi} are integrated and a novel bivariate predicting model is developed.

In order to find the optimal regression function, the following six typical bivariate equations were studied and compared with each other.

- 1) Linear: $Z = a_0 + a_1X + a_2Y$
- 2) Growth: $Z = e^{(a_0+a_1X+a_2Y)}$
- 3) Logarithmic: $Z = a_0 + a_1 \ln X + a_2 \ln Y$
- 4) Inverse: $Z = a_0 + a_1/X + a_2/Y$
- 5) Power: $Z = a_0 + a_1X^{a_2} + a_3Y^{a_4}$
- 6) Cubic: $Z = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4Y + a_5Y^2 + a_6Y^3$

The R square for each equation can be calculated as follows:

$$R^2 = 1 - \frac{\text{SSE}}{\text{SS}_{yy}}$$

where

$$\begin{aligned}
 \text{SSE} &= \sum (\text{DPU}_i - \hat{\text{DPU}}_i)^2 \\
 \text{SS}_{yy} &= \sum (\text{DPU}_i - \bar{\text{DPU}})^2
 \end{aligned}$$

and $\hat{\text{DPU}}_i$ is the predicted DPU value for each work station.

The calculations are performed in MATLAB-7.4.0.287 (R2007a). Table IX shows the values of R square for each bivariate equation. Among the six functions, the cubic is the best one. Compared with the univariate regression analysis in Tables VI and VIII, the value of R square is increased from 0.663 or 0.755 to 0.793.

As shown in Fig. 12, no cyclic or outliers can be found in the residues analysis, and the residues are quite acceptable. Therefore, the most suitable bivariate cubic equation is derived as follows:

$$\begin{aligned}
 \text{DPU}_i = & -7.2472 - 2.1257Cf''_{pi} + 9.7119Cf'_{Di} \\
 & + 0.8437 (Cf''_{pi})^2 - 2.4292 (Cf'_{Di})^2 \\
 & + 0.0516 (Cf''_{pi})^3 + 0.1964 (Cf'_{Di})^3. \quad (21)
 \end{aligned}$$

TABLE VIII
MODEL SUMMARY AND PARAMETER ESTIMATION (Cf''_{pi} VERSUS DPU)

Model Summary					Parameter Estimates				
Equation	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	0.685	47.750	1	22	6.134E-07	-6.546	5.756		
Logarithmic	0.571	29.334	1	22	1.935E-05	-2.278	12.866		
Inverse	0.401	14.737	1	22	8.927E-04	18.572	-20.467		
Quadratic	0.747	31.031	2	21	5.365E-07	4.878	-4.146	1.716	
Cubic	0.755	20.597	3	20	2.493E-06	-2.503	6.260	-2.512	0.506
Compound	0.220	6.215	1	22	2.068E-02	0.114	3.264		
Power	0.267	8.018	1	22	9.713E-03	0.176	3.187		
S	0.326	10.647	1	22	3.561E-03	4.239	-6.686		
Growth	0.220	6.215	1	22	2.068E-02	-2.168	1.183		
Exponential	0.220	6.215	1	22	2.068E-02	0.114	1.183		
Logistic	0.220	6.215	1	22	2.068E-02	8.742	0.306		

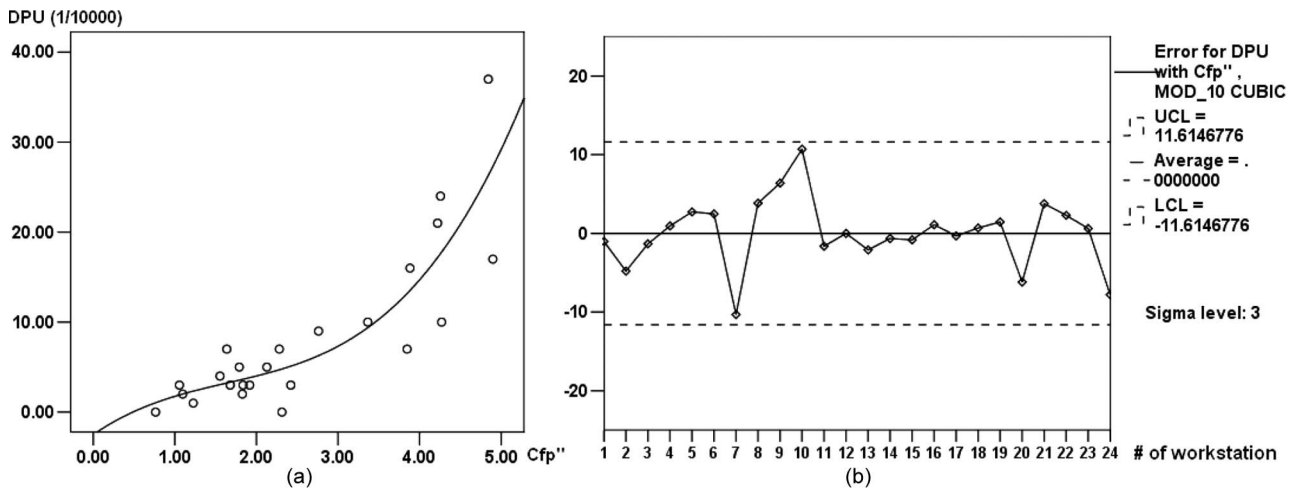


Fig. 11. Curve fit and residue analysis of Cf''_{pi} versus DPU. (a) Curve fitting. (b) Residue analysis.

TABLE IX
VALUES OF R SQUARE FOR BIVARIATE EQUATIONS

	Linear	Growth	Logarithmic	Inverse	Power	Cubic
$(Cf'_{Di} + Cf''_{Pi})$ vs. DPU	0.69	0.401	0.569	0.371	0.356	0.793

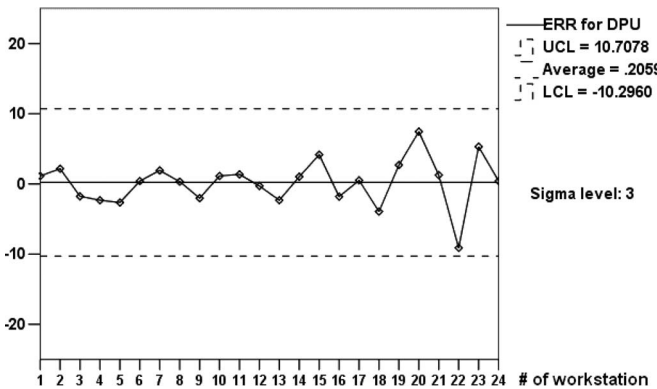


Fig. 12. Residue analysis of the bivariate cubic fitting.

With the newly developed model, we can predict the defect rate for each workstation of the multifunctional copier *DocuWorks*. As shown in Fig. 13, the actual DPU_i , DPU_i predicted by the Shibata model, and DPU_i predicted by the new developed model are displayed in one chart. It is obvious that the new developed model possesses a better performance on assembly defects prediction. The value of R square is increased from 0.257 to 0.793.

In this paper, all the actual DPU_i are collected during the early learning period. As stated in Section I, it takes several months for production to become stable with a low level of defects. We are concerned with the quality level in the early learning period more seriously than that in the later steady state period, in which DPU_i will be very low due to the experience

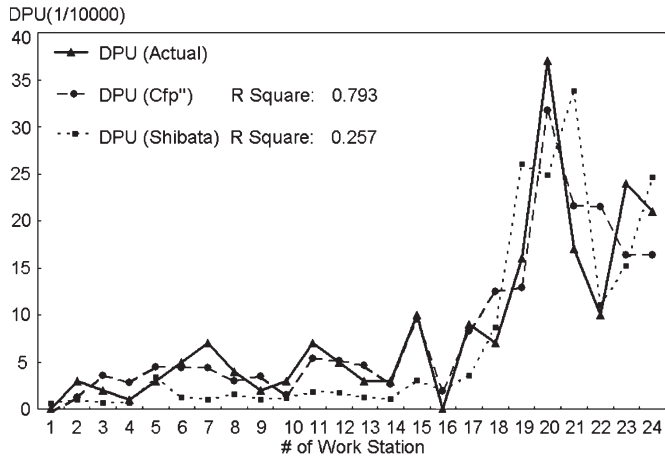


Fig. 13. Comparison of Shibata model and the new model.

TABLE X
R SQUARES FOR THREE CASES

	$(Cf'_{Di} + Cf''_{Pi})$ vs. DPU
<i>DocuWorks</i>	0.793
<i>DocuCenter</i>	0.701
<i>DocuPrinter</i>	0.743

accumulation and some improvement efforts. Therefore, it is more meaningful to focus on the assembly quality estimation and control for the early learning period.

VII. ADDITIONAL APPLICATIONS OF THE METHOD

A. Analysis of Two More Copiers

To validate the generality of the proposed method, two other different kinds of copiers, namely, *DocuCenter* and *DocuPrinter*, are evaluated with the new proposed method. These two copiers are more complicated when compared with the first case, *DocuWorks*. In the *DocuCenter*, a total of 1113 parts are included and assembled in 34 subassembly workstations and 26 main assembly workstations. *DocuPrinter*, consisting of 891 parts, is assembled in 19 subassembly workstations and 14 main workstations.

The two copiers, *DocuCenter* and *DocuPrinter*, are evaluated using the new method. First, the assembly complexity factors are calculated using (15) and (19). Then, the cubic regression equations are derived for the two copiers, respectively. The resulting equations are similar to (21) but coefficients are different from each other. Moreover, correlation analyses are conducted and the corresponding *R* squares are derived as listed in Table X.

The response surface of the *DocuCenter* is shown in Fig. 16. The point A corresponds to the original situation before improvement. As stated above, the response surface can be utilized to assist in decision-making. Here, the slope $S_{Cf'_{Di}}$ is much larger than the slope $S_{Cf''_{Pi}}$. Thus, we decided to decrease the design-based assembly complexity first.

The *R* square values in Table X demonstrate that the new designed method is accurate and stable for assembly defect rate prediction in copier assembly production.

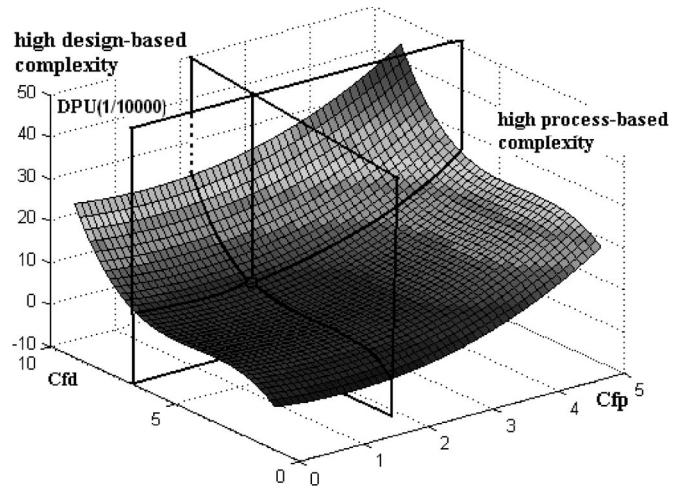


Fig. 14. Predicting surface of defect data for the *DocuWorks*.

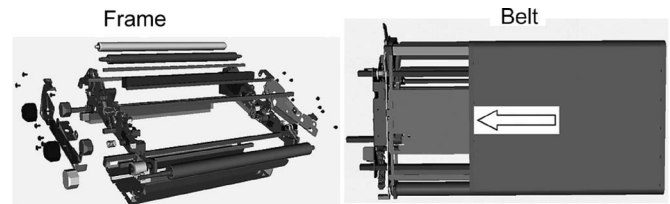


Fig. 15. Frame assembly and belt inserting.

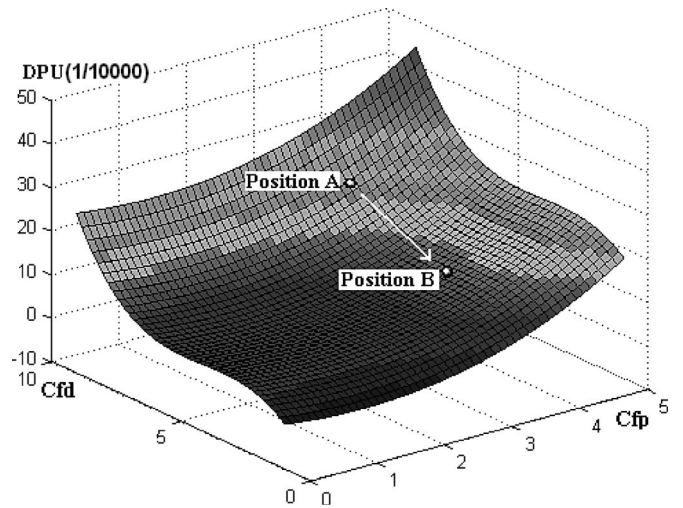


Fig. 16. Response surface for the *DocuCenter*.

B. Response Surface of the Prediction Model

The prediction model can be utilized as a decision tool in assembly quality evaluation and improvement. For instance, according to (21), the new prediction model can be charted as Fig. 14. The response surface of DPU over Cf'_{Di} and Cf''_{Pi} can provide a useful tool on suggesting the appropriate strategy for assembly quality improvement.

Generally, according to the values of Cf'_{Di} and Cf''_{Pi} , one can find a point on the response surface that is corresponding to the current assembly quality level. At this point, two tangents can be drawn in the two orthogonally intersecting planes, respectively. In addition, the slopes of the two tangent lines can be

TABLE XI
ESTIMATION OF THE IMPROVEMENT EFFECTIVENESS

	Cf_{Di}'	Cf_{Pi}''	Predicted DPU (10^{-4})	Actual DPU (10^{-4})
<i>Before improvement</i>	7.1	3.636	15.94	17.01
<i>After improvement</i>	4.7	3.531	10.53	8.89

quantitatively derived as $SC_{Cf_{Di}'}$ and $SC_{Cf_{Pi}''}$. Then, the following rules can be used to support assembly quality improvement.

- 1) If $SC_{Cf_{Di}'} > SC_{Cf_{Pi}''}$, then the design-based assembly complexity Cf_{Di}' should be reduced first.
- 2) If $SC_{Cf_{Di}'} < SC_{Cf_{Pi}''}$, then the process-based assembly complexity Cf_{Pi}'' should be reduced first.
- 3) Else, if $SC_{Cf_{Di}'} = SC_{Cf_{Pi}''}$, then either assembly complexity can be considered first.

In addition to the aforementioned rules, the cost and technical factors should also be carefully considered in decision making.

C. Analysis of a Copier Subassembly Using the Response Surface

In the copier company, a high defect rate was found when assembling the intermediate transfer module in the copier *DocuCenter*. The structure of this module is shown in Fig. 15. The picture on the right demonstrates the inserting of the belt onto the frame. The inner frame structure is illustrated on the left side. Several rollers are supported by brackets. These parts are connected through shaft-hole method and fixed by a number of screws. This module is very important and critical to the copy quality. However, the assembly of the module is too difficult to achieve the required shape and position accuracy. Either belt deflection or frame slant will cause a skewed copy or an abnormal colored line (or spot) on the copy.

Through careful analysis, we identified two main causes for the belt deflection.

- 1) To assemble a good frame, each of the metal brackets and rollers should be precisely positioned and clamped tightly while the screws are driven. Meanwhile, 15 screws were assembled horizontally which could increase the assembly complexity considerably. During this process, the tiny misalignment in each step can accumulate to induce the frame deflection.
- 2) The belt should be assembled exactly in the middle of the rollers. Any distortion or skewness would lead to defects in copy quality. Furthermore, since the surface of the belt must not be touched, the operator could only touch a very limited area on the two ends of the belt. Therefore, it was very difficult for the operator to hold the belt and assemble it into the required position.

Due to these reasons, the design-based assembly complexity was very high for this subassembly. To solve the retaining and positioning problems, a special fixture was designed. Meanwhile, a design revision changed the assembly direction from horizontal to vertical which greatly decreased the complexity of screwing and belt inserting. As a consequence, the assembly defect rate decreased significantly. Correspondingly, as shown in Fig. 16, the position A changed to position B after the improvement.

Table XI shows the values of the complexities Cf_{Di}' and Cf_{Pi}'' , the predicted DPU, and the actual DPU before and after the enhancement, respectively. One can see that the design-based complexity Cf_{Di}' is reduced considerably from 7.1 to 4.7. As a consequence, the actual DPU measured from the field study is decreased from 17.01×10^{-4} to 8.89×10^{-4} . By comparing the predicted DPUs and the actual DPUs, one can conclude that the new method is an effective tool in assembly quality forecasting and improvement.

VIII. SUMMARY

The continuously shortening product life cycle requires a faster response speed as well as a lower defect rate in assembly production. In this situation, assembly quality control is becoming one of the most demanding problems in the modern manufacturing environment. In this paper, the operator-induced assembly defect is studied systematically. Aiming at the copier assembly quality control, the new assembly complexity factors and a novel assembly defect prediction model are developed based on statistical analysis of a series of case studies.

The design-based complexity is redesigned using Ben-Arieh's method combined with the AHP method. The Fuji Xerox Standard Time, instead of SST, is employed in calculating the process-based assembly complexity factor. In addition, for the first time, the relationship between the time variation and the assembly defect is discovered and integrated into the calculation of the process-based assembly complexity factor.

With the new assembly complexity factors, a novel assembly defect prediction model is proposed. Through statistical analysis, the cubic equation is chosen as the most accurate fitting function in the DPU prediction. Three different assembly cases verify that the new developed model is accurate and stable for the copier assembly defect prediction. Furthermore, another case study demonstrates that the proposed method can be of great help in the assembly quality improvement.

The proposed model can act as a decision support tool for the assembly quality-oriented copier design and optimization. Whenever the assembly structure is determined in early stages of design, engineers can employ the prediction model to evaluate the design-based assembly complexity and process-based assembly complexity and, thereby, get the quantitative estimation of DPU of the new developed copier. Thereafter, some improvements can be made. When engineers first use this method, they will not have coefficients for the model and will have to try the method on typical products (perhaps on small subassemblies) and obtain real DPU data in order to calibrate the model. This will give them typical values for the coefficients for their kind of product. After that, they can use coefficients derived from experience on past products to start the evaluation of new ones. Gradually, they will build up knowledge of their products and a more mature model with more accurate coefficients will gradually be learned.

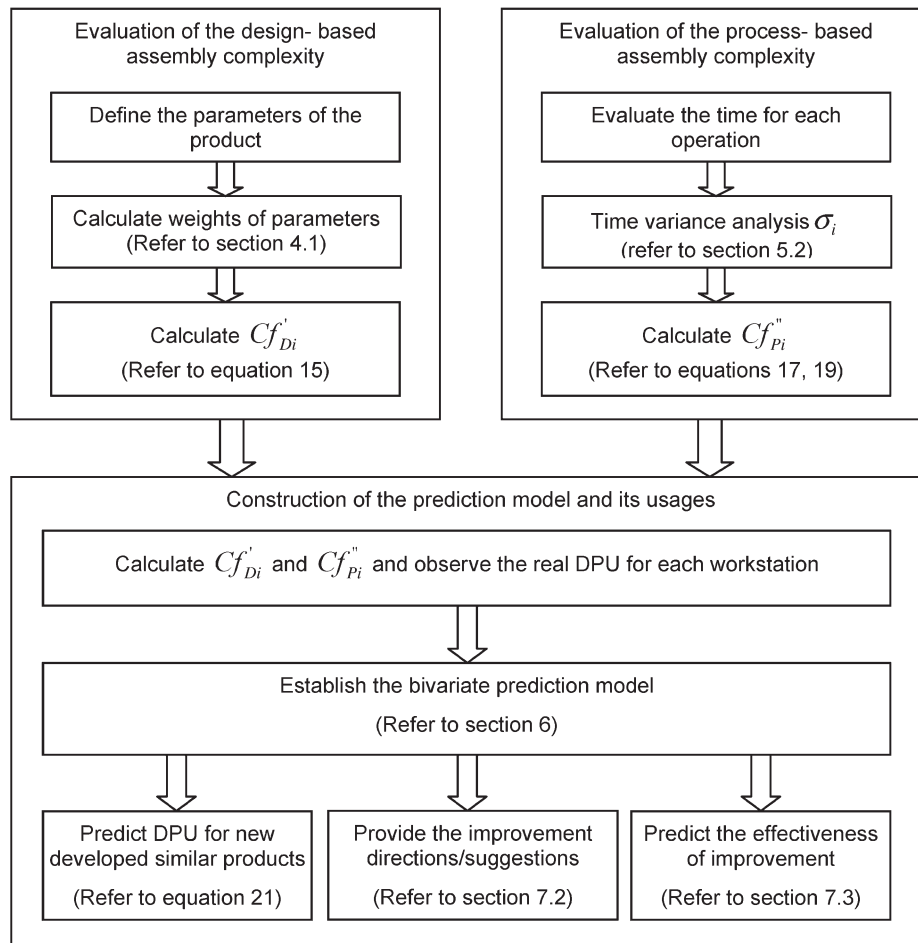


Fig. 17. General research route for operator-induced assembly defect.

Although the model is designed for copier assembly, the research approaches and the corresponding results can provide a reference framework for future explorations on other products, particularly for the electromechanical and mechanical products. According to the authors' experience, the general research route can be summarized as in Fig. 17.

ACKNOWLEDGMENT

The authors would like to thank the engineers and operators of Fuji Xerox China for their great help in data collection and analysis. The authors would also like to thank the Editor-in-Chief, Prof. W. Pedrycz, for his insightful suggestions on the enhancement of this paper.

REFERENCES

- [1] J. J. Aguilar, M. Sanz, D. Guillomia, M. Lope, and I. Bueno, "Analysis, characterization and accuracy improvement of optical coordinate measurement systems for car body assembly quality control," *Int. J. Adv. Manuf. Technol.*, vol. 30, no. 11/12, pp. 1174–1190, Oct. 2006.
- [2] D. W. Apley and Y. Ding, "A characterization of diagnosability conditions for variance components analysis in assembly operations," *IEEE Trans. Autom. Sci. Eng.*, vol. 2, no. 2, pp. 101–110, Apr. 2005.
- [3] D. Ben-Arieh, "Analysis of assembly operations difficulty: A fuzzy expert system approach," *J. Intell. Manuf.*, vol. 4, no. 6, pp. 411–419, Dec. 1993.
- [4] J. D. Booker, K. G. Swift, and N. J. Brown, "Designing for assembly quality: Strategies, guidelines and techniques," *J. Eng. Des.*, vol. 16, no. 3, pp. 279–295, Jun. 2005.
- [5] G. Boothroyd, "Design for assembly—The key to design for manufacturing," *Int. J. Adv. Manuf. Technol.*, vol. 2, no. 3, pp. 3–11, Aug. 1987.
- [6] A. Bourjault, "Contribution une approche methodologique de l'assemblage automatise: Elaboration automatique dessequences operatoires," Ph.D. dissertation, d'Etat Universite de Franche-Comte, Besancon, France, 1984.
- [7] D. Ceglarek and J. Shi, "Design evaluation of sheet metal joints for dimensional integrity," *J. Manuf. Sci. Eng.*, vol. 120, no. 2, pp. 452–460, 1998.
- [8] S. F. Chen and Y. J. Liu, "An adaptive genetic assembly-sequence planner," *Int. J. Comput. Integr. Manuf.*, vol. 14, no. 5, pp. 489–500, Sep./Oct. 2001.
- [9] P. De Lit, A. Delchambre, and J. M. Henrioud, "An integrated approach for product family and assembly system design," *IEEE Trans. Robot. Autom.*, vol. 19, no. 2, pp. 324–334, Apr. 2003.
- [10] Y. Ding, J. H. Jin, D. Ceglarek, and J. Shi, "Process-oriented tolerancing for multi-station assembly system," *IIE Trans.*, vol. 37, no. 6, pp. 493–508, Jun. 2005.
- [11] J. A. E. Eklund, "Relationships between ergonomics and quality in assembly work," *Appl. Ergon.*, vol. 26, no. 1, pp. 15–20, Feb. 1995.
- [12] T. L. De Fazio and D. E. Whitney, "Simplified generation of all mechanical assembly sequences," *IEEE J. Robot. Autom.*, vol. RA-3, no. 6, pp. 640–658, Dec. 1987.
- [13] T. L. De Fazio, D. E. Whitney, M. C. Lui, T. E. Abell, and D. F. Baldwin, "Aids for the design or choice of assembly sequences," in *Proc. IEEE Int. Conf. Syst., Man Cybern. (Cat. No. 89CH2809-2)*, 1989, vol. 1, pp. 61–70.
- [14] M. Hinkley, "A global conformance quality model: A new strategic tool for minimizing defects caused by variation, error, and complexity," Ph.D. dissertation, Dept. Mech. Eng., Stanford Univ., Stanford, CA, 1993.
- [15] L. S. Homem de Mello and A. C. Sanderson, "Two criteria for the selection of assembly plans: Maximizing the flexibility of sequencing the assembly tasks and minimizing the assembly time through parallel

- execution of assembly tasks," *IEEE Trans. Robot. Autom.*, vol. 7, no. 5, pp. 626–633, Oct. 1991.
- [16] F. S. Hsieh, "Analysis of flexible assembly processes based on structural decomposition of Petri nets," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 37, no. 5, pp. 792–803, Sep. 2007.
- [17] Q. Huang and J. Shi, "Variation transmission analysis and diagnosis of multi-operational machining processes," *IIE Trans.*, vol. 36, no. 9, pp. 807–815, Sep. 2004.
- [18] J. Jin and J. Shi, "State space modeling of sheet metal assembly for dimensional control," *J. Manuf. Sci. Eng.*, vol. 121, no. 7, pp. 756–762, Nov. 1999.
- [19] L. Lin, C. G. Drury, and S. W. Kim, "Ergonomics and quality in paced assembly lines," *Hum. Factors Ergon. Manuf.*, vol. 11, no. 4, pp. 377–382, 2001.
- [20] S. C. Liu and S. J. Hu, "Variation simulation for deformable sheet metal assembly using finite element methods," *J. Manuf. Sci. Eng.*, vol. 119, no. 3, pp. 368–374, Aug. 1997.
- [21] R. Mantripragada and D. E. Whitney, "Modeling and controlling variation propagation in mechanical assemblies using state transition models," *IEEE Trans. Robot. Autom.*, vol. 15, no. 1, pp. 124–140, Feb. 1999.
- [22] R. Mateo, "The impact of absenteeism on the quality of assembly line production: The importance of a specialization requirement," *Hum. Factors Ergon. Manuf.*, vol. 18, no. 1, pp. 49–69, Jan./Feb. 2008.
- [23] W. Mendenhall and T. Sincich, *Statistics for Engineering and the Sciences*. Englewood Cliffs, NJ: Prentice-Hall, 1995.
- [24] S. Miyakawa and T. Ohashi, "The Hitachi assembly evaluation method (AEM)," in *Proc. Int. Conf. Product Des. Assembly*, Newport, RI, Apr. 15–17, 1986.
- [25] K. S. Park, *Human Reliability—Analysis, Prediction, and Prevention of Human Errors*. New York: Elsevier, 1987.
- [26] G. Prabhakaran, R. Ramesh, and P. Asokan, "Concurrent optimization of assembly tolerances for quality with position control using scatter search approach," *Int. J. Prod. Res.*, vol. 45, no. 21, pp. 4959–4988, Nov. 2007.
- [27] V. N. Rajan, K. Sivasubramanian, and J. E. Fernandez, "Accessibility and ergonomic analysis of assembly product and jig designs," *Int. J. Ind. Ergon.*, vol. 23, no. 5, pp. 473–487, Mar. 1999.
- [28] H. Shibata, "Global assembly quality methodology: A new method for evaluating assembly complexities in globally distributed manufacturing," Ph.D. dissertation, Dept. Mech. Eng. Committee Graduate Studies, Stanford Univ., Stanford, CA, 2002.
- [29] D. Shin, R. A. Wysk, and L. Rothrock, "An investigation of human material handler on part flow in automated manufacturing systems," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 36, no. 1, pp. 123–135, Jan. 2006.
- [30] Q. Su, "Applying case based reasoning in assembly sequence planning," *Int. J. Prod. Res.*, vol. 45, no. 1, pp. 29–47, Jan. 2007.
- [31] Q. Su, "A hierarchical approach on assembly sequence planning and optimal sequences analyzing," *Robot. Comput.-Integr. Manuf.*, vol. 25, no. 1, pp. 224–234, Feb. 2009.
- [32] T. Suzuki, T. Ohashi, and M. Asano, "Assembly reliability evaluation method (AREM)," *CIRP Ann.—Manuf. Technol.*, vol. 52, no. 1, pp. 9–12, 2003.
- [33] M. S. Tavakoli, J. Mariappan, and J. Huang, *Design for Assembly Versus Design for Disassembly—A Comparison of Guidelines*, vol. 116. New York: Amer. Soc. Mechanical Eng., Des. Eng. Division (Publication) DE, 2003, pp. 389–395. no. 1.
- [34] M. Vineyard, K. Amoako-Gyampah, and J. R. Meredith, "Failure rate distributions for flexible manufacturing systems: An empirical study," *Eur. J. Oper. Res.*, vol. 116, no. 1, pp. 139–155, Jul. 1999.
- [35] H. Wang and D. Ceglarek, "Quality-driven sequence planning and line configuration selection for compliant structure assemblies," *CIRP Ann.—Manuf. Technol.*, vol. 54, no. 1, pp. 31–35, 2005.
- [36] C. Wartenberga, T. Dukicb, A. C. Falckc, and S. Hallbeckd, "The effect of assembly tolerance on performance of a tape application task: A pilot study," *Int. J. Ind. Ergon.*, vol. 33, no. 4, pp. 369–379, Apr. 2004.
- [37] R. F. Webbink and S. Hu, "Automated generation of assembly system-design solutions," *IEEE Trans. Autom. Sci. Eng.*, vol. 2, no. 1, pp. 32–39, Jan. 2005.
- [38] C. C. Wei, C. F. Chien, and M. J. Wang, "An AHP-based approach to ERP system selection," *Int. J. Prod. Econ.*, vol. 96, no. 1, pp. 47–62, Apr. 2005.
- [39] N. Wu, M. Zhou, and Z. Li, "Resource-oriented Petri net for deadlock avoidance in flexible assembly systems," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 38, no. 1, pp. 56–69, Jan. 2008.
- [40] B. Zhang and J. Ni, "Adaptive product, process and tooling design strategy for optimal dimensional quality of automotive body assemblies," *J. Manuf. Sci. Eng.*, vol. 125, no. 4, pp. 835–843, Nov. 2003.
- [41] F. Zhang and T. Luk, "A data mining algorithm for monitoring PCB assembly quality," *IEEE Trans. Electron. Packag. Manuf.*, vol. 30, no. 4, pp. 299–305, Oct. 2007.
- [42] W. Zhang, T. Freiheit, and H. Yang, "Dynamic scheduling in flexible assembly system based on timed Petri nets model," *Robot. Comput.-Integr. Manuf.*, vol. 21, no. 6, pp. 550–558, Dec. 2005.
- [43] S. H. Zheng, "Dynamic quality control in assembly systems," *IIE Trans.*, vol. 32, no. 9, pp. 797–806, Sep. 2000.
- [44] P. Zhu, H. Wang, and G. Chen, "Application of wavelet analysis to BIW assembly quality evaluation," *Int. J. Manuf. Technol. Manag.*, vol. 14, no. 1/2, pp. 189–200, Mar. 2008.



Qiang Su (M'09) received the B.S., M.S., and Ph.D. degrees from Xi'an Jiaotong University, Xi'an, China, in 1991, 1994 and 1997, respectively, all in manufacturing engineering.

From 1998 to 2000, he was a Postdoctoral Researcher with the Department of Management Science and Engineering, Tsinghua University, Beijing, China. From 2000 to 2004, he was a Postdoctoral Researcher and then a Senior Research Fellow with the Department of Industrial and Systematic Engineering, Florida International University, Miami. He joined the Department of Industrial Engineering and Logistics Management, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China, in 2004, where he is currently an Associate Professor. His research interests include production and service system optimization, quality and cost relationship analysis, and healthcare service improvement using engineering technologies.

Dr. Su is a member of the American Society for Quality. Since 2007, he has been serving as a member of the Editorial Board of the *International Journal of Six Sigma and Competitive Advantage*.



Lei Liu received the B.E. degree in industrial engineering from Shanghai Jiao Tong University, Shanghai, China, in 2006. He is currently working toward the Ph.D. degree in industrial engineering with Arizona State University, Tempe.

He was a Program Management Supervisor with Fuji Xerox of Shanghai Limited, Shanghai, China. His research interests are in applied statistics and quality management.

Mr. Liu is a member of China Association for Quality.



Daniel E. Whitney, (S'66–M'68–SM'84–F'02) received the Ph.D. degree in mechanical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1968.

He taught in the Department of Mechanical Engineering, MIT, from 1968 to 1974. From 1974 to 1993, he was with the Charles Stark Draper Laboratory, Cambridge. He is the coauthor of several books and more than 80 articles in scholarly journals. At both MIT and Draper, he has done research on robotics, mechanical assembly, design for automation,

the use of computers in the product development process, and complex systems and networks. He has also taken part in many product design activities with industrial companies, dealing with assembly problems for both military and commercial products. His interests include agile manufacturing, the use of computers in product development, understanding the role of assembly in the design and manufacturing processes, and understanding how companies decide what design and manufacturing skills and facilities are core competencies.

Dr Whitney is a member of Tau Beta Pi, Sigma Xi, the American Society of Mechanical Engineers, and the Subcommittee for Mathematics Education of the Royal Irish Academy (SME/RIA).