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A simulation analysis of the impact of finite buffer storage on manufacturing system reliability

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ABSTRACT

This paper develops a Monte Carlo Simulation (MCS) approach to estimate the system reliability for a multistate manufacturing network with parallel production lines (MMN-PPL) considering finite buffer storage. System reliability indicates the probability that all workstations provide sufficient capacity to satisfy a specified demand and buffers possess adequate storage. The buffers are modeled as a network-structured MMN-PPL. Storage usage of buffers is analyzed based on the MMN-PPL. MCS algorithms are developed to generate the capacity state and to check the storage usage of buffers to determine whether the demand can be satisfied or not. System reliability of the MMN-PPL is estimated through simulation. The MCS approach is an efficient method to estimate system reliability for an MMN-PPL with a reasonable accuracy and time. A pair of practical examples including a tile and a touch panel manufacturing systems shows that system reliability is overestimated when buffer storage is assumed to be infinite. Demand satisfaction probability is further addressed to provide guidance for a proper production policy.

1. Introduction

Multistate manufacturing network (MMN) modeling is widely applied to several practical manufacturing systems such as touch panels [15], apparel [3], and tile production [10]. In a network-structured MMN, each arc is regarded as a workstation and each node an inspection point. Each workstation consists of identical (or similar) machines performing the same function and thus the capacity of a workstation exhibits multiple levels due to the availability or unavailability of these machines. Workstations with multiple capacity states therefore comprise an MMN. To investigate the capability of an MMN, system reliability is an appropriate index to assess the probability of demand satisfaction. That is, system reliability is generally defined as the probability that an MMN can provide sufficient capacity to satisfy a specified level of demand [8,21,22]. In earlier MMN models [8,21,22], the minimal path (MP: a set of arcs and nodes forming an acyclic path with no return) method is a commonly adopted to identify minimal capacity vectors that workstations must provide to produce a specified level of demand [8,21,22]. Such vectors are utilized to calculate the system reliability of an MMN. However, in order to find all minimal capacity vectors, most MP-based algorithms [8,21,22] are constrained by flow conservation law, meaning that flow does not increase or decrease during processing [7].

Recent studies [10,11] indicated that the assumptions of MP and flow conservation may limit the applicability of MMN models. Using MP against flows return (rework) in an MMN while flow is changing is not allowed by flow conservation law. As a result, previous studies are not able to consider real-world scenarios that involve rework and scrap. To overcome

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this limitation of MP and the flow conservation law, recent work [10,11] has successfully considered rework and scrap in an MMN through graphical methods, where the MMN is decomposed into different paths to analyze flows from the general and rework paths. Once the amount of flow processed by each workstation is obtained, the loadings and minimal capacities needed for all workstations can be derived. System reliability is subsequently calculated in terms of minimal capacity vectors. Various studies further consider parallel production lines [11], joint production lines [11], quality issues [2,6], and a time threshold [12] to evaluate system reliability for an MMN. In particular, MMN with parallel production lines (MMN-PPL) is a suitable model for many real-world scenarios. Despite the previous contribution to MMN modeling, all past studies assume infinite buffer storage between workstations when system reliability is evaluated.

Assuming infinite buffer storage in an MMN simplifies flow analysis and reliability evaluation. In practice, however, each workstation operates at a distinct production rate and a workstation may starve when it must wait for the next work-in-process (WIP). In other situations, WIP may be blocked and have to wait before entering a workstation [1,19]. To reduce the possibility of blockage and starvation, buffer allows sequential workstations to operate independently of each other [4,9]. Thus, modeling buffers in an MMN is a practical approach to evaluate system reliability. Modeling buffers complicates an MMN by considering the dependency between workstations. Monte Carlo Simulation (MCS) is an appropriate tool to explore the phenomenon and capability of these more complicated systems. The main idea underlying MCS is to generate random samples repeatedly and to observe the behavior over a long period [16,20]. Utilizing MCS, Ramirez-Marquez and Coit [17] and Yeh et al. [23] proposed an approach to generate possible capacity states to estimate system reliability of a multistate system. Several further extensions of their work consider time constraints [13] and correlated failures [14] when estimating system reliability of a multistate system. The abovementioned MCS approaches, however, fail to consider relationship between components (arcs or nodes). Therefore, this paper develops an MCS approach to model buffers between workstations in order to estimate system reliability.

To the best of the author's knowledge, no previous study has considered finite buffer storage in an MMN to estimate system reliability. Because parallel production lines are much more realistic in the manufacturing, this paper focuses on system reliability estimation of an MMN-PPL. To accurately evaluate MMN-PPL, system reliability is defined as the probability that all workstations provide sufficient capacity to satisfy demand and buffers do not run out of storage. System reliability can be regarded as a performance index to quantify the probability of demand satisfaction for an MMN-PPL. First, buffers with finite storages are incorporated into a network-structured MMN-PPL model. Second, storage usage of each buffer is analyzed under different demand levels. Third, MCS-based algorithm based on the storage usage is developed to estimate system reliability. The impact of finite buffer storage on system reliability is further studied to compare with the case of infinite buffer storage. Moreover, the probability of satisfaction under different demand combinations is analyzed to guide production policy.

The remainder of this paper is organized as follows. The MMN-PPL model with finite buffer storages is developed in Section 2. Two MCS-based algorithms to estimate system reliability with both infinite and finite buffer storages are presented in Section 3. Section 4 provides an illustrative example of a tile manufacturing system to demonstrate the MCS algorithm. In Section 5, a more complicated case study of a touch panel manufacturing system is studied to demonstrate the scalability of the proposed approach. Conclusions of this paper are summarized in Section 6.

2. MMN model building

Incorporating buffers into the MMN-PPL model, this paper first utilizes an activity-on-arc (AOA) diagram to represent a multistate manufacturing system. In an AOA-formed MMN-PPL, each arc denotes a workstation (by a solid-line arc) or a buffer (by a dot-line arc), and each node denotes an inspection point following the workstation. Let $a_{j,i}$ be the ith workstation in the jth production line, the current capacity of $a_{j,i}$ is a random variable denoted by $x_{j,i}$; the maximal capacity of $a_{j,i}$ is denoted by $M_{j,i}$. Let $c_{j,i}$ be the number of possible capacity states of $a_{j,i}$; $x_{j,i(\alpha)}$ denotes the αth possible capacity state of $a_{j,i}$, where $\alpha = 1, 2, \ldots, c_{j,i}$. Hence, $x_{j,i}$ takes possible values $0 = x_{j,i(1)} < x_{j,i(2)} < \ldots < x_{j,i(c_{j,i})} = M_{j,i}$. To estimate system reliability of an MMN-PPL, the following assumptions are utilized in this paper:

(1) Each inspection point (node) is perfectly reliable; inspection point does not damage WIP or products
(2) The capacity $x_{j,i}$ of each workstation (arc) is a random variable which takes possible values from $0 = x_{j,i(1)} < x_{j,i(2)} < \ldots < x_{j,i(c_{j,i})} = M_{j,i}$ according to a given probability distribution.
(3) The capacities of workstations (arcs) are statistically independent.

2.1. MMN-PPL with buffers

This section depicts workstations and buffers as a network-structured MMN-PPL with the help of an AOA diagram. Let $G \equiv (\mathbf{N}, \mathbf{A}, \mathbf{B})$ be an MMN-PPL in which $\mathbf{N}$ is the set of nodes (inspection points) and $\mathbf{A} = \{a_{j,i} | j = 1, 2, \ldots, m;\ i = 1, 2, \ldots, n\}$ is the set of arcs (workstations). Arc $a_{j,i}$ is the ith workstation in the jth production line. The set of buffers is denoted by $\mathbf{B} = \{b_{j,(i,i+1)} | i$: a buffer is installed between $a_{j,i}$ and $a_{j,i+1}\}$. Please note that installing buffers between every pair of upstream ($a_{j,i}$) and downstream ($a_{j,i+1}$) workstations is not necessary. This implies that buffer storage is zero if no buffer is installed between workstations. According to related studies [5,18], installation of a buffer between the bottleneck and its upstream