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A new modeling method for both transient and steady-state analyses of inhomogeneous assembly systems

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ABSTRACT

Production system modeling (PSM) focuses on revealing the component-level principles of production procedures. Despite the extensive studies for PSM of serial production systems, assembly systems have received much less investigation. Among existing PSM researches on assembly lines, most are focused on the steady-state system performance, while the transient behavior of the inhomogeneous assembly systems is largely unexplored. This paper presents a new analytical PSM method for inhomogeneous assembly systems considering Bernoulli machines and finite buffers. By using the proposed 'Split-View' method, both transient and steady-state analyses of such systems can be performed. This model can be solved without using the traditional decomposition technique. The solvability of the established model has been proven theoretically. The sensitivity studies of system performance in both transient and steady states are numerically investigated. Numerical studies demonstrate the high accuracy of the method comparing with the simulation results.

1. Introduction

As one of the most fundamental production systems, assembly line commonly exists in the manufacturing industry, e.g., aircraft and automobile industry [1,2]. A typical assembly system consists of two or more serial production lines integrated through the assembly operation,Each serial production line is composed of a set of sequentially machines separated by embedded buffers [3,4]. The modeling analysis of assembly systems helps manufacturers optimize system layout, buffer capacity, and other aspects to promote productivity and reduce cost.

In the past decades, extensive efforts have been devoted to the performance evaluation of production systems [5–8]. Among these analyses, Production System Modeling (PSM) is extremely valuable since it reveals the relationship between fundamental component-level characteristics (such as buffer capacities and machine reliabilities) and their impact on system-level measures (such as throughput and work-in-process). Numerous research on PSM for serial production lines have been conducted [9–13]. For example, the authors of [9] proposed an approximate decomposition method for the evaluation of system performance of assembly/disassembly (A/D) systems with the discrete time model. This model was later extended to A/D systems with machines having exponentially distributed processing times in [10]. The authors of [11] presented an improved decomposition method for the analysis of inhomogeneous A/D systems (the "inhomogeneous" represents the machines have the non-identical processing times). The authors of [12] introduced the modeling analysis of the multiple products manufacturing system with split and merge. In [13], an overlapping decomposition method was proposed for the estimation of production rate of manufacturing systems with parallel lines. Despite the existing valuable studies regarding the performance evaluation of assembly systems, there is a universal problem for the researches on assembly systems using the decomposition technique, which is that only issues related system performance at the steady-state can be addressed.

Transient performance represents the system behavior in the stage that the production line has not yet reached the steady state. Compared to the performance measures of the steady state, the measures during the transient period is dynamic and can be quite different from those of the steady state [14]. The PSM for transient analysis receives much research interests recently due to its significant practicality, such as the evaluation of production loss during the warming-up period. As an example, the authors of [15] investigated that a 12% of production loss exists in a serial production line due to transients for a plant with a work shift of 8 h.

Unlike the fact that numerous PSM methods on the steady-state performance of production systems have been proposed, the transient situation is less studied and needs to be further explored. Research efforts regarding the analysis of transient behavior in the manufacturing systems are generally divided into two categories: simulation-based and

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analytical methods [8,14–19]. Typically, the simulation-based methods are highly accurate to depict the system performance during the transient period. However, the high cost of development resources, the long execution time and the low flexibility to system redesign limit the efficiency [14,16]. Moreover, these methods are also inadequate to understand the fundamental principle of production procedures. On the other hand, the analytical PSM methods can inherently incapacitate the drawbacks of the simulation-based methods. The authors of [15] studied the transient performance for the serial Bernoulli production line with two-machines. The authors of [17] derived the closed-form expressions for the transient performance of serial Bernoulli production lines with more than two machines, while the exact evaluation requires enormous memory space as well as computation time [17]. Thus, the authors performed a computational procedure to approximate the measures of transient performance based on the recursive aggregation. More recently, the authors of [8] proposed a novel modeling method for both steady-state and transient analyses of serial Bernoulli production lines. This method overcomes the restrictions of previous methods on the number of machines and capacity of buffers. This method was later extended by the authors of [18] to perform the transient analysis of Bernoulli production systems with rework loop. In [19], the authors studied the closed-form formulas to perform the transient analysis of assembly lines with machines having the identical processing times. However, the exact evaluation of system performance is practical only for small size systems since the model may take enormous amount of memory and computing power to implement [19]. Due to the limitations of computing resources, the authors have to conduct an aggregation-based procedure to calculate the transient performance approximately [19]. In brief, although the number of analytical PSM methods for transient behavior and complex structured system is growing, the transient analysis of inhomogeneous assembly lines remains unexplored.

Motivated by the above-mentioned status quo, we proposed a new analytical PSM method for inhomogeneous assembly systems with Bernoulli machines and finite buffers. By applying the proposed 'Split-View' method, both transient and steady-state analyses of such systems can be performed. This model is based on the probability theory, which can be solved directly without using the traditional decomposition or aggregation technique. The solvability of the model has been proven theoretically. Numerical case studies and sensitivity analysis are performed to illustrate the effectiveness of the proposed methods.

The rest of this paper is organized as follows. In Section 2, the general layout of inhomogeneous assembly systems is presented. Section 3 introduces the modeling procedure based on the proposed 'Split-View' method. The existence of solutions and numerical studies are given in Section 4. The method is applied in Section 5 to numerically investigate the relationships between fundamental parameters of PSM and system performance in both transient and steady-state. The conclusions and future work of the method are provided in Section 6.

2. General system layout

The general system layout of inhomogeneous assembly systems is shown in Fig. 1, where machines are denoted by rectangles and buffers are denoted by circles. This production system consists of n ($n \geq 2$) branch lines merging into a main line at machine $m_{0,1}$. Branch k ($k=0$, 1, …, n) contains N_k machines. Let s ($s=1$, 2, …, N_k) represent the sequence of a branch. The machine in the s^{th} sequence of the branch k is denoted by $m_{k,s}$ and the corresponding buffer is denoted by $b_{k,s}$. Each machine is up with probability $P_{k,s}$ ($0 < P_{k,s} \leq 1$) and down with probability 1- $P_{k,s}$. Each buffer has a finite capacity $C_{k,s}$. The processing time of $m_{k,s}$ is denoted by $t_{k,s}$. In the frame of this layout, n parts produced in each branch line must be assembled to form a new part for further processing at machine $m_{0,1}$. It is assumed that the first machines, $m_{k,1}$ ($k=1$, 2, …, n), are never starved, and the last machine, $m_{0,N0}$, is never blocked.

3. Modeling of inhomogeneous assembly systems

3.1. The 'split-view' method

The theory behind the 'Split-View' method is to split every machine of the inhomogeneous assembly system into a set of serial virtual unit machines, each of which has the 'unit processing time'. The 'unit processing time', t_u, can be set as the greatest common divisor of the processing times of machines. Therefore, the original inhomogeneous assembly system can be equivalently transformed into a substituted system that is composed of unit machines. In order to ensure that there is only one part being processed by the original machine at the same time, the virtual closed assembly line with a one-capacity buffer is introduced for the transformed system (as shown in Fig. 2). The transformed system layout of $m_{k,s}$ and the assembly node are presented in Fig. 2(a) and (b), respectively. Let z represent the number of unit machines of $m_{k,s}$. Thus, z= $t_{k,s}/t_u$. The original machine, $m_{k,s}$, can be equivalently replaced by the union of machines, $m_{k,s}^r$ ($k = 0,1,\ldots,n$; $r = 1,2,\ldots,z$). In order to record the production status, we introduce z-1 buffers, $b_{k,s}^e$ ($e = 1,2,\ldots,z\text{-}1$) between $m_{k,s}^r$. Moreover, the one-capacity buffer on the virtual closed assembly line is denoted by $b_{k,s}^0$. Based on the definitions of machines and buffers, two rules regarding the system running are adopted: 1) the part from $b_{k,s\text{-}1}$ is transported to $m_{k,s}^1$ by assembling the part in $b_{k,s}^0$; 2) $b_{k,s}^0$ is refilled only when $m_{k,s}^z$ produced. Obviously, $m_{k,s}^e$ ($e = 1,2,\ldots,z\text{-}1$) is never blocked. The original machine, $m_{k,s}$, is starved only when $b_{k,s}^0$ is full and $m_{k,s}^1$ is starved. Similarly, $m_{k,s}$ is blocked only when $b_{k,s}^{z-1}$ is full and $m_{k,s}^z$ is blocked.

The following modeling assumptions also adopt the 'Split-View' method. First, the production horizon is segmented into the discrete time-slots that equal to t_u. The occupancy of each buffer can be changed by one part at most in each time-slot. Second, it is assumed that $m_{k,s}^r$ is up with probability $\sqrt[z]{P_{k,s}}$ and down with probability 1- $\sqrt[z]{P_{k,s}}$. The uptime and downtime of each unit machine are determined independently from other unit machines'. Third, the states of machines are determined at the beginning of each time-slot, and the states of buffers are determined at the end of each time-slot. Fourth, the blocked-before-service and time-dependent-failure conventions [8] are employed.

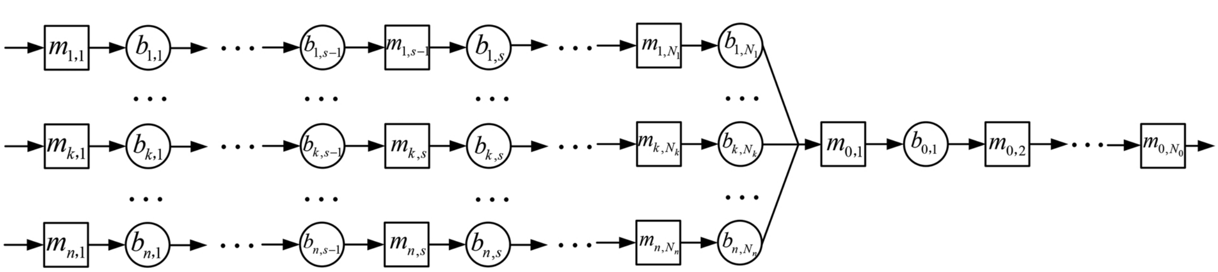

Fig. 1. General layout of inhomogeneous assembly systems.