

Performance Evaluation of a Reconfigurable Production Line

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Abstract: This paper presents an analytical method for evaluating the throughput of a production line composed of two reconfigurable machines separated by a finite capacity buffer. This means that each machine is composed of essential and non essential equipment. The failure of any essential equipment induces the shutdown of the entire machine. The failure of the non essential equipment implies the continuity of the machine service with a reduced level of functionality. To assess the accuracy of the proposed method, simulation and numerical experiments have been conducted. The proposed model can be used as the building block for performance evaluation of longer production lines using either decomposition or aggregation techniques.

Keywords: *Performance evaluation, Reconfiguration, Degradation, Manufacturing lines*

1. Introduction

A reconfigurable system is defined as a system that may allow service continuity under failure, on the basis of a reduced level of performance. Such a system is considered in [1] as a set of equipments partitioned into a subset of essential equipments and a subset of non-essential equipments. Essential equipment is one whose failure causes the entire system shut-down. In contrast, at the failure of non-essential equipment, the service is allowed to continue but implies degradation in production. This continuity of the service may be accomplished elegantly, rather than just by throwing money at the problem with brute-force redundancy. Redundant units involve higher deployment costs, provide functionality that is only useful in the case of failure, and cannot help if the failure is systematic. While it may be that brute-force redundancy is the only way to satisfy stringent availability requirements for essential functions, not every function is essential. In fact, much of the increasing level of computing power, automation and flexibility in manufacturing systems provides extra functionality rather than basic essential functions. Thus, there is a room in many manufacturing systems to implement reconfiguration and graceful degradation of functionality, in order to enhance the dependability for non-essential (but highly desirable) functions. A gracefully degrading system can be viewed as a system in which faults are masked and only manifest themselves in a reduced level of system functionality.

In the domain of real-time control of manufacturing systems, automatic reconfiguration mechanisms are being increasingly used for the design of robust reconfigurable systems. This can be achieved by automatically installing, at the occurrence of a failure, a new control strategy to obtain maximal functionality using remaining system resources, resulting in a system that still functions, albeit with lower overall utility.

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Reconfiguration has been identified as a key mechanism for an automatic graceful degradation facility in several works (*e.g.*, [2-4] and references therein). In [2], the key insight of such reconfiguration is to re-synthesize the supervisory control, in response to a failure, in such a way as to allow automated manufacturing system operational safety. In [3], the authors propose the concept of intercellular transfers at failure to allow the reconfiguration, and to improve overall performance of cellular manufacturing systems. In [4], the authors describe an architecture-based approach to gracefully degrading systems based upon product family architectures combined with automatic reconfiguration. Examples of reconfiguration mechanisms can be found in [2] and [5].

The objective of this paper is to evaluate analytically the throughput of a production line composed of two reconfigurable machines separated by a finite capacity buffer. This means that each machine is composed of essential and non essential equipments. The failure of any essential equipment induces the shutdown of the entire machine. The failure of the non essential equipment implies the continuity of the machine service with a reduced level of functionality. Parts are moved from machine 1 to machine 2 by some kind of transfer mechanism. The machines are separated by finite capacity buffers. The parts are stocked in the buffer when machine 2 is down or busy.

The remainder of this paper is organized as follows. Section 2 gives a brief literature review on the performance evaluation of production lines. Section 3 presents the assumptions and some notations. Section 4 describes the method proposed to evaluate the throughput of two reconfigurable machines separated by a finite capacity buffer. Simulation results and numerical experiments are reported in Section 5. Finally conclusions are given in Section 6.

2. A Brief Literature Review

We discuss three research areas 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 the availability and the throughput of unreliable production lines with multi-state machines.

First, there is a substantial literature on flow models of unreliable production lines. The objective of the majority of these models is to evaluate the throughput for lines composed of several machines and intermediate buffers: see for example [11,12] for a survey. The 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 [13]. Analytical approximation methods are generally based on the Markov model developed for a line with two machines and one buffer [14] and either aggregation approach [15-17] or decomposition approach [18-22]. Other papers developing aggregation methods are [23-26]. All these papers consider binary-state machines.

Second, machines with different functioning modes are usually studied, for buffer-less systems, at the basis of MSS reliability theory [27]. Different reliability measures can be considered for MSS evaluation and design. Among them, the throughput is a common

performance measure of MSS, but it is usually evaluated without considering any intermediate buffer.

Finally, our model can be viewed as an outgrowth of the small body of literature devoted to the throughput evaluation of unreliable production lines with multi-state machines. In [28], 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 [29,30]. 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 [31–34]. Finally, the objective of the models in [35] is to analyze how production system design, quality, and productivity are inter-related in production systems. They calculate total throughput, effective throughput (*i.e.*, the throughput of good parts), and yield. Unlike [35], we consider in this paper that the machines are reconfigurable, *i.e.*, they can continue their service with a reduced level of functionality.

Assumptions and Notation

A reconfigurable machine is defined as a set of equipments partitioned into a subset of essential equipments and a subset of non essential equipments. The failure of essential equipment causes the entire machine shut down. In contrast, at the failure of non-essential equipment, the service is allowed to continue with a reduced level of functionality. The following assumptions are also used for single reconfigurable machine:

1. Essential equipment is either up (good), or failed with a constant failure rate;
2. Equipment can fail only when the machine is in one of its operating states;
3. Only one repair crew is assigned to repair the failing equipments. If the system is in a state where both non essential equipment and essential equipment are failed, the essential equipment will be repaired first;
4. Any repaired equipment is as good as new, and its repair rate is constant. Repair times are independent and identically distributed [6,7];
5. Failure times are independent and identically distributed;
6. The system is completely observable, *i.e.*, there is perfect information to determine instantaneously the failure of any essential or non essential equipment;
7. The system is considered as a perfect fault-coverage wherein all failures can be repaired and are therefore covered.

The throughput evaluation of production line containing two reconfigurable machines separated by a finite buffer is very important, because it is at the basis of the development of any decomposition or aggregation method for longer lines. This evaluation is however challenging because of the introduction of the degraded mode at each machine level. The considered tandem production line is shown in Fig. 1, where the machines are denoted by M_1 and M_2 and the intermediate buffer is denoted by B_1 . Parts flow from outside the system to machine M_1 , then to buffer B_1 , then to machine M_2 after which they leave the system. It is assumed that the flow of processed parts resembles a continuous fluid. The capacity of the buffer separating the two machines M_1 and M_2 is denoted by h_1 . A machine is *starved* if its upstream buffer is empty. It is called *blocked* if its downstream buffer is

full. Indeed, the production rate of the tandem production line may be improved by the buffer, as it may prevent blocking and/or starvation of machines. As it is usually the case for production systems, we assume that the 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.



Figure 1: Two-machine-one-buffer Production Line

Each machine M_j (with $j = 1, 2$) can experience three states: nominal, degraded, and failed. We assume that all times to failure and times to repair are exponentially distributed. Let $MTBF_{1j}$ denote the *Mean Time Between Failures* of machine M_j from the nominal state; then $\lambda_{1j} = \frac{1}{MTBF_{1j}}$ is its corresponding failure rate. Similarly, $MTTR_{1j}$ and

$\mu_{1j} = \frac{1}{MTTR_{1j}}$ are the *Mean Time To Repair* and the repair rate. On the other hand, $MTBF_{2j}$ is the *Mean Time To Degrade* of machine M_j , and $\lambda_{2j} = \frac{1}{MTBF_{2j}}$ is its corresponding degradation rate, while $MTTR_{2j}$ denote the *Mean Time To Recover* machine M_j to the nominal operating mode with a corresponding repair rate $\mu_{2j} = \frac{1}{MTTR_{2j}}$.

We assume that the processing times of each machine are deterministic, *i.e.*, a fixed amount of time is required to perform the operation, in both nominal operating and degraded operating modes. Thus, a machine M_j has constant nominal cycle time θ_j^N and

nominal production rate $U_j^N = \frac{1}{\theta_j^N}$. The nominal rate U_j^N represents the maximum rate at

which the machine M_j can operate while being in its nominal operating state and not slowed down by an upstream or a downstream machine [9]. Similarly, a machine M_j has a

constant degraded cycle time θ_j^D and a degraded production rate $U_j^D = \frac{1}{\theta_j^D}$. The

degraded rate U_j^D represents the maximum rate at which the machine M_j can operate while being in its degraded operating state and not slowed down by an upstream or a downstream machine. It is assumed that the considered line is homogenous, which means that all machines have the same nominal processing time and the same degraded processing time. That is, $U_1^N = U_2^N = U^N$ and $U_1^D = U_2^D = U^D$. The following additional assumptions are also used:

- The first machine is never starved, *i.e.*, there is always available part at the input;
- The last machine is never blocked, *i.e.*, finished parts leave machine M_2 immediately or there is always available space for part storage at the output of the line;
- The degraded rate for a given machine is less than the nominal rates of all the machines of the line;

- There exists a stationary regime where steady-state behaviour is reached.

4. Description of the Method

The performance evaluation of a two-machine-one-buffer production line is based on the following steps. Considering the Markov chain that represents the two-machines-one-buffer line where each machine can operate in a degraded functioning mode, the Chapman-Kolmogorov (CK) equations are defined for both internal and boundary states. These equations and the condition that all probabilities sum up to one lead to a system of equations that can be solved simultaneously to compute state probabilities and density functions which allow us to determine the availability, the production rate and the average buffer level.

4.1 Equations for Internal States

The internal states correspond to the composition [8] of the stochastic automata of machines M_1 and M_2 . Following the same procedure as in [8, 10], we write 16 internal state equations. If we denote by f the probability density, examples of these equations are:

$$\begin{aligned} & (U_2^N - U_1^N) \frac{\partial f(x, N_1, N_2)}{\partial x} - (\lambda_{11} + \lambda_{12} + \lambda_{21} + \lambda_{22}) f(x, N_1, N_2) + \mu_{11} f(x, F_1^N, N_2) \\ & + \mu_{12} f(x, N_1, F_2^N) + \mu_{21} f(x, D_1, N_2) + \mu_{22} f(x, N_1, D_2) = 0 \end{aligned} \quad (1)$$

$$\begin{aligned} & -U_1^N \frac{\partial f(x, N_1, F_2^N)}{\partial x} - (\lambda_{11} + \lambda_{21} + \mu_{12}) f(x, N_1, F_2^N) + \mu_{11} f(x, F_1^N, F_2^N) + \mu_{21} f(x, D_1, F_2^N) \\ & + \lambda_{12} f(x, N_1, N_2) = 0 \end{aligned} \quad (2)$$

4.2 Solution of the Internal State Equations

We assume the form $f(x, \alpha_1, \alpha_2) = C e^{\rho x} G_1(\alpha_1) G_2(\alpha_2)$, which was successfully adopted in [9], where:

$$G_i(\alpha_i) = \begin{cases} 1 & \text{if } \alpha_i = N_i \text{ or } \alpha_i = D_i \\ G_i(F_i^N) & \text{if } \alpha_i = F_i^N \\ G_i(F_i^D) & \text{if } \alpha_i = F_i^D \end{cases} \quad i = 1, 2 \quad (3)$$

In order to define the steady-state probabilities of the system, we need to solve the internal state equations. For this, we have to find the values of C , ρ and $G_i(\alpha_i)$. Substituting the form of (3) in the internal equations, we obtain after manipulations an equation which is a 3rd degree polynomial. The roots K_m ($m = 1, 2, 3$) of this polynomial allow the determination of the values of $G_i(\alpha_i)$ and ρ :

$$G_{1m}(F_1^N) = G_{1m}(F_1^D) = \frac{\lambda_{11}}{\mu_{11} + K_m} \quad (4)$$

$$G_{2m}(F_2^N) = G_{2m}(F_2^D) = \frac{\lambda_{12}}{\mu_{12} - K_m} \quad (5)$$

$$\rho_m = \frac{-K_m}{U_2^N} \left[\left(\frac{\lambda_{11}}{\mu_{11} + K_m} \right) + \left(\frac{\lambda_{12}}{\mu_{12} - K_m} \right) \right] + \frac{(\mu_{22} - \lambda_{22})}{U_2^N} \quad (6)$$

We can therefore write as suggested in [9] as:

$$f(x, \alpha_1, \alpha_2) = \sum_{m=1}^3 C_m e^{\rho_m x} G_{1m}(\alpha_1) G_{2m}(\alpha_2), \quad (7)$$

where the remaining unknowns are the C_m (with $m = 1, 2, 3$) which are determined from the solutions of the boundary state equations.

4.3 Equations for the Boundary States

There are also 16 possible states of the form $(h_1, \alpha_1, \alpha_2)$ (*i.e.*, high boundary states) and 16 possible states of the form $(0, \alpha_1, \alpha_2)$ (*i.e.*, low boundary states). However, not all of these states are reachable. Once the reachable states have been identified following the procedure in [10], and after some simplifications, we get 6 equations with 6 unknowns for high boundary states and 6 equations with 6 unknowns for low boundary states. By solving these equations, we can then express all the state probabilities of both internal and boundary states of the system as functions of the only remaining unknowns C_m (with $m = 1, 2, 3$). The probability corresponding to f is denoted by p . By using the normalization equation below, we can determine the values of these unknowns, and thus evaluate the state probabilities of the system:

$$\sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \left[\int_0^{h_1} f(x, \alpha_1, \alpha_2) dx + p(0, \alpha_1, \alpha_2) + p(h_1, \alpha_1, \alpha_2) \right] = 1 \quad (8)$$

4.4 Performance Measures of the System

Once the state probabilities of the system have been determined, we can evaluate the performance measures of the system, namely the average buffer level, and the availability and the production rate of each machine. The average buffer level is:

$$\bar{x} = \sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \left[\int_0^{h_1} x f(x, \alpha_1, \alpha_2) dx + h_1 p(h_1, \alpha_1, \alpha_2) \right] \quad (9)$$

The availability of machine M_1 is:

$$E_1 = \sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \int_0^{h_1} p(x, N_1, \alpha_2) dx + p(0, N_1, N_2) + \sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \int_0^{h_1} p(x, D_1, \alpha_2) dx + p(0, D_1, N_2) + p(0, D_1, D_2) + p(h_1, N_1, N_2) + p(h_1, D_1, D_2) + \frac{U^D}{U^N} p(h_1, N_1, D_2) \quad (10)$$

The production rate of machine M_1 is:

$$PR_1 = U^N \times \left[\sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \int_0^{h_1} p(x, N_1, \alpha_2) dx + p(0, N_1, N_2) + p(h_1, N_1, N_2) \right] + U^D \times \left[\sum_{\alpha_2=N_2, D_2, F_2^N, F_2^D} \int_0^{h_1} p(x, D_1, \alpha_2) dx + p(0, D_1, N_2) + p(0, D_1, D_2) + p(h_1, N_1, D_2) + p(h_1, D_1, D_2) \right] \quad (11)$$

Similarly, the availability and the production rate of machine M_2 are:

$$E_2 = \sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \int_0^{h_1} p(x, \alpha_1, N_2) dx + p(h_1, N_1, N_2) + \sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \int_0^{h_1} p(x, \alpha_1, D_2) dx \\ + p(0, N_1, N_2) + \frac{U^D}{U^N} p(0, D_1, N_2) + p(0, D_1, D_2) + p(h_1, D_1, D_2) + p(h_1, N_1, D_2) \quad (12)$$

$$PR_2 = U^N \times \left[\sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \int_0^{h_1} p(x, \alpha_1, N_2) dx + p(0, N_1, N_2) + p(h_1, N_1, N_2) \right] + \\ U^D \times \left[\sum_{\alpha_1=N_1, D_1, F_1^N, F_1^D} \int_0^{h_1} p(x, \alpha_1, D_2) dx + p(0, D_1, N_2) + p(0, D_1, D_2) + p(h_1, N_1, D_2) + p(h_1, D_1, D_2) \right] \quad (13)$$

5. Validation by Simulation

An object-oriented discrete events simulation tool has been developed for the studied multi-state production lines. Using this tool, simulation experiments have been conducted to assess the accuracy of the proposed method. Many examples are considered where all failure and repair rates are assumed to have an exponential distribution and for each example. Five levels of degradation were considered. Each example was run for 20 replications of 100 time-units warm-up period and 4,000 time-units simulation period. For each of the evaluated three performance measures, a percentage error is calculated according to the following expression:

$$Error \% = \frac{Analytical - Simulation}{Simulation} \times 100 \quad (14)$$

The obtained results have shown that the average absolute value of the percentage error for the production rate estimation of the system is less than 4.09 %, while this error is less than 2.91 % for the system availability.

6. Conclusion

In this paper, we proposed an analytical method for the performance evaluation of a tandem production line where the machines can operate in a degraded functioning mode. The main characteristic of the proposed method is its ability to evaluate performance measures of the line, namely the availability, the production rate, and the average buffer level. Simulation experiments have illustrated the accuracy of the method. This method can be used as the building block for the throughput evaluation of longer production lines with reconfigurable machines, using decomposition or aggregation techniques.

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