Journal of Manufacturing Systems 46 (2018) 208–220

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

Technical Paper

Analysis, design, and control of Bernoulli production lines with waiting time constraints☆

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ARTICLE INFO

Article history:
Received 7 October 2017
Received in revised form
15 December 2017
Accepted 1 January 2018

Keywords:
Time constraint
Yield analysis
Bernoulli machine
Optimal buffer design
Production control

ABSTRACT

Waiting time constraints between two processes are one of common scheduling requirements in many production systems, such as semiconductor, automotive, food, and battery manufacturing. When the time constraints are introduced, quality inspection should be carried out on parts that have exceeded a given time limit and such parts are subject to be re-processed or scrapped, which incurs additional expenses and efforts. Therefore, the foremost goal is to maximize yield, which is defined by the production rate of parts that do not violate the time constraints. In this paper, we present a mathematical model of Bernoulli production lines to evaluate yield and examine its properties with respect to time constraints, buffer capacity, and machine reliability. System properties such as monotonicity and asymptotic characteristics are analyzed. With the analysis results, an efficient algorithm to design an optimal buffer capacity is developed. It is shown that, in contrast to traditional production lines, there is no monotonicity of yield on the reliability of an upstream machine; that is, an upstream machine becoming more reliable does not always contribute to increasing yield. Therefore, optimal control policies are presented to control the upstream machine for maximal yield. Finally, a case study is introduced to illustrate the applicability of the method.

1. Introduction

Waiting time constraints between two processes are typical scheduling requirements in many production systems such as semiconductor, automotive, food, and battery manufacturing. Specifically, in semiconductor manufacturing, there are several reasons to enforce the waiting time limit. First, when a wafer lot has been completed at the previous machine, the next machine must start processing this wafer lot within a pre-designated time limit according to process recipes. For example, after cleaning processes, the subsequent diffusion process should be started within a certain period of time. Otherwise, wafer surfaces gradually lose the effects of cleaning while waiting for the next process and this cannot ensure the success of the subsequent process. Secondly, if wafers are exposed to the atmosphere over the pre-determined time period, quality degradation can occur. This is because the complicated and highly dense circuits can be contaminated due to the particles or dust suspended in the air. Thirdly, wafers are naturally oxidized over time if they are remained in the air. Other examples on time constraints in food, battery, and automotive industries can be found in [1–3].

When the time constraint is introduced, a key performance measure of the system is yield. The yield is defined by the production rate of parts that do not exceed the waiting time limit. Certainly, parts with time constraint violations might be recovered through repair or re-processing. Nevertheless, the foremost goal is to maximize yield because repair and re-processing impede productivity and incur additional expenses. Therefore, from the perspective of factory floor engineers, an analytical model that can estimate the yield for given buffer capacity, time limits, and machine reliability is needed, which is useful for analysis of yield properties such as monotonicity and asymptotic characteristics on production parameters, and developing methods to design optimal buffer capacity and control policy.

Although there have been numerous efforts on modeling and analyzing production systems during the last six decades, studies on production lines with time constraints are still limited. To bridge this gap, we first develop an analytical model to evaluate yield in two-machine Bernoulli lines, and analyze its properties on produc-

☆ This paper was supported by Konkuk University in 2017.
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https://doi.org/10.1016/j.jmsy.2018.01.001
0278-6125/

tion parameters such as buffer capacity, machine reliability, and time limits. Based on the presented formula, we investigate monotonicity and asymptotic properties of the yield. To help engineers make right decisions on production control, machine improvement, and buffer allocation, we present an efficient procedure for optimal buffer design. Finally, for production control, we introduce an approximation method for optimal machine reliability.

The rest of the paper is organized as follows: In Section 2, the related studies are reviewed. Section 3 introduces assumptions and formulates the problem. Section 4 presents a mathematical model to evaluate yield as a function of time constraints, buffer capacity, and machine reliability. In Section 5, system characteristics such as monotonicity and asymptotic properties are investigated. Section 6 is devoted to developing an efficient algorithm to design optimal buffer capacity. Section 7 develops the optimal machine reliability for production control. A case study at an automotive stamping plant is introduced in Section 8. Finally, summary of the work and directions on future research are discussed in Section 9. All proofs are provided in Appendix A.

2. Literature review

There have been substantial studies on modeling and analysis of production systems (see monographs [4–7] and reviews [8–10]). Performance analysis, optimal system design, production control, etc., have been the central issues.

Perishability and quality deterioration due to time constraints have been studied in a broad range of systems. For serial production lines, [11] has initiated the work of performance evaluation of two-stage transfer lines. For multiple stages, an approximation method has been developed in [12]. A bufferless automatic transfer line is studied in [13]. The system-theoretic properties of Bernoulli lines with deteriorating quality are presented in [2]. The transient behavior of two-machine Bernoulli lines with perishable products are investigated in [3].

In production-inventory systems, inventory control and scheduling problems have been addressed widely (see, for instance, reviews [14,15]). For instance, [16] studies the optimal production policy in deteriorating inventory-production systems by using linear quadratic regulator technique. The optimal order quantities of perishable products with positive order lead times are presented in [17]. Heuristic algorithms to overcome computational complexity in complicated inventory control systems have been developed in [18,19].

In an automated manufacturing system, the time constraint is also one of the critical scheduling requirements in terms of maximizing production rate or identifying schedulability. For example, [20] presents a scheduling method using a branch and bound algorithm to minimize makespan in a two-machine flow shop with limited waiting time constraints, and a job sequencing problem is studied in [21] in a similar environment. Optimal scheduling methods of cluster tools for semiconductor manufacturing under time constraints have been developed in [22,23], and schedulability analysis has been performed in [24–26]. Moreover, capacity planning for wafer fabrication with time constraints between two operations is investigated in [27]. The research introduced in [28,29] examines the production control problems in serial and parallel machine lines under process queue time constraints. Reliable machines and infinite buffers are considered.

In addition, there have been a number of studies on optimal buffer design. Particularly, [30] develops a method based on dynamic programming to optimally allocate intermediate buffers in automatic transfer lines. Again using a dynamic programming algorithm and a decomposition method, [31] investigates the minimum-total-buffer allocation for a desired throughput in production lines with phase-type processing times. An efficient algorithm of buffer space allocation is proposed in [32] for both primal and dual problems to minimize buffer space and maximize throughput, respectively. Additional studies on optimal buffer design of production lines can be found in [33,34]. However, all of the above-mentioned studies on optimal buffer design do not consider waiting time constraints. Moreover, production control also has attracted significant research attention. A review of different control methods and a comparison of performance has shown that there is an equivalence among them [35]. In recent years, real-time control in manufacturing systems becomes prevalent (e.g., [3,36,37]).

In spite of all these efforts, with waiting time constraints, a mathematical formula of yield and its properties have not been studied thoroughly. In addition, methods for optimal buffer design and production control to maximize yield are still needed. The goal of this paper is intended to contribute to this end.

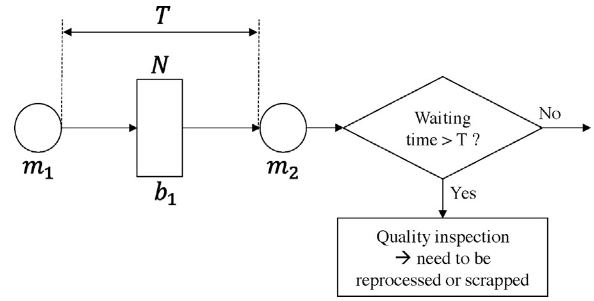

Fig. 1. A two-machine Bernoulli line with a waiting time constraint.

3. System description

Consider a two-machine production line with a waiting time constraint illustrated in Fig. 1. The following assumptions define the machines, the buffer, and their behaviors and interactions.

i) The production line consists of two machines, m_1 and m_2, and one buffer, b_1, represented by circles and a rectangle, respectively (see Fig. 1).
ii) Machines m_1 and m_2 have a constant and identical processing time. Such a time is defined as the machine's cycle time and hereafter for simplicity we assume that cycle time is equal to 1 without loss of generality.
iii) The machines follow the Bernoulli reliability model; that is, in each cycle, machine m_i, $i = 1, 2$, is able to produce a part with probability p_i and fails to do so with probability $1 - p_i$. It is assumed that the machine status is determined at the beginning of each cycle.
iv) Buffer b_1 has a finite capacity N, $1 \leq N < \infty$. First-in-first-out (FIFO) is assumed for the buffer outflow process. The buffer occupancy changes at the end of each cycle.
v) From the time when a part is stored into the buffer b_1 after finishing its processing at m_1, the maximum allowable cycle before starting the next process at m_2 is constrained by T (see Fig. 2). When such a cycle exceeds T, it has to be inspected for quality and is subject to be re-processed or scrapped.
vi) Machine m_1 is blocked during a time slot if it is up, buffer b_1 is full at the beginning of the time slot, and machine m_2 does not take a part from b_1. Machine m_2 is never blocked.
vii) Machine m_2 is starved during a time slot if it is up and buffer b_1 is empty at the beginning of the time slot. Machine m_1 is never starved.