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Modeling and Performance Evaluation of Multistage Serial Manufacturing Systems with Rework Loops and Product Polymorphism

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Abstract

This paper studies multistage serial manufacturing systems with the integrated consideration of machine failures, process defects, multiple rework loops, etc. In particular, multiple rework loops and product polymorphism lead to a more complex conversion of internal material flows, and therefore it's difficult to model and analyse such manufacturing systems. A modular modeling method based on Generalized Stochastic Petri Nets (GSPN) is presented to characterize the material flows, it is capable of representing the processing differences resulting from product polymorphism comparing with traditional Markov model or Queuing network model. By analysing the model, the processing ratio of each workstation is inferred. Using 2M1B (two-machine and one-buffer) Markov cell model as the building blocks, which is obtained based on the GSPN models for their isomorphism, an overlapping decomposition method is then developed for evaluating the performance of the multistage serial systems with rework loops. Numerical experiments and a case study of a powertrain assembly line illustrate the efficiency of the proposed method.

Keywords: Manufacturing system; Rework loops; Product polymorphism

1. Introduction

This paper studies multistage serial manufacturing systems with rework loops and product polymorphism. In many manufacturing systems, some defective products are unexpectedly produced due to process variations or other factors. Usually rework is done instead of scrapping these products for economic reasons as seen in semiconductor, glass, steel, food industries, etc. [1]. The products in the systems can be often divided into four states, the qualified, the defective, the rework, and the scrapped. To manage, operate and improve the performance of such systems, modeling and performance evaluation are necessary and important.

A number of numerical analysis methods have been proposed for stochastic manufacturing systems with unreliable machines, multiple failure modes, preventive maintenance, etc. Queueing network models, Markov models and decomposition methods have been widely used as a faster and more viable alternative to simulation in the analysis of the systems [2]. When considering quality issues, the material flows in the systems, including rework flow and scrap flow, complicate modeling and make it more challenging to study the systems [3]. Connors et al. [4] proposed an open queueing network model for analysis of semiconductor manufacturing facilities, where the wafer lot sizes are affected by rework and scrap. Kang et al. [5] analyzed a parallel machine with rework. A dispatching algorithm is given to evaluate total tardiness, maximum lateness and mean flow-time, etc. Ju et al. [6], Lin et al. [7] and Biller et al. [8] studied multistage manufacturing systems with a single rework loop, where defective products are mostly assumed to be randomly generated with Bernoulli-type quality failure. Being constructed as a stochastic-flow network, systems are divided into several general processing paths and one rework path using decomposition technique. In addition, Liu et al. [9] proposed an approximation method of transforming an M-machine re-entrant line into a 2M-machine

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serial line. However, models for evaluating multistage manufacturing systems with generally complex Markovian machines are not available. Some researchers have extended approximate decomposition methods, such as using two machines and one finite intermediate buffer (2M1B) [10] or three machines and one buffer (3M1B) [11] as building blocks. Considering multiple rework loops, Cao et al. [12] developed a new 3M1B model in addition to the 2M1B models. In the decomposition approach, both 2M1B and 3M1B models are used.

In practice, the production systems are more complex. For instance, there are several rework loops in power train assembly lines. Due to the construction of the system, the defective and scrapped must be sent out of the line only through the rework entrance as well as the rework being sent back on line. Before assembly processes, each workstation will read the RFID information of the product and identify the state of product. While the product is the qualified from upstream or the one need to be reworked here, the process will start. Otherwise, the product will be immediately sent out of the workstation if it's the defective, or the scrapped from upstream, or the rework that will not be reworked here but downstream. However, the material flows information is not characterized in these models above. Thus these models are not extensible to multistage manufacturing system with multiple rework loops and product polymorphism.

In this paper, an optimal solution to model and evaluate the performance of multistage serial manufacturing systems with rework loops and productive polymorphism is proposed. Unlike the previous models proposed in the literature, a model based on Generalized Stochastic Petri Nets (GSPN) is presented to characterize the complex state transition resulting from the conversion of internal material flows. Based on analyzing the process differences in the model affected by multiple rework loops and products polymorphism and using 2M1B model as the building blocks, a decomposition approach is developed for evaluating the performance of the systems.

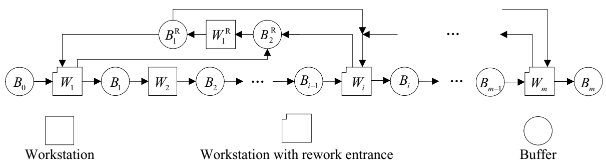

Fig. 1. The manufacturing system with rework loops

2. Problem Formulation and System Modeling

2.1. Problem Formulation

The manufacturing system studied in this paper is configured in serial layout. The main line consists of m on-line workstations, $m-1$ on-line buffers of finite capacity and r rework entrances that form $r-1$ rework loops. The rework entrances are located on the several workstations. Between two rework entrances R_j, $j=1,2,\dots,r-1$ and R_{j+1} adjacent, there are $m_j \geq 3$ on-line workstations and m_j-1 on-line buffers. With other off-line buffers B_j^{R} and off-line pre-rework stations W_j^{R}, all of them above construct a standard rework loop L_j. Fig. 1 shows the system with rework loops.

Due to the construction of the system, it is assumed that the defective and scrapped from the workstations between W_{j-1}^{R} and W_j^{R} which are the workstations with rework entrances, must be sent out of the line through the entrance R_j, while the rework after pre-rework processing must be sent back through R_{i-1}. In addition, the defective and scrapped from W_i^{R}, must be sent out from the current workstation through R_i while the rework corresponding must be sent back through R_i.

For convenience, the following notations are used throughout the paper:

- μ_i = The processing rate of workstation $W_i, i=1,2,\dots,m$;
- λ_i, r_i = The failure and repair rate of $W_i, i=1,2,\dots,m$;
- α_i = The state of workstation W_i, $\alpha_i \in \{0(\text{down}), 1(\text{up})\}$ (see assumption 2), $i=1,2,\dots,m$;
- θ_i = The qualified rate of $W_i, i=1,2,\dots,m$;
- PR_i = The production rate of $W_i, i=1,2,\dots,m$;
- k_i = The capacity of on-line buffer $B_i, i=1,2,\dots,m-1$;
- x = The inventory of the system.

We make the following assumptions regarding the system:

1) The workstation won't process the defective or the scrapped from the upstream, or the reworked to the downstream. In addition, the process time of the pre-rework stations and the transport time are negligible.
2) All workstations are unreliable and subjected to operation-dependent failures. Therefore, each unreliable workstation has two states: up and down.
3) In this model, the capacity of off-line buffers B_j^{R} is infinite. the upstream workstation is never starved and the downstream workstation is never blocked.
4) The system is based on First Come First Serve (FCFS). While the products arrive simultaneously, the product from the upstream on-line buffer is a higher priority than the one from the off-line buffer. This considers to avoid the deadlock which may occur in the system.
5) If the products have been reworked failed, they are marked as the scrapped and sent through the entrance specified to the scrapped area. Each defective product has only one time to be reworked.

2.2. Modeling for Systems

In the system, multiple rework loops and products polymorphism lead to a more complex conversion of internal material flow. Fig. 2a and Fig. 2b show the material flow conversion in the general workstation and the workstation with a rework entrance respectively.

Based on Fig. 2, GSPN model blocks of workstations are built as shown in Fig. 3a and Fig. 3b respectively. The main meanings of places and transitions are shown in Table 1 and Table 2.