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Research on Rework Strategies for Reconfigurable Manufacturing System Considering Mission Reliability

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Abstract

Rework strategies that involve different checking points as well as rework times can be applied into reconfigurable manufacturing system (RMS) with certain constraints, and effective rework strategy can significantly improve the mission reliability of manufacturing process. The mission reliability of process is a measurement of production ability of RMS, which serves as an integrated performance indicator of the production process under specified technical constraints, including time, cost and quality. To quantitatively characterize the mission reliability and basic reliability of RMS under different rework strategies, rework model of RMS was established based on the method of Logistic regression. Firstly, the functional relationship between capability and work load of manufacturing process was studied through statistically analyzing a large number of historical data obtained in actual machining processes. Secondly, the output, mission reliability and unit cost in different rework paths were calculated and taken as the decision variables based on different input quantities and the rework model mentioned above. Thirdly, optimal rework strategies for different input quantities were determined by calculating the weighted decision values and analyzing advantages and disadvantages of each rework strategy. At last, case application were demonstrated to prove the efficiency of the proposed method.

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Keywords: Reconfigurable manufacturing system; Rework strategy; Mission reliability; Logistic regression model

1. Introduction

To facilitate the adaptation of manufacturing enterprises to the rapidly changing market environment, National Research Institute of the U.S. and Engineering Research Center of University of Michigan developed the reconfigurable manufacturing system (RMS) [1]. when the market environment changes with the reconfiguring module or by moving, relying on the existing hardware and software resources, this system can realize logical reconstruction of virtual manufacturing units and quickly adjust production procedure within the prescribed scope of planning and configuration, changing and adding some reconfigurable equipments, providing the functionality and capacity required in each production cycle [2, 3]. Rework is a common measure in manufacturing process to make the unqualified products meet the intended use requirements, and rework scheduling is a key procedure of production scheduling under the reconfigurable manufacturing mode. The path and frequency of rework can be determined correspondingly according to characteristics of this type of manufacturing system, to better save resources and costs.

Based on distribution probability of processing capacity of equipment, literature [4] studied the method of evaluating the reliability of RMS when the rework path was known. In this research, logistic regression model was used to study reliability of the rework-involved manufacturing process, based on which, reliability model of rework process of the RMS was constructed, and rework strategy of the RMS was studied systematically. Literature [9] proposes the concept of

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mission reliability of the quick response manufacturing system, and studies the impact of rework on parameters related to mission reliability in the working process. Although reliability of manufacturing process can be improved significantly with effective rework strategies, the work load can be increased while the basic reliability reduced in the process of rework.

In this research, based on the logistic regression, change of the basic reliability along with the work load was studied firstly, rework models of the single procedure and the RMS were established respectively to study the change rule of mission reliability; Secondly, influence of the input variable, time of rework and other factors on the manufacturing process were analyzed, and the method for optimizing the rework strategy of RMS that considers the mission reliability was studied; Finally, the method for determining the optimal rework strategy was analyzed with case analysis under different input conditions.

2. Reliability model of RMS

2.1. Logistic regression analysis

Logistic regression is a type of statistical method firstly put forward by P.F.Verhuist[5], a Belgian mathematician in 1838, and is used to analyze and predict the discrete dependent variables with a single variable or multiple continuous or discrete variables. The logistic curve has been applied in demographic research before the end of the 19th century. Since the 20th century, the logistic regression model has been used widely as a kind of effective data processing method in biomedicine, criminology, ecological engineering, health science, linguistics, wildlife zoology and biological science, etc. In recent years, application of logistic regression model in mechanical engineering has been studied and certain results have been obtained. CAO et al[6] used the logistic regression model to establish the mapping model between degradation parameters and failure probability, and used the method of SVR degradation trend estimation to predict the remaining useful life of equipment. LIAO et al[7] employed the proportional hazard model and the logistic regression model to study the service life prediction of bearing, etc. Chen[8] proposed an evaluation method that is based on the logistic regression model, and accurately estimated reliability indexes of tools.

Average value of standard logistic distribution is zero, and variance is π2/3≈3.29, in this condition, a relatively simple Equation of the cumulative distribution function was obtained[11]:

$$P = \frac{1}{1+e^{-t}} \tag{1}$$

Such function is referred to as the logistic function, and its distribution presents an "S" shape, as shown in Fig. 1.

On the left side of the chart, when t approaches negative infinity, logistic function

$$P = \frac{1}{1+e^{-(-\infty)}} = \frac{1}{1+e^{\infty}} = 0 \tag{2}$$

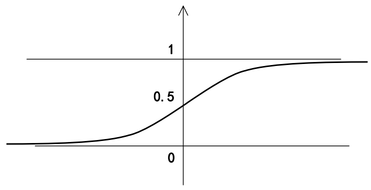

Fig. 1. Curve Chart of the Logistic Function

In contrast, when t approaches positive infinity,

$$P = \frac{1}{1+e^{-¥}} = 1 \tag{3}$$

Value range of the Logistic function fell between 0 and 1 no matter which value t took, which guarantees that the probability obtained by Logistic model will not be more than 1 or less than 0, namely the function was applicable to the study of probability. In addition, as shown in Fig. 1, when the value of t moves to the right starting from the negative infinity, and when t increases, value of this function rises slowly and then rapidly, after that the rise begins to slow down gradually; when t approaches positive infinite, the function value approaches 1. This trend is consistent with the changing trend of P, unreliability in the manufacturing process, with the work load change. However, the changing trends vary in different manufacturing processes, thus according to the changing rule of the reliability function, R, reliability of Logistic function based manufacturing process was put forward to represent this mapping relation more accurately, thereby:

$$R = 2\left(1 - \frac{1}{1+e^{-\alpha w}}\right) \tag{4}$$

Wherein, w denotes work load in the manufacturing process, parameter α was estimated by analyzing a large amount of historical data obtained in the actual working process.

2.2. Rework reliability of manufacturing process

Reliability of manufacturing process refers to the capacity of a system in manufacturing the qualified products under the specified processing conditions within the specified production cycle, and the reliability is determined by production capacity and load in the manufacturing process[10]. Production capacity refers to the processing efficiency in the manufacturing process within the given time and under the specific conditions, for example, the higher the acceptability rate in unit time and for determined work load, the stronger the production capacity; work load refers to the requirements for manufacturing process in actual production, such as the total production of a task in unit time. Work load and production capacity are independent with each other: when production capacity is greater than work load, the specific requirements can be met and reliability of the manufacturing process is high; when work load is greater, the specific requirements cannot be met and reliability of the manufacturing process is low. Production task failure mainly includes acceptability rate below the required level, production cycle exceeding the prescribed time, and production cost exceeding the expected acceptable range, etc.

It is clear from the engineering experience that in a manufacturing process, the more the products processed within a unit time, the poorer the quality of the products and the lower the reliability in the manufacturing process. In this case, P (P=1-R), changing trend of reliability degree of the manufacturing process and that of logistic regression curve were consistent, thus the logistic function was employed to represent the change of basic reliability in the manufacturing process along with the work load change.

Single procedure rework model is shown in Fig. 2, the arrows represent the processes and circles represent the buffer zone. A process e is involved in a manufacturing process, and the input of raw materials in a unit time is recorded as I, defective products are detected from the buffer zone after e and returned to the buffer zone before e to rework. After n times of rework, O, final output of conforming products in the manufacturing process is obtained.

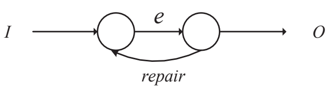

Fig. 2. Single procedure Rework Model

If the time of rework in the process is denoted by n, w, actual processing amount in the process can be expressed as:

$$w = I\sum_{j=0}^{n}(1-R)^{j} \tag{5}$$

From the simultaneous equations obtained by Equations (4) and (5), basic reliability R of the actual processing amount w and procedure after n times of rework can be got, and output of the manufacturing process can be calculated:

$$O = w \times R \tag{6}$$

Based on the output O, mission reliability R_m of the procedure, i.e. qualification rate of the manufacturing process can be got:

$$R_m = \frac{O}{I} \tag{7}$$

2.3. Rework reliability model of RMS

Fig. 3 shows a manufacturing system composed of f procedures, an inspection point is set after procedure r, and the products that fail to meet the design requirements are returned to procedure k to rework, basic reliability R_i of procedure e_i is a function of its work load w_i, denoted by $R_i(w_i)$.

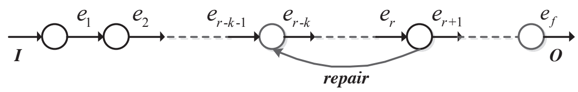

Fig. 3. Rework Model of the Manufacturing System

From the above analysis, w_i^n, actual processing amount of procedure i after n times of rework can be calculated by:

$$w_i^n = \begin{cases} I\prod_{j=1}^{i\text{-}1} R_j, & i = 2,\ldots,r\text{-}k\text{-}1 \\ I\prod_{j=1}^{i\text{-}1} R_j\left(1+\sum_{h=1}^{n}\left(\prod_{j=r\text{-}k}^{r\text{-}1} R_j(1-R_r)\right)^{h}\right), & i = r\text{-}k, r\text{-}k+1,\cdots,f \end{cases} \tag{8}$$

The basic reliability R_i. of all procedures is determined by w_i^n, actual work load of every procedure, processing amount and basic reliability of every procedure after rework of n times can be got from the simultaneous equations composed of Equations (5) and (8), thus output and mission reliability of the manufacturing system can be calculated.

3. Rework strategy optimization

The mission reliability of a manufacturing process was improved by rework in the previous procedure, however, the work load was increased, and the basic reliability was reduced. Along with the increase of the number of times of rework, work load of the procedure in which the products were reworked was further increased, and when the work load exceeded the bearable scope (production capacity), the basic reliability declined sharply, affecting the whole processing procedure. Therefore, in rework strategy optimization, production capacity of the procedure should be considered, and proper processing amount and number of times of rework should be determined in view of the different rework paths obtained according to advices proposed by experts.

3.1. Rework strategy optimization for single procedure

Fig. 4 shows the relation between the basic reliability of a process and the processing amount, horizontal coordinates denote w, the processing amount, and ordinates the reliability R. A_0 denotes the processing amount of a procedure without rework, i.e. amount of input is I, then the basic reliability and the mission reliability are ordinate values of A_0. A_1 denotes that after a time of rework, actual processing amount of a procedure is increased to w^1, the basic reliability corresponds to ordinate value of A_1, and mission reliability corresponds to ordinate value of B_1. The rest can be done by analogy.

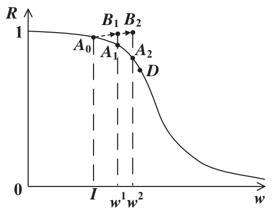

Fig. 4. Variation of Reliability

Basic reliability shows a trend of monotonic decline along with the increase of work load, this trend is not obvious when the work load gradually increases from 0; however, when the work load increases to a certain degree (as shown in Fig. 4, the right side of D), the basic reliability begin to fall sharply. As the rework strategy study is generally targeted at the part with higher basic reliability, it is meaningless to take rework when the basic reliability is lower, which may reduce the mission reliability of a procedure.

Optimization of single procedure rework strategy mainly refers to the optimized decision of number of times of rework at different requirements on task input. Output, mission reliability and unit production cost of the procedure per unit time were taken as the decision variables, corresponding output, mission reliability and unit production cost of n times of rework were calculated under different input conditions, and the optimal number of times of rework was obtained based on decision value calculated with the actual engineering weight distribution.

3.2. Rework strategy optimization for RMS

Rework strategy optimization for RMS mainly contains two aspects: setting of rework paths and selection of number of times of rework when different task input are required. In setting the rework path in RMS, checking points are usually set after the key working procedure or after key features are formed, while the rework points are usually set before several procedures with major recovery functions based on the influence on key quality characteristics and expert experience, so that setting of the checking points and the rework points is aimed to select the optimal rework path within the limited paths.

In analyzing a rework path, the rework model shown in Fig. 3 can be simplified to Fig. 5.

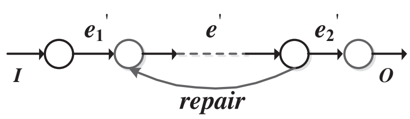

Fig. 5. Simplification of Rework Model of RMS

Wherein, procedure e_1 to e_{r-k-1} is simplified as e_1', procedure e_{r+1} to e_n is simplified as e_2'; e_{r-k} to e_r can be viewed as a process. Input $I'=I\times R_1'$ in the rework part, the relationship between basic reliability and work load of e' can be got, and the following simultaneous equation for n times of rework is got:

$$\begin{cases} w' = I'\sum_{h=0}^{n}(1-R')^{j} \\ R' = \exp(-(w'/W')^{t'}) \end{cases} \tag{9}$$

From Equation (9), w', actual processing amount of the rework part can be calculated, and from Equations (7) and (8), output O' and mission reliability R_m' of the rework part are obtained, finally obtaining output O and mission reliability R_m of the RMS.

Take output, mission reliability and production costs per item per unit time of the RMS as the decision variables, through calculating the output, mission reliability and production costs of each rework path in n times of rework at different output I, the corresponding decision value can be got from Equation (10).

$$Z = \overline{O}\omega_1 + \overline{R_m}\omega_2 - \overline{C}\omega_3 \tag{10}$$

Wherein, $\bar{O}$, $\overline{R_m}$ and $\bar{C}$ are the results obtained by normalization processing of the calculated output, mission reliability and unit cost respectively, ω_1, ω_2 and ω_3 are the weights assigned according to actual demands. The result corresponding to maximum decision value Z obtained from Equation (10) is the optimal rework strategy.

4. Case studies

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In the manufacturing process of a pipe, certain key dimensional features require RMS as is shown in Fig. 6. The features need to be tested after the key procedure of "pipeline installation" to see if it meets the specified requirements. If it does not meet the requirements and it meets the rework criteria, it will be returned to the previous procedure to be reworked and reprocessed. It is learned from designing analysis and expert ratings that the two procedures of trial assembly of pipeline and welding of pipe joints have rather large effects on the feature, thus two rework paths are obtained: checking point is set after the procedure of "pipeline installation" and rework point is set before "trial assembly of pipeline" as the rework path 1, and before the procedure of "welding of pipe joints" as rework path 2.

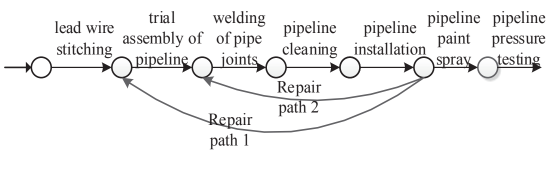

Fig. 6. Manufacturing Process of a Pipeline

Based on statistical analysis of the large amount of historical production data and Logistic regression, the estimated α value and the processing costs of each corresponding procedure are obtained, as shown in Table 1.

Table 1. Parameter List of the Slide Valve Manufacturing

Procedure	Estimated α	Processing costs per item b/£
Lead wire stitching	0.00116	20
Trial assembly to installation of pipeline	0.00219	100
Trial assembly of pipeline	0.00134	15
Welding of pipe joints to pipeline installation	0.0189	85
Pipeline paint spray	0.0182	35

In addition, according to the information provided by the factory, the price of raw materials a = £100 per piece, cost of rework scheduling C_d = £500, and cost of procedure C_k = £1000.

According to the above conditions, use the above equation to calculate the system output O and the mission reliability R_m, the single-piece production cost C can be calculated by Equation (11).

$$C = \frac{C_k + I \times a + \sum w_i \times b_i + n \times C_d}{O} \quad (11)$$

Based on the emphasis on output, mission reliability and cost of production by enterprise, weight can be distributed asω_1=0.4, ω_2=0.2 and ω_3=0.4, and then Equation (11) can be used to calculate decision value Z, and the greater decision value is the optimal rework solution. According to the results, the trend of decision value Z changing with input I and rework times n is shown in Fig. 7, in which Curve 1 corresponds to rework path 1, and Curve 2 corresponds to rework Path 2, and the rework strategy of pipeline manufacturing is the upper part after the combination of the two curves.

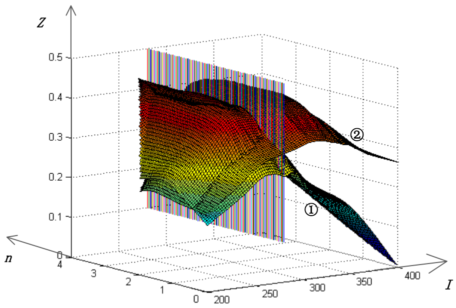

Fig. 7. Rework Decision in Pipeline Manufacturing Process

By analyzing the calculation results, the optimal rework strategy of the manufacturing process is the results got at input of 320 and rework times of 2, then select rework path 2, and the maximum decision value Z=0.4332 under the weight. Thus, the following results come out: output at this point is 287, mission reliability is 0.897, and single-piece processing cost is £305.732.

Rework strategy of pipeline manufacturing process obtained from the above analysis can help companies to determine the input, rework path and rework times according to the needs of specific tasks. For example, when the input that a company provides for pipe manufacturing process is 280, calculate the optimal rework strategy with the method. In Fig. 7, draw a cross-section in which I=280, then intersect with the rework strategy curve of pipeline manufacturing process, the results of different rework strategies are as follows:

As can be seen from the table, when the input is 280, rework path 2 with one time of rework is the optimal rework strategy. The actual production of the pipeline manufacturing company proves that this method can effectively improve the utilization of productive resources and the mission reliability of the manufacturing system.

Table 2 Comparison of Different Rework Strategies at Input of 280

Rework path	Rework times	Output /piece	Mission reliability	Unit cost/£	Z
1	0	237	0.846	299.325	0.2651
1	1	257	0.918	302.899	0.4027
1	2	261	0.932	312.042	0.4034
1	3	262	0.936	315.259	0.3938
2	0	248	0.886	296.270	0.3286
2	1	261	0.932	304.268	0.4102
2	2	262	0.936	316.603	0.3957

5. Conclusion

Reasonable rework strategy can guarantee higher yields, lower unit costs, and reliable mission reliability, thus it is of great significance for the manufacturing system. In this paper, the author introduces the method of Logistic regression into the production process of manufacturing system, analyzes the trend of basic reliability of the manufacturing process changing with the work load, and establishes a function of basic reliability of the manufacturing process changing with the work load. Applying this method to rework strategy optimization of the manufacturing system, we can calculate the corresponding output, mission reliability and unit cost of different rework strategies with different inputs. Based on actual weight distribution, the decision value can be calculated, and optimal rework strategies can be obtained, and then the most appropriate input, rework path and times can be further determined.

This research will be conducted further in the following aspects:

- The impact of each procedure on mission reliability in the manufacturing system needs to be further studied, because the research can help to sort the procedures to be improved and optimize resource allocation;
- In RMS with complex rework processes, such as the condition when rework paths are reciprocal or nested with each other, the method of determining the optimal rework strategy in the manufacturing process needs to be studied further.

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