Int J Adv Manuf Technol (2016) 85:1471–1481
DOI 10.1007/s00170-015-8026-x

ORIGINAL ARTICLE

Assembly process control method for remanufactured parts with variable quality grades

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Received: 15 June 2015 / Accepted: 25 October 2015 / Published online: 9 November 2015

Abstract How to maximize the use of remanufactured parts with variable quality grade and improve the precision of reassembly (remanufacturing assembly) is the key to reassembly quality control. Firstly, based on analyzing the characteristics of reassembly for complex mechanical product, an assembly process control method of remanufactured product with different quality grade is proposed. Optimization model of reassemble scheme was constructed, which can describe the transmission process and the status of assembly precision in each assembly station, and characterize the relationship between assembly precision and remanufactured parts with various quality grades. Then, the solution is given by genetic algorithm, which can respond to abnormal quality situation during reassembly process and realize optimal control for reassembly process. Finally, a quality control of a prototype system for the remanufactured engine assembly is developed, which shows the feasibility and validity of the proposed method.

Keywords Remanufacturing assembly · Uncertainty · Quality control · Genetic algorithm

1 Introduction

With the rapid development of the economy and the society since the twenty-first century, the contradiction between the economic growth and the energy source has become an increasingly prominent problem in the world. To maintain the sustainable development, countries all over the world put forward some solutions. They try to change the consumption idea and improve manufacturing technology to save energy and reduce environment damage. Remanufacturing technology aims at low carbon, energy saving, and material saving, which have been paid more and more attention all around the world. Remanufacturing is a generic term of technical renovation or engineering activities of waste electromechanical products. As an extension of the manufacturing industry chain, it has become an effective way to solve the resource crisis and environmental pollution problems. Now the small-scale, narrow-range remanufacturing industry has formed a huge contrast with abundant resources for remanufacturing. Therefore, the remanufactured product quality and the service security have been the bottlenecks in the development of remanufacturing industry.

In order to relieve the contradiction between limited resources and unlimited waste, a lot of researches and application works have been working on remanufacturing waste electromechanical products all over the world [1]. It mainly focuses on remanufacturing reverse logistics [2, 3], closed-loop supply chain [4, 5], disassembly modeling [6], production planning [7], economic lot scheduling problem [8], and economic and technical evaluation [9–11]. However, little research has been undertaken on the production process management of remanufacturing. The relevant literatures are as follows.

In the aspect of quality evaluation and application of remanufactured parts, Mark Ferguson and others verified the value of quality classification in the assembly process. And they also proposed a simple greedy heuristic algorithm to calculate the optimal solution [12]. Based on the fuzzy analytic hierarchy process (AHP), Zhou presented a quality evaluation model to quantify the reusability degree of the recycling parts on the end-of-life wheel loader, and a management system of recycling process to strengthen the management of the

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whole repairing process was developed and the efficiency of work flow was also improved [13]. Aiming at the uncertainty problem of process and time for remanufactured parts, Tang established open-loop queuing network model of remanufacturing system. He discussed the influence of quality uncertainty of parts on the rework time [14].

In the aspect of scheme research for remanufacturing assembly, Jin made a further study about the optimal assembly method of remanufacturing system products. It was under the condition of recycled product quality uncertainty and customer demand diversification [15, 16]. Liu studied the tolerance the hierarchical matching method of remanufactured parts, which faces the target of uncertainty and quality, and applied the mathematical model and example to prove its feasibility and effectiveness [17, 18].

As for the management direction of remanufacturing product quality, Niu introduced the method of tolerance design into the remanufacturing engineering and proposed an optimization mathematical model of remanufacturing tolerance design. It can effectively guarantee and improve the quality of remanufactured products [19]. Ge studied the online quality control methods for the assembling of remanufactured engines' cylinder block and cover under uncertainty [20]. Shen studied the quality control method for remanufacturing assembly based on the Jacobian-Torsor model [21].

The above studies made an important contribution to the development of the remanufacturing industry. It has become a key for further development of remanufacturing industry about how to make full use of remanufacturing resource, how to improve the quality of remanufacturing, and how to realize a large amount of remanufacturing production. As the key part of remanufacturing production, assembly has an important influence on the quality, performance, time limit, and cost. Combined with the previous research results, based on the analysis of assembly characteristics about complex mechanical products, this paper proposes an assembly process control method for remanufactured parts with variable quality grade. It also develops a quality control prototype system of the remanufactured engine assembly process in a remanufacturing factory. This provides the theoretical and technical support for the quality control of remanufactured products.

2 The characteristics of complex mechanical product reassembly

The parts for complex remanufacturing mechanical products used in the assembly process contain not only original parts but also remanufactured and reused parts. Therefore, the reassembly process has the following features:

1. Reused and remanufactured parts have a large discrete degree on quality attributes and center migration, which resulting in an increase of error range of reassembly quality and a decline in remanufacturing assembly precision.
2. In the complex reassembly environment, there is a dynamic, nonlinear, coupling interaction between the various uncertain factors. And different degrees influence the quality and performance of the final products. This hardly guarantees the quality stability and service security of remanufacturing products.
3. The differences in error, cost, quality, and quantity of original, reused, and remanufactured parts lead to diversified characteristics of reassembly scheme.
4. The reassembly quality control of remanufacturing complex mechanical products generally follows the product assembly standards. It ignores the difference of quality attributes between manufacturing and remanufactured parts. It would influence reassembly quality and cost and cause the waste of remanufacturing resources.

By analyzing the uncertainty of reassembly, it is obvious that the quality uncertainty of remanufactured parts has led to the higher uncertainty in reassembly process, reassembly structure, and reassembly control. These changes are the reason for the drastic change of reassembly quality and the diversification of reassembly scheme, which will affect the product quality ultimately. In other words, the uncertainty of remanufactured part's quality is the major influencing factor of reassembly process uncertainty.

Due to differences in ultra-poor size, residual stress, surface deformation, internal cracks, etc., variant processing technologies should be adopted according to the characteristics of remanufactured parts, which leads to dimensional precision uncertainty of the remanufactured parts. While the original parts used in the remanufacturing process obtain a relatively uniform texture and better quality by casting, forging, stamping, rolling, and other processing methods, the remanufactured parts and the original are different.

In actual remanufacturing process, it will have a strong impact on the quality of remanufactured product if the original assembly standard is adopted in the remanufacturing process. Therefore, how to maximize using remanufactured parts with variable quality grade and improve the precision of reassembly have become a difficulty to be solved in reassembly quality control.

Based on the above analysis, a control method for reassembly process of complex mechanical products is urgently needed. Within the scope of cost control, it should improve the utilization rate of remanufactured parts, maximize the use of remanufacturing resources, reduce the negative impact of uncertainty, and improve the reassembly precision of remanufactured products.

3 Reassembly process control method

Based on the quality attribute difference and the cost difference among the remanufactured parts, the reused parts, and the original parts, this paper makes a measurement on quality attributes of these reassembly parts by block coding and calculation of dimension chain. Then, considering the dynamic compensation cost of remanufacturing assembly, a reassembly scheme optimization model is built with the target of minimizing comprehensive cost. Using optimization algorithm, the paper takes repeatedly optimal matching for the remanufactured parts. After each matching, the optimal reassembly scheme and the number of products are recorded to judge whether it meets the order requirement or not. If it does meet the order requirements, the reassembly scheme will be the output. Otherwise, the information will be updated, and the remaining parts will be continuously selected; certainly, the number of the optimal assembly scheme and the number of products will also be recorded. Hence, it can be judged whether it meets the requirement. When the entire assembly scheme meets the requirement of the order, it will be the output. During the optimization process, it can make a timely response to abnormal situation such as part shortage and tolerance problem and take reassembly control measurement such as loop compensation adjustment, work clamp fixture calibration, and correction of reassembly process parameters, which realize the online instruction and quality control for assembly process of remanufactured complex mechanical products.

The reassembly process control method flow chart of the remanufactured parts with variable quality grade is shown in Fig. 1.

Step 1 According to the actual demand of production and orders, we need to pre-set related parameters such as key quality control point, key quality threshold, its fine-grained classification, etc.

Step 2 Timely input the quality attribute information of the assembly parts and other information requested by the system through the online real-time information collection technology.

Step 3 The system determines whether the component meets the assembly requirements under the quality threshold constraint. If it satisfies, it will be graded based on the fine-grained levels of the quality control threshold and then the parts data of each level will be dynamically updated. If it does not, the system will give an alarm prompting operators to process, such as temporary storage with marks, adjusting the tolerance compensation parts, etc., then return to the parts' information input interface.

Step 4 After all remanufactured parts assembly information is inputted, optimal feasible assembly solution for the entire assembly process or a procedure is

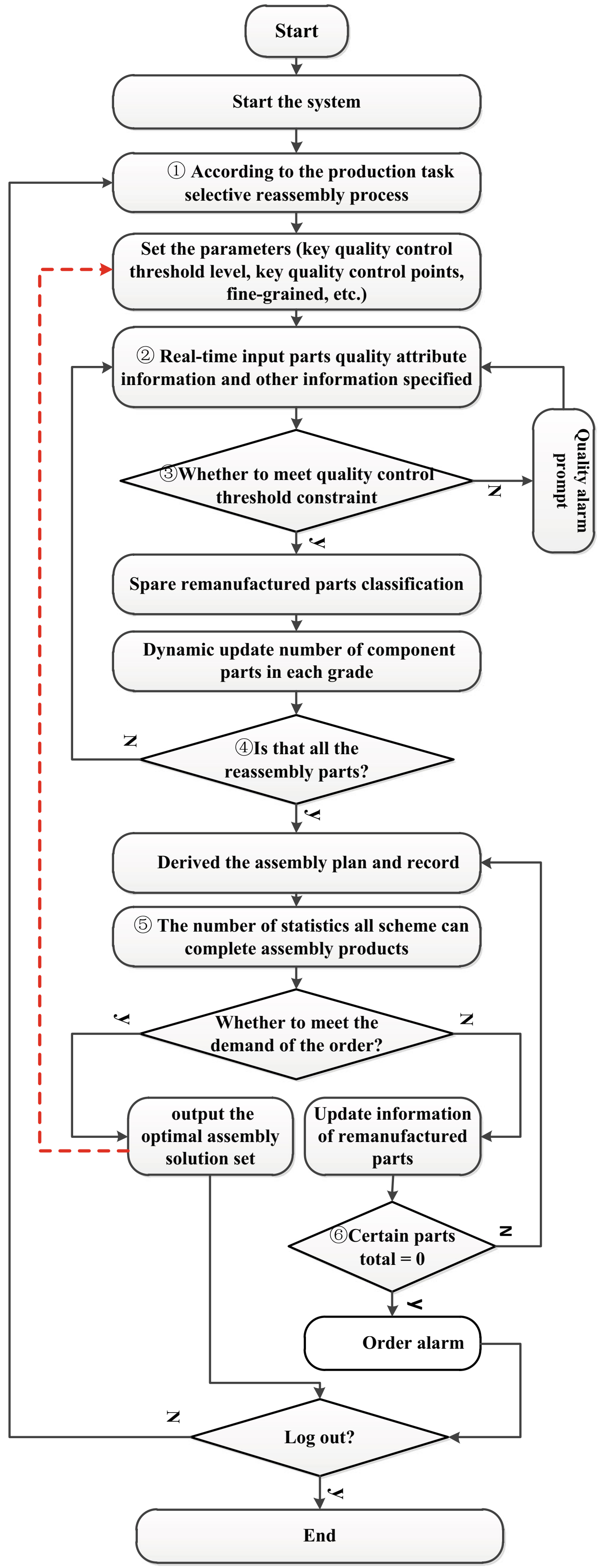

Fig. 1 The reassembly process control method flow chart

deduced by genetic algorithm in accordance with the objectives and constraints of the model. The system marks the solution number 1 and then records the number of assembled products it can complete.

Step 5 Calculate the sum of all assembly solutions and judge whether it can satisfy the order demand. If it satisfies, the system will output the solution 1. If it does not, the system will update the number of parts, namely the number of each level parts minus the number of parts used in the solution 1.

Step 6 After updating, if the total number of at least one kind part is zero, which means there are no parts of these parts' all levels left, the alarm will be given to warn the parts' shortage. If all kinds of parts are remaining, the system will deduce the optimal assembly solution, and that is solution 2.

Step 7 Calculate the sum of all assembly solutions and judge whether it can satisfy the order need as step 5. If it satisfies, the system will output the solution 1 and solution 2. If it does not, the system will update the number of parts, namely the remaining number of each level parts minus the number of parts used in the solution 2.

Step 8 Repeat step 6. If all kinds of parts are remaining, the system will deduce the optimal assembly solution, and that is solution 3. The iteratively processing in turn until the optimal assembly schemes meet the order requirements, output the remanufacturing optimal assembly scheme set, and make timely warning to the abnormal conditions of the parts' quality problem and the parts' shortage, which can improve assembly precision and utilization of remanufactured parts with minimum comprehensive cost. In the case of an infinite loop, it can be solved by the expert guidance, quality control threshold level revision, system quitting, etc. The assembly scheme set, which will be stored into the historical database, is helpful to the model parameters of feedback correction for updating and correcting the method.

4 The mathematical model and its solution

4.1 Grouping of remanufactured parts

Because of the discrepancy in quality attribute between the remanufactured parts and the original parts, it is more likely to generate assembly deviation during the reassembly process of a complicated mechanical product. The assembly deviation takes reassembly resources as carrier and forms a quality deviation flow after coupling, accumulating, and transmitting, along with the assembly process. It intensifies the instability of reassembly quality and affects reassembly precision. Therefore, how to make full use of the remanufactured parts with variable quality grades and improve the assembly precision of remanufactured product have become a challenge to reassembly quality control.

Liu Mingzhou et al. [17] proved that the dimensional variance could be enlarged by one rate and the dimensional tolerance could be widened by 40 %, if we divide dimensional tolerance of the remanufactured parts into the positive level and the negative level in the ideal state. Therefore, the classification matching method for the remanufactured parts can amplify remanufacturing precision to economic degree and reduce the influence of uncertain factors. This method can also reduce the instability of reassembly quality, thus assures the quality of the remanufactured product.

4.2 Optimization model of reassemble scheme

The optimization model of reassemble scheme is described as follows:

Definition 1 Suppose that x is the set of assembly parts, and it consists of the repair parts, the reuse parts, and the original parts, where x_i represents the ith assembly parts, i=1, 2,…n; x_{ij} is the jth grade of the ith assembly parts, j=1, 2,…m.

Definition 2 u_{ij} is the corresponding operation of assembly parts x_{ij}, the operation cost of x_{ij} is $u(x_{ij})$.

Definition 3 y_i represents the assembly quality attributes (such as variance, torque, bending, and roundness) after assembling the ith parts. Respectively, y_0 is the initial point; y_n is the ultimate quality of the remanufactured product; $\overline{y}i$ is the assembly quality standard threshold value after assembling the ith part. The value can be acquired online by information collection technology.

Assuming that there is only one part assembled at each station in the reassembly process, the remanufacturing assembly precision transfer model can be expressed as:

$$\begin{cases} y_i - 1 + Ax_{ij} + Bu_{ij} + w_i = y_i \\ y_i \subseteq \overline{y}_i \end{cases} \quad (1)$$

where, i represents the ith assembly station; $x_{ij} \in R^{p\times 1}$ represents the vector of the ith assembly parts; $u_{ij} \in R^{q\times 1}$ represents the operation input vector of the ith assembly station; $y_i \in R^{r\times 1}$ represents the vector of assembly precision; $y_i - 1$ represents the quality attribute after assembling ($i-1$)th parts. $w_i \in R^{r\times 1}$ is the process noise of reassembly system, and the mean value of w_i is 0. A, B, and w_i can be confirmed according to the actual production date.

Formula (1) can exactly describe the transmission process and the status of assembly precision in each assembly station and quantitatively describe the relationship between assembly precision and the remanufactured parts with various quality grades (Fig. 2).

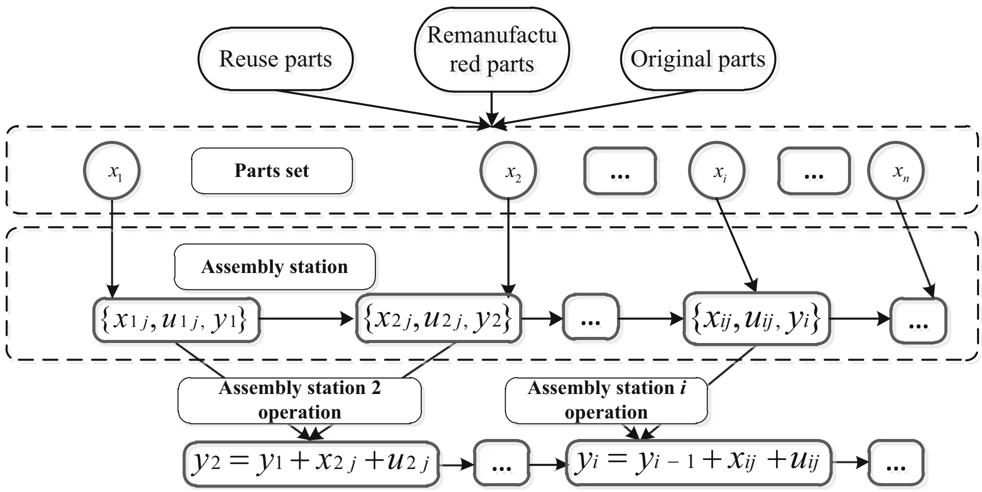

Fig. 2 Transmission network diagram of remanufactured complex mechanical product assembly precision

Reassembly indemnifying measures cost Different operations should be adopted to different grades of the remanufactured parts. We need to add compensation measures (such as parameters amendment and precision adjustment) to the low-grade remanufactured parts, so the corresponding operation cost $u(x_{ij})$ is various.

Component cost The reassembly parts consists of the original parts, the remanufactured parts, and the reused parts. The self-value cost $s(x_{ij})$ of the remanufactured parts with variable grades is different.

The selection of the parts grade has a significant impact on the quality of the final product as the assembly cost, and the self-value cost of component with variable grades is different. The assembly scheme optimization model for remanufactured complicated mechanical product is constructed aiming at a minimum composite cost in this paper.

$$\min C = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[s(x_{ij}) + u(x_{ij})\right]$$
$$s.t\begin{cases} y_i - 1 + Ax_{ij} + Bu_{ij} + w_i = y_i \\ y_i \subseteq \overline{y}_i \\ \sum_{j=1}^{m} x_{ij} = 1 \end{cases} \quad (2)$$

4.3 Model solution based on genetic algorithm

Genetic algorithm is an efficient search algorithm which is based on natural selection and genetic [22]. This method combined the survival of the fittest theory and the random information exchange mechanism. Genetic algorithm is used for solving optimization problem in computer science artificial intelligence. It is one of the evolutionary algorithms. Genetic algorithm has the advantages of no special requirements, simple computation, and fast convergence rate, especially in the search for the global optimal solution with high efficiency. Therefore, genetic algorithm is used to solve the assembly scheme optimization model of the remanufactured complex mechanical product:

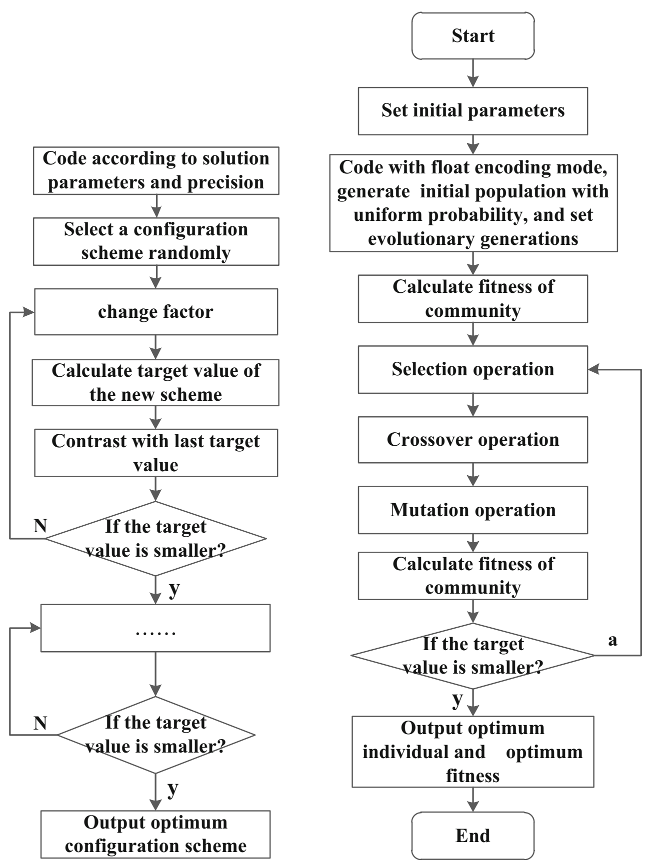

Fig. 3 Solution procedure of genetic algorithm

1. Encoding

    Encoding mechanism is the foundation of the evolutionary process of genetic algorithm. It has immense impact on the population diversity and search capability of the algorithm. Float-point encoding can maintain better population diversity on mutation operation, so this method is adopted in this paper. According to the assumption condition of the model, the encoding rule is built as follows:

    (a) In accordance with the assembly station sequence of the remanufactured complicated mechanical product, they are encoded as 1, 2… *n*;
    (b) Sort the sequence of the parts' grade in reassembly station, and code it in sequence: 1, 2… *m*;
    (c) A genic value of chromosome corresponds to a remanufactured part in assembly station;
    (d) An antibody corresponds to a reassembly optimization configuration scheme.

2. Individual fitness function

    Only the fitness value of each individual in population is used to search optimization solution in genetic algorithm. Therefore, the selection of fitness function has a direct influence to globally optimal solution and convergence rate of the algorithm. Assembly scheme optimization model for remanufactured complex mechanical product is a minimum optimization problem

$$fit(F) = 1/[F + c] \tag{3}$$

The objective function value is always a positive one, therefore $c=0$. It is implied from the fitness function that the smaller target value corresponds with the bigger fitness value, and the probability to be selected is higher.

3. Population initialization

    To prevent the new individual except the candidate assembly stations appearing in the operation process, we code the assembly station or the assembly parts based on the arrangement sequence in initial space. This paper adopts random procedure to generate initial population to overcome the drawback of trapping into local optimum situation.

4. Genetic operator

    Selection operator: It is used to ascertain crossover individual or recombination individual and to calculate how many generation individual can be produced from

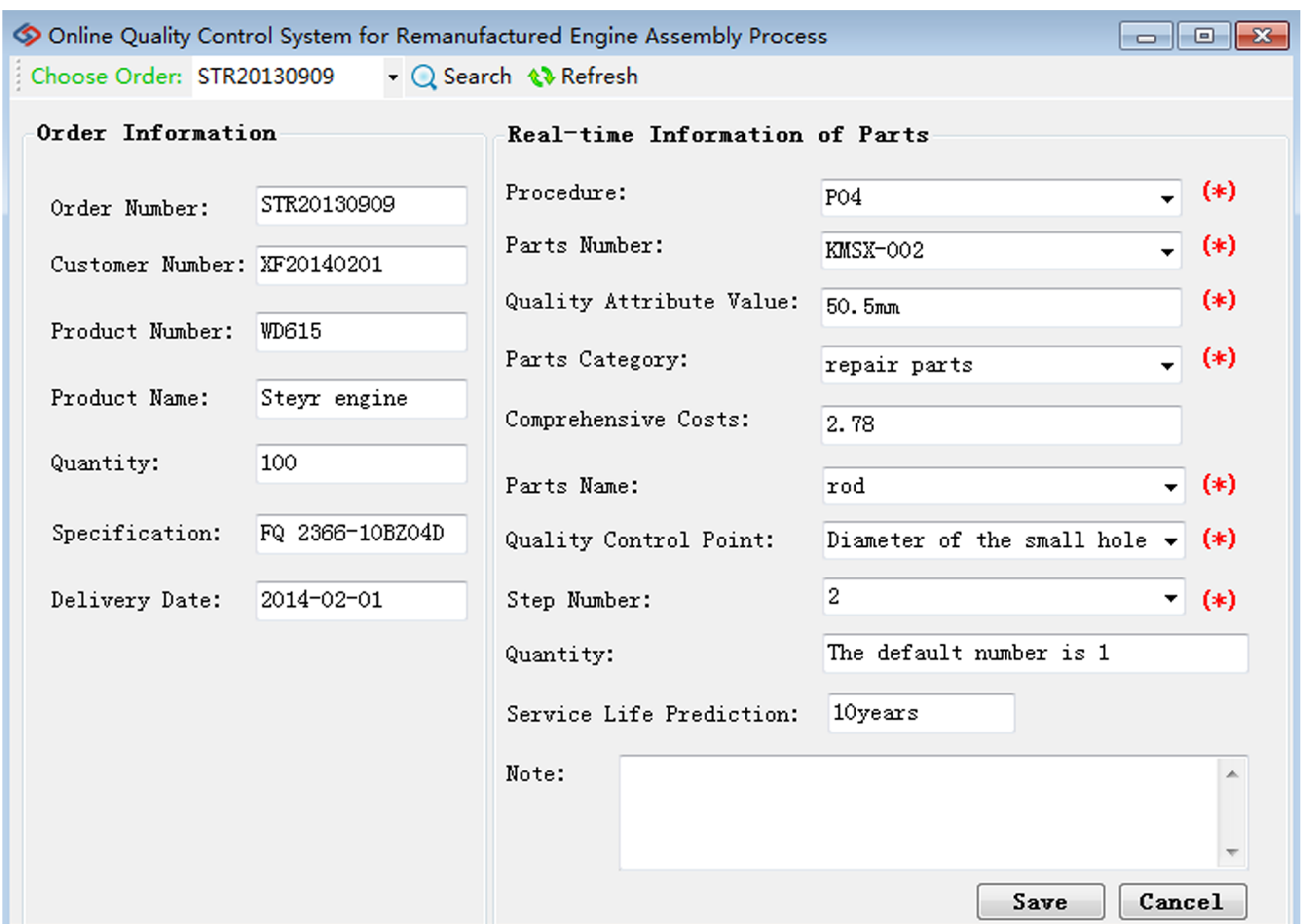

Fig. 4 Real-time information input for remanufactured engine-connecting rod

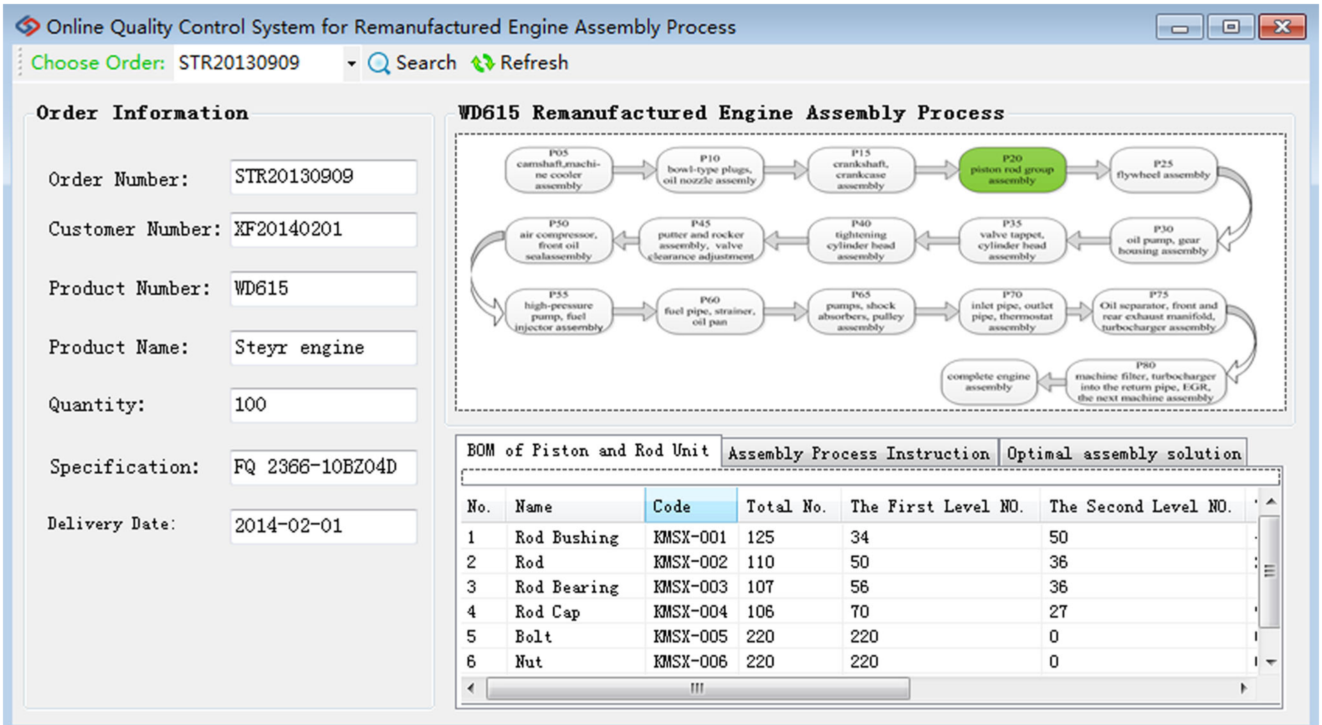

Fig. 5 WD615 remanufacturing engine piston-connecting rod unit full information

selected individual. To protect the superior individuals, we arrange the individuals in the population from high to low according to the sequence of fitness, and distribute the probability to be selected based on the fitness sequence.

Crossover operator: It decides the frequency of crossover operation. The higher frequency, the quicker it will converge to the optimal solution region. This paper chooses uniform crossover method to select crossover probability within [0, 1].

Mutation operator: It is influenced by chromosome length and population size. If we choose higher mutation probability, the diversity of sample model will

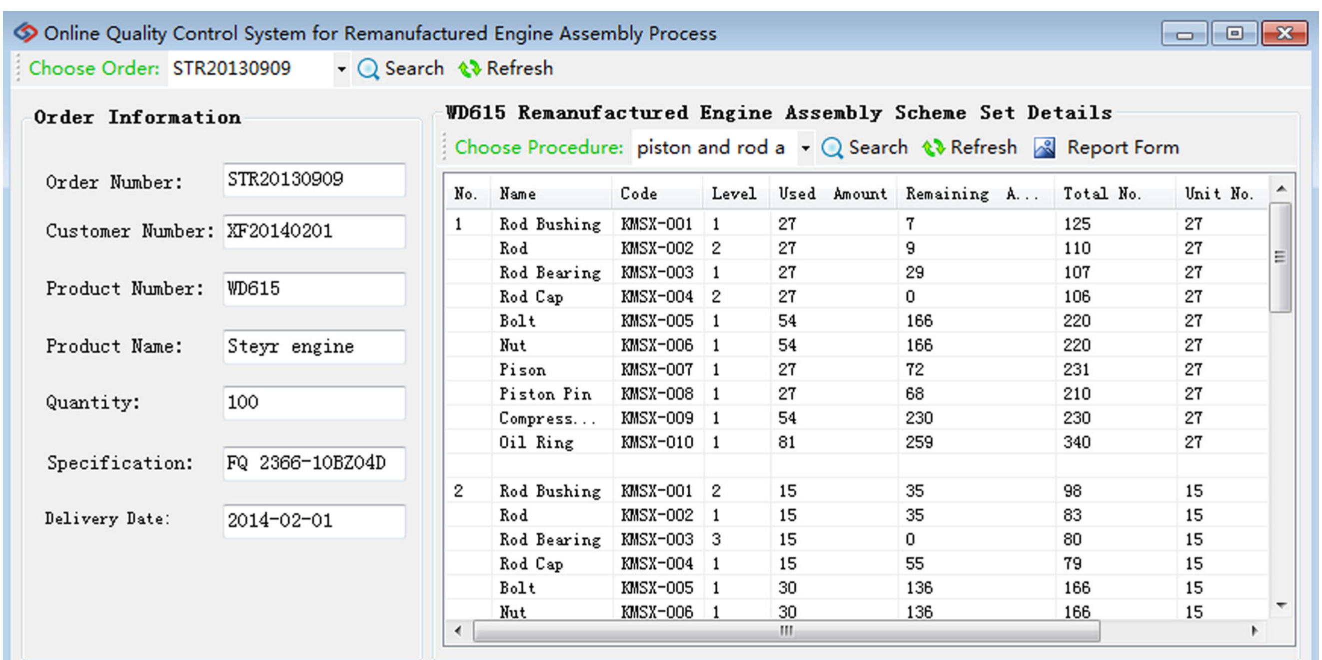

Fig. 6 The optimal assembly scheme set of WD615 remanufactured engine piston-connecting rod unit

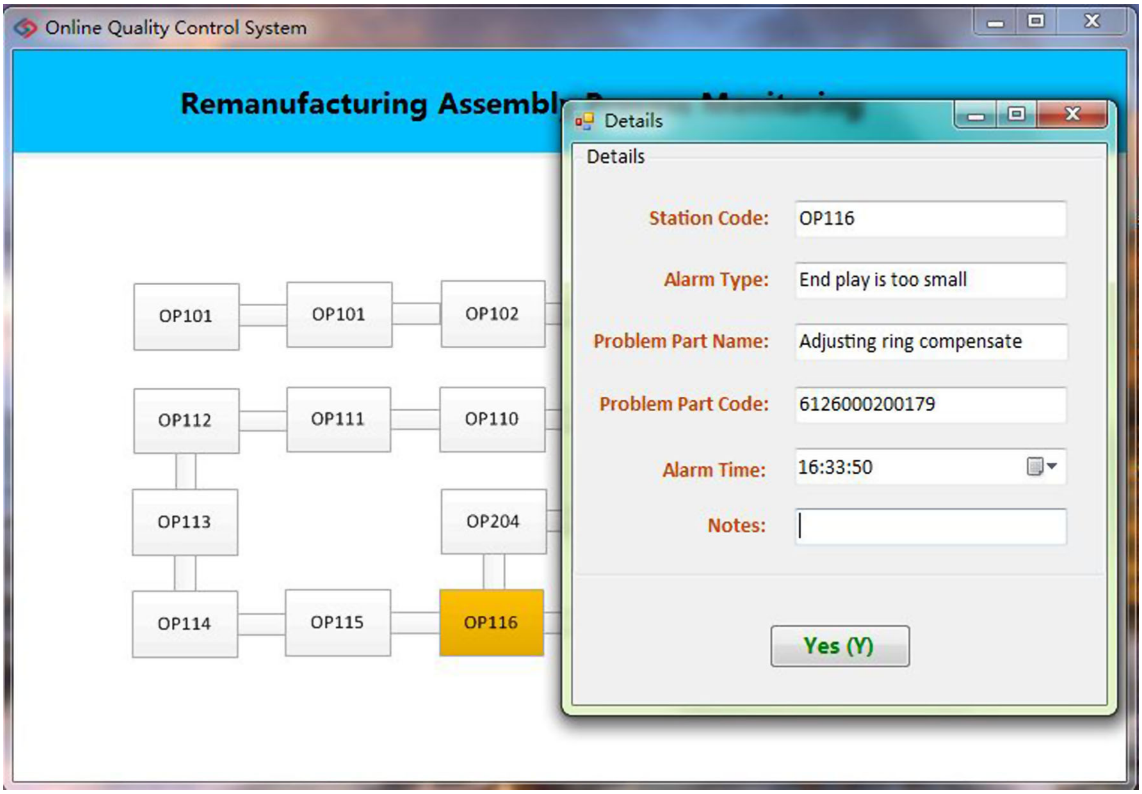

Fig. 7 Real-time monitoring of remanufacturing assembly process

be increased, but it will result in the instability of the system. Therefore, we choose uniform mutation method and select a smaller mutation probability in this thesis.

5. Procedure of genetic optimization

   The solution procedure of reassembly scheme optimization model for remanufactured complex mechanical product based on genetic algorithm is shown in Fig. 3:

5 The quality control of a prototype system

5.1 Enterprise requirement

The quality control system of remanufactured engine assembly process is developed in a remanufacturing engine company. After removing, cleaning, and detecting, it can acquire reused parts from recycling scrap engine. Besides, we can get the remanufactured parts by technical transformation or reprocessing. These two kinds of parts are reused for the assembly of the remanufactured engine. There are several problems existing in the reassembly process of STR series engine, including the multiple uncertain factors during assembly process, the big dispersion degree of quality attributes values of reassemble parts, the large error range of assembly quality, and the low utilization rate of the remanufactured parts. Meanwhile, the assembly scheme is diversified due to the mix assembly of reused, repaired, and new parts. The back repair rate has reach up to 15 % resulting from the problems above. Taking the assembly process control of a certain engine of remanufactured STR as a research object, the operation condition will be introduced.

5.2 System display

With an example of the remanufactured engine (Model WD615) piston and rod assembly, the operation and application for the quality control of prototype system is described as follows. Through the online real-time information collection technology, the quality attribute information of the assembly parts and other information are timely requested by the quality control system. The diameter of the small hole is one of the key quality points of rod No. KMSX-002. The quality control system set the standard quality control threshold as [49, 50.5]. The first level of the quality control threshold is [49, 49.5], the second level is [49.5, 50] and the third level is [50, 50.5]. As shown in Fig. 4, the input value is 50.5, which satisfies the

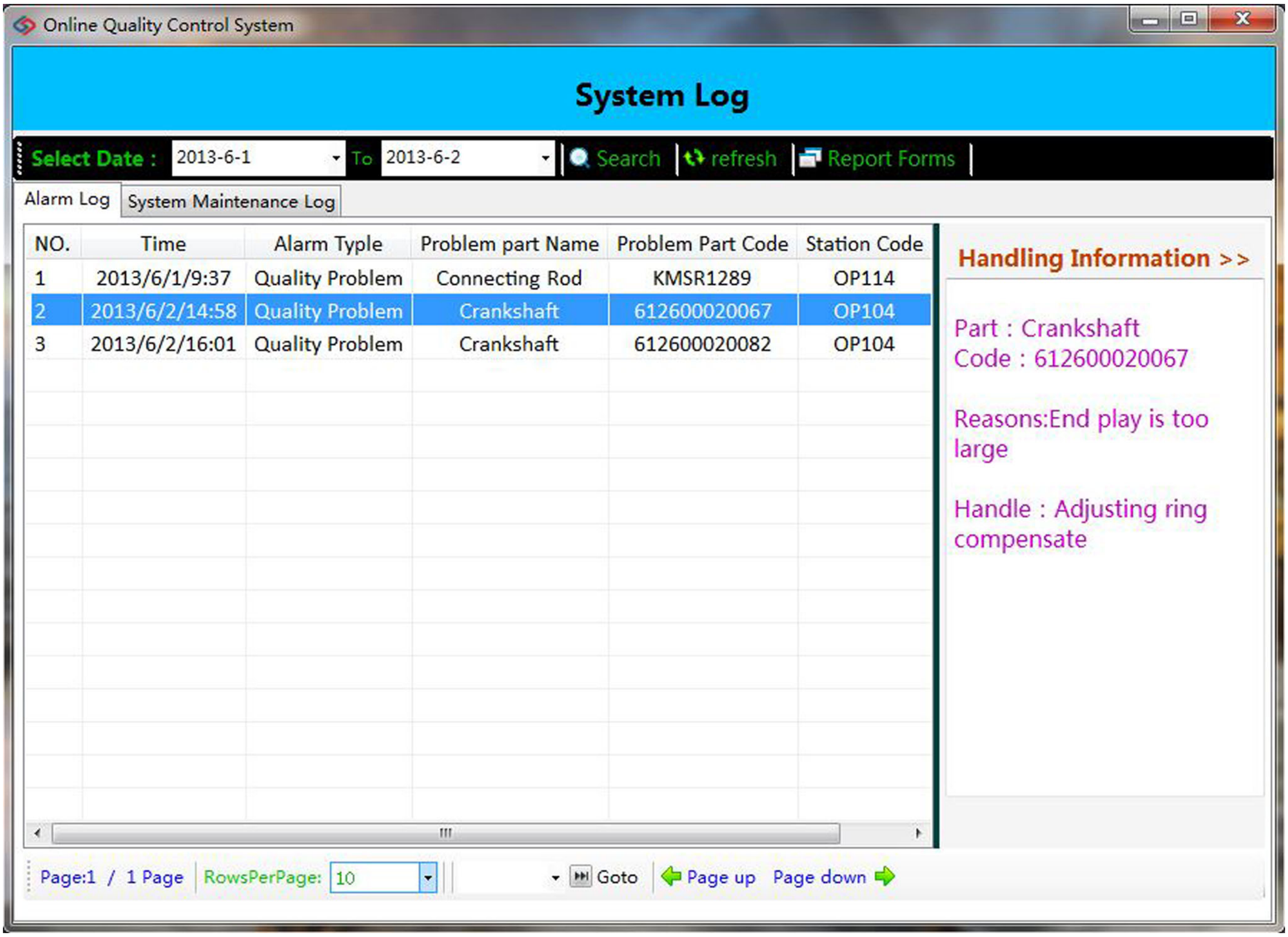

Fig. 8 The active compensation system log of remanufacturing quality

constraint of quality control threshold and belongs to the third level. Then the parts data of each level is dynamically updated.

All the remanufactured parts assembly information is inputted as shown in Fig. 5, and then the optimal feasible assembly solution is deduced in accordance with the model in Section 2. The system marks the optimal feasible assembly solution 1 and then records the numbers of piston connecting rod unit which is 27.

If the numbers of the piston connecting rod unit of solution 1 cannot meet the order requirement, then the quantity information of the unused parts will be updated in the system. Moreover, the optimal assembly solution (solution 2) will be deduced again, which is shown in Fig. 6. The above steps are repeated until the numbers of piston-connecting rod units reach to the order requirement of 100.

The system can monitor reassembly process and track, diagnose, and report the quality of each location. Figure 7 is the display of the real-time monitoring system in the remanufacturing assembly process. The system can track, diagnose, and report the reassembly process. Then, the quality

Table 1 2012 and 2013 series of STR remanufactured engine hot test inspection qualification rate of contrast

STR series of remanufacturing engine hot test inspection

	Project	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2012	Check the numbers	804	677	804	1147	1408	1002	1425	1189	967	768	843	800	986.17
	Unqualified number	59	36	41	53	73	75	109	86	74	40	53	48	62.25
	Failure rate (%)	7.34	5.32	5.10	4.62	5.18	7.49	7.65	7.23	7.65	5.20	6.29	6.00	6.26
2013	Check the numbers	768	809	806	974	1303	1502	1467	1291	1404	1253	1009	1100	1140.5
	Unqualified number	32	32	26	36	55	77	62	42	50	52	38	26	44
	Failure rate (%)	4.17	3.96	3.23	3.70	4.22	5.13	4.23	3.25	3.56	4.15	3.77	2.36	3.81

Table 2 2012 and 2013 STR series engine remanufacturing cumulative frequency in the top 15 parts quality compensation

Number	2012 Quality compensation frequency (top 15)		2013 Quality compensation frequency (top 15)	
	Defective parts	Compensation for the frequency	Defective parts	Compensation for the frequency
1	Piston	1560	Clutch	792
2	Fuel filter	1524	Adjustable fault	648
3	Thermostat	1360	Thermostat	582
4	Rockerarm	1248	Supercharger	549
5	Oil pump	908	Rocker	476
6	Camshaft	860	Air compressor	471
7	Supercharge	812	Water pump	364
8	Clutch	805	Piston ring	349
9	Adjustable fault	653	Flywheel	208
10	Air compressor	537	Piston	203
11	Tappet	498	Fuel filter	187
12	Piston ring	459	Camshaft	179
13	Water pump	398	Tappet	152
14	Exhaust pipe gasket	307	Oil atomizer	121
15	Flywheel	290	Oil pan	97

To protect the rights and interests of enterprises, the above is a processed data

information of work stations is monitored. Figure 7 also displays the real-time monitoring system about work stations.

The system makes a timely response to the abnormal situation appearing in the work stations and reminds the way of real-time advisories. It also gives the system log for remanufacturing quality (Fig. 8).

5.3 Effect contrast

With the cooperation of production department and quality department, we acquired the following information in Table 1 according to the service data, overhaul report statistics, and the management information of site quality in 2012 and 2013.

Since the reassembly process control method was implemented in 2013, the average qualified rate of remanufacturing engine's hot test reduced by 2.45 %, the after-sale cost caused by quality problem decreases 237.49 million Yuan, and the claim frequency about remanufactured engine quality is declined compared with 2012.

Since the implementation of quality control system, remanufactured engine quality is significantly improved, and the compensation frequency about all remanufactured parts decreased by 22.3 %. The details are as shown in Table 2.

6 Conclusion

Based on the analysis of the characteristics of complex mechanical product reassembly, the control method of the assembly process for the remanufactured parts with variable quality grades is proposed in this paper. Firstly, the paper builds the optimization model of assemble scheme for minimizing the cost and gets solutions based on genetic algorithm, which maximizes the use of remanufacturing resources. It also improves the control ability of reassemble process and assembly accuracy of remanufactured products. Then, using the quality control prototype system to verify the assembly process control method is feasible and effective. And the method provides a tentative thought and research direction for the lean management of remanufacturing assembly, which can effectively guarantee the remanufacturing product quality and provide theoretical and technical supports for further large-scale production in the remanufacturing industry.

Acknowledgments This research is supported by the National Basic Research Program (973 Program): fundamental science research of mechanical equipment remanufacturing (project number: 2011CB013406) and also supported by the National Natural Science Foundation of China (51375133).

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