Journal of Manufacturing Systems 48 (2018) 33–48

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

Scheduling policies in flexible Bernoulli lines with dedicated finite buffers[☆]

Kyungsu Park[a], Jingshan Li[b,*], Shaw C. Feng[c]

[a] Department of Industrial & Management Systems Engineering, Dong-A University, Busan, South Korea
[b] Department of Industrial and Systems Engineering, University of Wisconsin, Madison, WI 53706, USA
[c] Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

ARTICLE INFO

Keywords:
Bernoulli reliability machine
Flexibility
Production rate
Scheduling policy
Dedicated buffer

ABSTRACT

This paper is devoted to studying scheduling policies in flexible serial lines with two Bernoulli machines and dedicated finite buffers. Priority, cyclic and work-in-process (WIP)-based scheduling policies are investigated. For small scale systems, exact solutions are derived using Markov chain models. For larger ones, a flexible line is decomposed into multiple interacting dedicated serial lines, and iteration procedures are introduced to approximate system production rate. Through extensive numerical experiments, it is shown that the approximation methods result in acceptable accuracy in throughput estimation. In addition, system-theoretic properties such as asymptotic behavior, reversibility, and monotonicity, as well as impact of buffer capacities are discussed, and comparisons of the scheduling policies are carried out.

1. Introduction

To respond to rapid market change and customized demands, flexibility is becoming prevalent in modern manufacturing industry. Substantial efforts have been devoted by manufacturers to diversifying products and flexibilizing equipment, where multiple types of products are processed in the same production system. For example, vehicles with different styles, engines, colors, interior materials and other options are produced on one general assembly line. Customized computers or notebooks are assembled in the same production unit. Similar observations are found in other manufacturing systems as well.

In many flexible manufacturing systems, dedicated machines and buffers are used for specific type of products to avoid mismatch and disorder. For instance, in fuel injector production lines, components at different fabrication stages are stored in dedicated buffers in front of the central washers, waiting for cleaning. In motorcycle manufacturing, the transmission cases for multiple motor families are routed with separate conveyors specific to each family. In semiconductor manufacturing, multiple dedicated buffers are used to accommodate the diversity in physical configuration limits, temperatures, and avoid chemical contaminations. In many sequence based assembly lines, dedicated buffers could avoid sequence disruption due to scraps of defective parts. Similar examples can be found in many other flexible manufacturing systems.

Clearly, scheduling and control policies play an important role in such systems to ensure the desired productivity and quality. Numerous scheduling algorithms have been proposed and used on the factory floor. Among them, priority, cyclic, and work-in-process (WIP)-based policies are the prevalent ones due to their simplicity in control logic, while many other scheduling policies (e.g., processing time or due-day based and queue length based policies) can be equivalent into these policies. In addition, as one of the most important key performance indicators (KPIs), the production line throughput (or production rate) has been studied for decades (see, for instance, monographs [1–5] and reviews [6–8]). Similarly, manufacturing flexibility has also been addressed for a long time (e.g., reviews [9–14]). However, due to the complexity in flexible systems, analysis of KPIs (such as production rate) under different scheduling policies in flexible manufacturing systems still needs in-depth study, particularly in scenarios with unreliable machines and finite dedicated buffers.

The main contribution of this paper is in developing efficient analytical methods to study the scheduling policies of two-machine flexible lines with unreliable Bernoulli machines and dedicated finite buffers. Three scheduling regimes are studied: priority, cyclic and WIP-based policies. For small scale systems, a Markov chain method to derive exact solutions is presented. For larger ones, an iterative method is introduced based on decomposition of the system into multiple interacting serial lines. Numerical study shows that such a method leads to acceptable accuracy in production rate estimation without computation intensity. Ideas of extending the study to longer lines are explored. In

☆ This work is supported in part by NIST grant 70NANB14H260 and the National Research Foundation of Korea (NRF) grant No. 2018R1C1B5046069, funded by the Korea government (Ministry of Science and ICT).
* Corresponding author.
E-mail address: jingshan.li@wisc.edu (J. Li).

https://doi.org/10.1016/j.jmsy.2018.05.013
Received 7 March 2018; Received in revised form 30 April 2018; Accepted 31 May 2018
0278-6125/

addition, system-theoretic properties, such as monotonicity, reversibility, and asymptotic behaviors, are discussed analytically or based on experimental results. The impact of buffer capacity on line performance is investigated and comparisons between the scheduling policies are carried out.

The remainder of the paper is organized as follows: in Section 2, related literature is briefly reviewed. Section 3 introduces the assumptions for formulates the problem. Sections 4 and 5 present solution methods for smaller scale and larger systems, respectively. Discussions on system properties and buffer impact are provided in Section 6, and conclusions are formulated in Section 7. All proofs are given in Appendix.

2. Literature review

During the last three decades, substantial studies on flexible manufacturing system have been conducted. A classical paper [9] reviews several analytical models of flexible manufacturing systems and provides guidance for research directions. In paper [10], more accumulated literature is reviewed by defining various concepts of flexibility in manufacturing, such as machines, processes, operations, products, routings, expansions and market flexibility. Monographs [2,11] investigate stochastic flexible manufacturing systems, while [1] and [12] analyze the systems from a deterministic perspective. The issues of performance analysis, optimal system design and production control, etc., are addressed. In reviews [8,13,14], the concept and problems related to flexibility are discussed.

Since multiple types of products are processed on the same line in many flexible manufacturing systems, scheduling and control play an important role. For production lines with unreliable machines, Refs. [15,16] apply a decomposition method to analyze the systems with a static priority rule to select the part type for production. The multi-product kanban like control systems are analyzed in [17], and the production capacity of flexible manufacturing systems with fixed production ratios is studied in [18]. Similarly, papers [19,20] present an analytical method with a general probabilistic constraint by decomposing the lines and aggregating states of machines, which are also used to model the priority rule. However, such models could not preserve the desired product composition (i.e., product mix ratio) in the system. More recently, paper [21] introduces the definition, problem and performance portrait of multi-job serial lines.

For cyclic rule, papers [22,23] address the performance of multi-product kanban systems with sequence-independent setup times using a decomposition method. A two-product polling model is introduced in [24] under different kinds of cyclic policy via both exact and decomposition methods. The studies in [25,26] extend the model from cyclic rule and compare the system performance under different scheduling policies. They also investigate the robustness of the policies and provide practical guidance for operation management. Paper [27] further extends the work to machines with arbitrary processing times.

In addition, for systems with constant work-in-process (CONWIP), paper [28] studies kanban assignment to multiple product types. A parametric decomposition method is provided in [29] for performance evaluation in closed queueing networks. Moreover, Ref. [30] presents an analysis of line production rate and average inventory level for each part type based on priority policy. Paper [31] considers a flexible manufacturing system consisting of common lines and dedicated branches to process different product types through addressing the split and merge behaviors. More recent works on multi-product lines appear in [32–34], where serial lines with shared (or non-dedicated) buffers are studied. Such works are extended to lines with setups and assembly systems in [35] and [36], respectively. Optimal production control has been investigated in [37,38] for partially flexible systems, where dedicated downstream lines are supplied by a flexible upstream line with batch operation and setups, using Bernoulli and geometric models, respectively.

In spite of these efforts, there is no available work to analyze different scheduling policies in flexible production lines with unreliable machines and dedicated finite buffers, investigate system properties and compare line performance. This paper intends to contribute to this end.

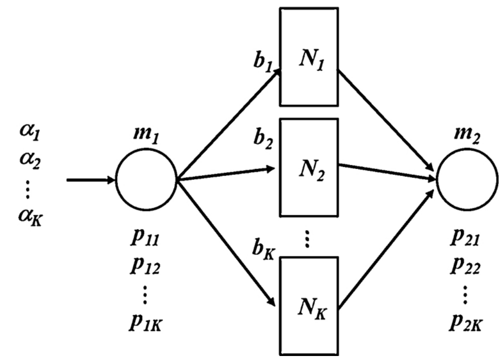

Fig. 1. Two-machine production line with K product types and dedicated buffers.

3. Assumptions and problem formulation

Consider a flexible two-machine line with finite dedicated buffers (see Fig. 1, where the circles represent the machines and the rectangles are the buffers). The following assumptions define the product arrival, the machines, the buffers, their interactions and scheduling policies.

(1) The production line can produce K types of products, denoted as types 1, 2, …, K.
(2) The production line consists of two machines, m_1 and m_2, and K buffers, b_1 to b_K, between the machines, each dedicated to one product type.
(3) The arriving parts enter the system in a first come first serve (FCFS) manner, waiting to be processed by m_1. They follow a discrete distribution with probability α_j for product type j, $j = 1, \ldots, K$. In addition, $\sum_{j=1}^{K} \alpha_j = 1$.
Remark 1
Assumption (3) implies that if the next part to be processed by machine m_1 is type j, but m_1 fails to process it, then m_1 cannot process another part type i, $i \neq j$. Similar assumption for machine m_2 is introduced.
(4) Both machines m_1 and m_2 have a constant and identical cycle time. The time axis is slotted with the duration of cycles.
(5) The machines follow Bernoulli reliability model independently. In each cycle, machine m_i, $i = 1, 2$, is up with probability p_{ij} for product type j, $j = 1, \ldots, K$, and down with probability $1 - p_{ij}$.
(6) Each buffer b_j, $j = 1, \ldots, K$, has a finite capacity, $0 < N_j < \infty$.
Remark 2
Assumptions (4)–(6) introduce a Bernoulli reliability model of the line. Bernoulli models have been widely used in manufacturing systems studies (see monograph [5]). Such models are suitable for assembly type of machines whose average downtime is comparable to its cycle time. Bernoulli models have been successfully applied in automotive and many other industries (see case studies in and representative papers [34–36,39–47]). In case of machines having different cycle times, a transformation can be introduced to make an equivalence of the original system into a Bernoulli line. Specifically, define $T_{up,i}$ and $T_{down,i}$ as the average up- and downtimes of machine m_i, respectively. Let c_i be the capacity or speed of machine m_i, and $c_{max} = \max_i c_i$. Then the Bernoulli machine parameter p_i can be calculated as

$$p_i = \frac{c_i}{c_{\max}} \cdot \frac{T_{\mathrm{up},i}}{T_{\mathrm{up},i} + T_{\mathrm{down},i}}, \quad i = 1, 2.$$