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An aggregation method for performance evaluation of a tandem homogenous production line with machines having multiple failure modes

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ABSTRACT

This paper presents an analytical aggregation method for evaluating the throughput (or production rate) of tandem homogenous production lines. Unlike in existing aggregation methods, each machine can have more than one failure modes. The flow of processed parts is considered as a continuous flow of material. The aggregation algorithm consists in recurrent replacing of a dipole by a single machine. To assess the accuracy of the proposed method, simulation and numerical experiments have been conducted. A comparison is made between our method and existing aggregation techniques that consider only one failure mode. It is shown that by distinguishing among different failure modes, a more accurate throughput evaluation is obtained.

1. Introduction

In production lines, machines can be subjected to different kinds of failures, which occur with different frequencies and require different amounts of time to be repaired. This paper presents an analytical method for performance evaluation of a tandem production line (see Fig. 1), where parts are moved from one machine to the next by some kind of transfer mechanism. Each machine is subjected to one or many failure modes. The machines are separated by finite capacity buffers. The parts are stocked in these buffers when downstream machines are down or busy.

Performance of a tandem production line is usually measured in terms of production rate (or throughput), i.e. steady state average number of parts produced per time unit. In this paper, we develop an aggregation method to evaluate production rate of a tandem production line where machines can be subjected to multiple failure modes. Existing aggregation techniques are not able to properly deal with more than one failure modes. Therefore, different failure modes must be approximated in an average failure. This approximation may cause an error that is not negligible, especially when reliability parameters (average failure time and average repair time) of different failure modes have different orders of magnitude [17,18]. The proposed method is able to deal with such situations adequately. To assess the accuracy of this method, simulation and numerical experiments have been performed. This aggregation method is sufficiently rapid for evaluation of alternatives within combinatorial optimization algorithms such as those developed in [19–21].

The remainder of this paper is organized as follows. Section 2 gives a brief literature review that shows the importance of the contribution in the context of reliability engineering. Section 3 presents assumptions and notations. Section 4 outlines the aggregation method proposed to evaluate production rate of tandem production lines with multiple failure modes. A detailed description of this method is given in Section 5. Simulation results and numerical experiments are reported in Section 6. Finally conclusions are given in Section 7.

2. Prior literature

There are three main bodies of literature that are related to the research presented in this paper. The first is the literature of flow models of unreliable production lines, most often presented for binary state machines: one up (good) state and one failure state. The second concerns multi-state system (MSS) reliability models, which are frequently used in evaluating performance measures of series and parallel systems (in the reliability block diagram sense) without any intermediate buffer. Finally, our model can be seen as an outgrowth of a small body of literature that discusses approaches for evaluating availability and throughput of

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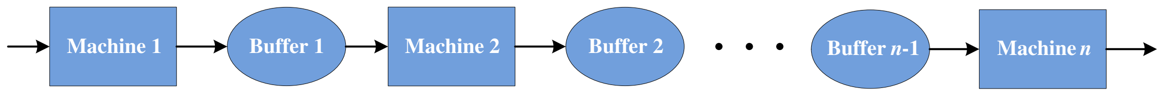

Fig. 1. Tandem production line.

unreliable production lines with multi-state machines. We discuss each of these three research areas next.

There is a substantial literature on flow models of unreliable production lines. The objective of the majority of these models is to evaluate throughput for lines composed of several machines and intermediate buffers: see for example [1,2] for a survey. Throughput is in general difficult to evaluate exactly by analytical Markov models. As a result, most of the methods used to analyze long lines are based either on analytical approximation methods or simulation. Simulation models are applicable to a wide class of systems, but are more expensive computationally [3]. Analytical approximation methods are generally based on the Markov model developed for a line with two machines and one buffer [4] and either aggregation approach [5–7] or decomposition approach [8–12]. Other papers developing aggregation methods are [13–16]. All these papers consider one failure mode per machine.

Machines with different functioning and failure modes are usually studied, for buffer-less systems, on the basis of multi-state system reliability theory [36]. In this theory, the system may rather have more than two levels of performance varying from perfect functioning to complete failure. A multi-state system (MSS) may perform at different intermediate states between working perfectly and total failure. The basic concepts of MSS reliability were first introduced in [24–27]. These works defined the system structure function and its properties. They also introduced the notions of minimal cut set and minimal path set in the MSS context, and studied the notions of coherence and component relevancy. A literature review on MSS reliability can be found for example in Ref. [28]. The methods currently used for MSS reliability estimation are generally based on four different approaches: (i) structure function approach, which extends Boolean models to the multi-valued case (e.g., [25–27]); (ii) Monte-Carlo simulation technique (e.g., [29]); (iii) Markov process approach (e.g., [30,31]); and (iv) universal moment generating function (UMGF) method (e.g., [32,33]). In practice, different reliability measures can be considered for MSS evaluation and design [34,35]. Among them, throughput is a common performance measure of MSS, but it is usually evaluated without considering any intermediate buffer.

Finally, we view our model as an outgrowth of the small body of literature devoted to throughput evaluation of unreliable production lines with multi-state machines. In [37], the authors develop models for two multi-state machine systems with intermediate finite buffers. These models consider that each machine has three states. In the first state, the machine is operating and producing good parts. In the second state, the machine is operating and producing bad parts, but the operator does not know this yet (quality failures). In the third state, the machine is not operating (operational failures). Others papers that study quality–quantity interactions are [39,40]. To approximate general processing, failure, and repair time distributions by using phase-type distributions, more detailed models of production systems where each stage is modelled by using more than two states have been used [41–44]. Finally, the objective of the models in [38] is to analyze how production system design, quality, and productivity are inter-related in production systems. They calculate total throughput, effective throughput (i.e. throughput of good parts), and yield. Unlike [38], we consider in this paper conditions when a machine can be subjected to multiple failure modes.

In all the above-mentioned papers, to estimate production rate we need to evaluate availability, which is known in reliability engineering to be an important measure for repairable systems. Estimation of availability of buffered systems is a very challenging problem, mainly because of the behaviour of the buffers. It is therefore usually assumed in the literature that times to failure and times to repair are exponentially distributed. This assumption is also used by many contributions dealing with buffer-less structures in reliability engineering. Generally, in practice it allows for an approximate analytical estimation of some important performance measures. While production managers want to evaluate a *production rate*, the objective of reliability engineers is to estimate *availability*, both performances being indeed linked by the formula *production rate*$=$*nominal production rate* $\times$ *availability*, where *nominal production rate* is the number of produced parts in the case of no failure. We believe that this paper is a step towards bringing together production management and reliability engineers around a problem studied hitherto separately.

3. Assumptions and notations

We consider a tandem production line as shown in Fig. 1. The machines are denoted by $M_1, M_2, \ldots, M_n$ and the intermediate buffers by $B_1, B_2, \ldots, B_{n-1}$. Parts flow from outside the system to machine M_1, then to buffer B_1, then to machine M_2, and so forth until they reach machine M_n, after which they leave the system. It is assumed that the flow of processed parts resembles a continuous fluid. A buffer capacity separating adjacent machines M_j and M_{j+1} (with $j=1, 2, \ldots, n-1$) is denoted by N_j. A machine is *starved* if its upstream buffer is empty. It is said to be *blocked* if its downstream buffer is full. Indeed, production rate of the tandem production line may be improved by buffers, as they may prevent blocking and/or starvation of machines. As is usually the case for production systems, we assume that failures are operation-dependent, i.e. a machine can fail only while it is processing parts (it is said to be working). Thus, if a machine is operational (i.e. not down) but starved or blocked, it cannot fail.

Each machine M_j can fail in R_j different modes. We assume that all times to failure and times to repair are exponentially distributed. Let $MTBF_{ij}$ denote *mean time between failures* of machine M_j in mode i (with $i=1, 2, \ldots, R_j$); then $\lambda_{ij}=1/MTBF_{ij}$ is its corresponding failure rate. Similarly, $MTTR_{ij}$ and $\mu_{ij}=1/MTRF_{ij}$ are the *mean time to repair* and the repair rate of M_j in mode i.

We assume that processing time of each machine is deterministic, i.e. a fixed amount of time is required to perform the operation. Thus, machine M_j has a constant cycle time θ_j and a nominal production rate $U_j=1/\theta_j$. The nominal rate U_j represents the maximum rate at which machine M_j can operate when it is not slowed down by an upstream or a downstream machine [22]. It is assumed that the considered line is homogenous, which means that all machines have the same processing time. That is, $U_1=U_2=\cdots=U$.

The following additional assumptions are also used:

- The first machine is never starved, i.e. there is always available part at the input of the line;
- The last machine is never blocked, i.e. finished parts leave the machine M_n immediately or there is always available space for part storage at the output of the line;