CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013
Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1333087

Research on the Rework Strategies of RMS Based on Process Reliability

Wei Dai*, Jin An, Yu Zhao

School of Reliability and System Engineering, BeiHang University, BeiJing,China
dw@buaa.edu.cn

Rework Strategies are indispensable in order to improve the process reliability of reconfigurable manufacturing system (RMS). Process reliability is an integrated measurement of production ability of RMS, which serves as a performance indicator of the production process under specified technical constraints, including time, cost and quality. The process reliability of RMS with rework process is studied, and the rework process is decomposed into one general processing path and several reworking processing paths. A novel model and algorithms is introduced to obtain the inputs, outputs, costs, and process reliability of each machine, as well as the rework strategies under different batch size of RMS based on process reliability is presented. Case study on machining process of slide valve is employed to illustrate the proposed algorithm, which shows that the proposed methodology can make the rework strategies of RMS effectively and efficiently.

1. Introduction

How to respond changes in market demands quickly and economically is a huge challenge for today's manufacturing, which is transformed gradually from mass production mode to multi-varieties mode. The Engineering Research Center of the University of Michigan, USA proposed the concept of reconfigurable manufacturing system (RMS) (Koren et al., 1999). Reconfigurability is an engineering technology that deals with cost-effective, quick reaction to market changes. Reconfigurable manufacturing systems, whose components are reconfigurable machines and controllers, as well as methodologies for their systematic design and rapid ramp-up. For different batch size, RMS can adjust production function and capability of manufacturing system through lower conversion costs and higher equipment utilization, and adapt to the dynamic manufacturing environment consequently.

In the research of RMS, reliability is a very important indicator to measure system performance (Zhang, 2009). Considering the system reliability is conducive to estimate and distribute the intended target and mission. The setting of rework strategies is reconfiguring manufacturing process and it is common means of RMS. In order to accomplish the productive mission with low cost and high quality, a novel model and algorithms is introduced to obtain the inputs, outputs, costs, and process reliability of each machine, as well as the rework strategies under different batch size of RMS based on process reliability is presented in the paper.

2. Literature review

2.1 Reliability of manufacturing process

Прoников,A.C (1978) from the Soviet Union gave the definition of equipment's process reliability: within the prescribed scope and time, the nature that equipment was able to maintain the decisive quality indicator values of process. He also stressed the need to define equipment's reliability according to the purpose of analysis. Song (1994) considered the process system reliability is the ability that process is made to meet the technical requirements. Zhang and Guo (2009) provided the definition of process system reliability: the ability that response manufacturing systems quickly to achieve process quality parameters of design documents within specified conditions and time. Barringer (2000) gave the definition of process reliability: the point on a Weibull probability plot where the demonstration production line shows a distinct cusp because of cutbacks and /or crash and burn problems.

2.2 Reliability of manufacturing process

Rework is the action on a nonconforming product to make it conform to the requirement (ISO 9000:2000). The phenomena of production batch changes, machine failures, defects, multiple rework loops, etc., results in much difficulty in analyzing process modeling of RMS, and therefore the performance analysis of such systems has been investigated limitedly in the past. Buscher and Lindner (2007) has developed an optimization method to determine the economic production and rework quantity as well as the corresponding batch size for both activities. Liu et al. (2008) found simultaneously the optimal number of production and rework setups in a cycle, their sequence, and the economic production quantity of each setup. Cao and Subramaniam (2012) came up with the decomposition analysis of rework systems requiring the development of a three-machine and one-buffer line (3M1B) model in addition to the 2M1B models (Gershwin, 1994). This model is developed specifically for rework systems, and is capable of characterizing multiple rework loops. Lin and Chang (2012) revised a manufacturing system with reworking actions as a stochastic-flow network in which the capacity of each machine is stochastic. But they assumed the nonconforming products can rework only once on the same machine. In actual production, rework times is not limited to once. But reworking too many times will cost more, and the reworking machine may not bear the processing tasks. So it is necessary to find optimal rework strategies and realize the target of low cost and high quality.

3. Rework strategies based on process reliability of RMS

3.1 Reliability of RMS

Reliability of reconfigurable manufacturing system is an integrated measurement of production ability of RMS, which serves as a performance indicator of the production process under specified technical constraints, including time, condition, task, cost etc. The specified time are the given continuous processing cycles; the specified production conditions include environmental conditions, maintaining conditions and application conditions in process; the specified tasks are given production intensity, which is consist of throughput and its technical specifications required to achieve. Basic reliability is used to describe the ability of machines to complete specified production task strength, namely $R(x) = P(\xi > x)$ and x means production task strength. Mission reliability is used to estimate the ability of products in process to complete specified production task strength. In the paper, it can be calculated by the ratio of output to input.

With the increase of reworking frequency, the machines need rework nonconforming products will process more units. When the machines' processing amount is more than they could afford, the process reliability falls sharply. According to daily product data of a certain machine within a year, distribution law can be given as *Table 1:*

Table 1: Distribution law of daily product data

Daily product data	W_1	W_2	W_3	······	
probability	P_1	P_2	P_3	······	$\sum p_i = 1$

Based on the definition of basic reliability and daily product data, equipment's basic reliability presents the following variation trend shown in *Figure.1*.

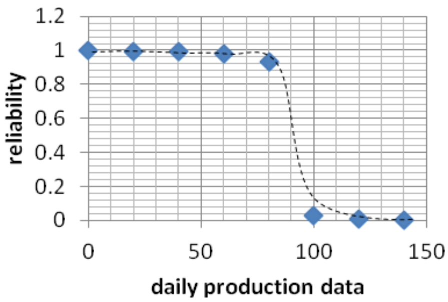


Figure.1 Variation trend of equipment's basic reliability

In *Figure.1*, the curve is usually Weibull distribution (Barringer, 2000).

3.2 Assumptions

The model is based on assumptions below:

1. Each inspection station is perfectly reliable.
2. The capacity of each machine is a random variable according to a given probability distribution.
3. The capacities of different machines are statistically independent.
4. The nonconforming products detected by the inspection station are either all reworked, or all scrapped in each path.

3.3 Optimization method of rework strategies

The optimization method includes the following steps:

Step 1. Rework system of RMS analysis and calculation.

First, the paper considers a production line with n machines and $n-1$ buffers. The r th machine is an inspection machine, if the nonconforming products are detected by it, they will return to the machine caused defects for reworking (see *Figure.2*). In *Figure.2*, buffers are indicated by circles, and machines are indicated by arrows.

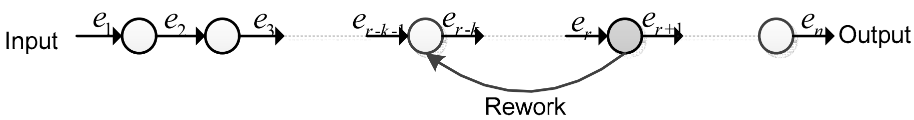
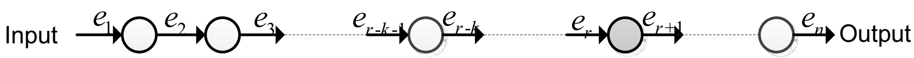
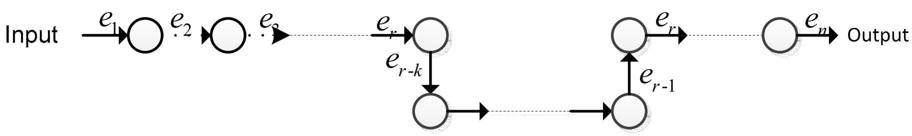


Figure.2: The processes with only one rework action

We decompose the rework system in *Figure.2* into one general processing path and one reworking path, it is showed in *Figure.3.*



(a) General processing path



(b) Reworking path

Figure 3: The decomposition of rework system

When calculating the rework system of RMS, general processing path and reworking path need to be considered at the same time.

The input raw materials/WIP (work-in-process) processed by the i th machine (w_1 , w_2 ;$\cdots$, w_n) after reworking m times can be calculated as Eq(1):

$$w_j = \begin{cases} I\prod_{i=1}^{j-1} p_i, \quad j = 1,2,L,r-k-1 \\ I\prod_{i=1}^{j-1} p_i + \sum_{t=1}^{m}\left(I\prod_{i=1}^{r-1} p_i q_r\right)\left(\prod_{i=r-k}^{r-1} p_i q_r\right)^{t-1}\prod_{i=r-k}^{j-1} p_i, \quad j = r-k, r-k+1,\cdots,n \end{cases} \tag{1}$$

The notations used in Eq(1) are as follows:

I =the input units of raw materials; p_i =the yield rate of i th machine; q_i =the rework rate of i th machine; r =defective WIP output from r th machine; k =defective WIP are reworked starting from previous k machine.

p_i need to be determined by iterative calculation. Iterative manner is as follows: firstly, on the basis of variation of daily production data, approximate curve can be fitted out just like $R(x) = exp(-(x/\eta)^m)$. Secondly, yield rate p_1 can be achieved by plugging I into fitting reliability function, and then w_2 can be calculated through Eq(1). Based on w_2 and fitting reliability function, we can get yield rate p_2 . The rest p_i and w_i may be deduced by analogy.

Step 2. Mission reliability calculation

The output of the system is equal to the sum of general processing path's output and reworking path's output, when only need rework once. The formula is as Eq(2):

$$O_2 = I\prod_{i=1}^{n} p_i + I\prod_{i=1}^{r-1} p_i q_r \prod_{i=r-k}^{n} p_i \tag{2}$$

In Eq(2), O is the output unites of products. Based on the decomposition method, we can figure out output of the system when need rework m times. The results can be expressed by Eq(3):

$$O_{m+1} = O_m + \left(I\prod_{i=1}^{r-1} p_i q_r\right)\left(\prod_{i=r-k}^{r-1} p_i q_r\right)^{m-1} \prod_{i=r-k}^{n} p_i \tag{3}$$

And the mission reliability of processing system is $R_t = O_{m+1} / I$.

Step 3. Production costs calculation

The notations used in this part are as follows:

a_0 =unit price of the input raw materials; b_i = processing costs of a part of i th machine; w_i = the input raw materials/WIP processed by the i th machine.

Manufacturing costs of a complete product C include raw materials costs C_m, processing costs C_p , and scheduling costs of rework C_d , it can be expressed by Eq(4):

$$C = C_m + C_p + C_d \times m \tag{4}$$

In Eq(4), $C_m = a_0 I$, $C_p + C_s + C_r = \sum_{j=1}^{n} w_j b_j$, C_d can be given according to the practical situation.

Step 4. Decision values calculation

Firstly, the calculated mission reliability and costs are normalized. Then, according to the given weight ω_1, ω_2 of costs and mission reliability, decision values can be obtained through the formula $Z = C'\omega_1 - R_b'\omega_2$, and the minimum among decision values corresponds to the optimal rework strategy.

4. Case Application

Machining process of slide valve's excircle of servo-valve need pass through four processes: rough grinding, accurate grinding, bedding-in, lubrication. And these four processes need four different machines shown in the following *Figure.4*. In the processing, whether the excircle's dimensions are within the prescribed limits need to be inspected when accomplish the bedding-in. If nonconforming dimensions are detected, they are required to return to machine e_2 for reworking, namely $r=3, k=1$.

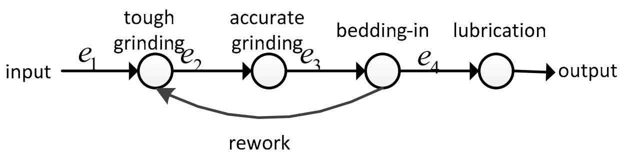


Figure.4 Machining process of slide valve's excircle.

Suppose that: $I=500$, unit price of the input raw materials $a_0 = €20$, processing costs per part of each machine are : $b_1 = b_2 = €1$, $b_3 = €5$, $b_4 = €6$. Scheduling costs of rework once is $C_d = €5$. According to equipment's daily production data, reliability function of four processing equipment can be fitted. Both the reliability functions of e_1 and e_2 are $R_1(x) = exp(-(x/800)^{3.9})$, both the reliability functions of e_3 and e_4 are $R_2(x) = exp(-(x/800)^{3.5})$.

On the basis of computational methods previously put forward, we can get results shown as *Table 2:*

Table 2: Results of example

Rework times	Output	Unit costs	Input raw materials/WIP processed by the i th machine	Mission reliability
zero	349	43.217	w_1=500,w_2=426,w_3=391,w_4=367	0.698
one	368	41.796	w_1=500,w_2=449,w_3=412,w_4=387	0.736
two	369	41.851	w_1=500,w_2=450,w_3=413,w_4=388	0.738
three	369	41.986	w_1=500,w_2=450,w_3=413,w_4=388	0.738
⋮	⋮	⋮	⋮	⋮

According to the results above and weights $\omega_1 = 0.8, \omega_2 = 0.2$ that manufacturing company has given, decision values can be achieved: $Z_0 = 0.60096$, $Z_1 = 0.56154$, $Z_2 = 0.55973$, $Z_3 = 0.55999$. Z_2 is the minimum, so the maximal rework times for this production process is two.
Besides, optimal rework strategies are calculated when inputs are 100, 200, 300, 400, 600 respectively, the results are shown in *Table 3*:

Table 3: Optimal rework strategies in different inputs

	Maximal rework times			
Input	0	1	2	3
100	0.60413	0.60535	0.60657	0.60778
200	0.59873	0.59934	0.59995	0.60055
300	0.60128	0.5887	0.58911	0.58951
400	0.60047	0.57741	0.57554	0.57584
500	0.60096	0.56154	0.55973	0.55999

*the shadows are the optimal rework strategies

When input equals 600, the reliability is only 0.722064.It means nearly 30% raw materials are scrapped from e_1 and it will result in great wastes. From the example, we can see when inputs are within a certain range, if they are relatively small, no rework is the best rework strategies. With the increase of input, the reworking frequency has a corresponding increase. This is because that storage of equipment will decrease with the increase of input, and yield rate is reducing. So the frequency of rework needs to be increased to meet the engineering requirements. This is consistent with the concept of process reserve in ГОСТ27.004-85 of the former Soviet standard. Therefore, the proposed method in this paper is feasible. Note that the input should be controlled within the capabilities of equipment. The paper realized this by maintaining the value of reliability at 0.8 or more.

5. Conclusions

This paper generalizes the model and algorithms of rework strategies optimization of RMS based on process reliability. The paper decomposes the rework system into one general processing path and several reworking paths, and provides numerical methods to obtain inputs, outputs, costs and process reliability of each machine. It also gives the computational methods of optimal rework strategies under different batch sizes. Case study on machining process of slide valve shows that the proposed methodology can make the rework strategies of RMS effectively and efficiently.
In this paper, the rework processes are designated, that is to say that the processes where nonconforming products/WIP are detected and modified are given. In the future research, genetic algorithm will be applied to determine the optimal reworking process in order to improve computational accuracy. And then comprehensive rework strategies will be given through expend the proposed methods in this paper.

References

Barringer P., 2000, Process reliability and six-sigma, National Manufacturing Week Conference Track for Manufacturing Process and Quality.

Buscher U., Lindner G., 2007, Optimizing a production system with rework and equal sized batch shipments. Elsevier, 34, 515-535.

Cao Y.X., Subramaniam V., Chen R.F., 2012, Performance evaluation and enhancement of multistage manufacturing system with rework loops. Elsevier, 62, 161-176.

Gershwin S.B., 1994, Manufacturing systems engineering. Englewood Cliff: Prentice Hall.

International Standardization Organization, 2000, ISO9000:2000(E), Quality Management Systems — Fundamentals and Vocabulary.

Koren Y., Heisel U., Jovane F., 1999, Reconfigurable manufacturing systems. Elsevier, 48, 527-540.

Liu N., Kim Y., Hwang H., 2008, An optimal operating policy for the production system with rework. Elsevier, 56, 874-887.

Lin Y.K., Chang P.C., 2012, Evaluate the system reliability for a manufacturing network with reworking actions. Elsevier, 106, 127-137.

Проников,А.С., 1978, Надежностьмашин. М.: Машиностроение, 592 (in Russian).

Song B.W., Li Z.N., 1994, Mechinical manufacturing process reliability. IEEE,12,4-7 (in Chinese).

Zhang J.Y., Xie L.Y., Li B., 2009, Reliability analysis of non-series manufacturing systems based on petri nets, Chinese Journal of Mechanical Engineering, 12, 95-100, DOI: 10.3901/JME.2009.12.095.

Zhang K.L., Guo B., 2009, Study of process system reliability model considering error propagation. IEEE, 27, 23-27 (in Chinese).