Applied Mathematical Modelling 39 (2015) 3619–3636

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Performance evaluation of a multi-product production line: An approximation method

Farshad Jarrahi, Walid Abdul-Kader *

Industrial and Manufacturing Systems Engineering, University of Windsor, Windsor, Canada

ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 3 October 2014
Accepted 30 November 2014
Available online 11 December 2014

Keywords:
Performance
Evaluation
Multi-product
Unreliable
Production line
Buffer

ABSTRACT

This paper develops an analytical method to measure the performance of a multi-product unreliable production line with finite buffers between workstations. The performance measure used in this paper is Total Cycle Time. The proposed method is an approximation that generalizes the processing times to ease the variation of product types in a multi-product system.

A decomposition method is then employed to approximate the production rate of a multi-product production line. The decomposition method considers generally distributed processing times as well as random failure and repair. A GI/G/1/N queuing model is also applied to obtain parameters such as blocking and starvation probabilities that are needed for the approximation procedure. Several numerical experiments under different scenarios are performed and results are validated by simulation models in order to assess the accuracy and strength of the proposed method. Consequent analysis and discussion of the results are also presented.

1. Introduction

A production line is a common type of production system. It is also known as transfer line or flow line, and can be represented as a tandem queuing system. In this paper, we use the terms "production line" and "flow line" interchangeably. A production line consists of a number of workstations or machines in series with intermediate buffers between successive workstations or machines. Examples of flow lines can be observed in electronic components assembly and high-volume automotive parts production industries.

The amount of time the material (part) spends in a workstation may be considered as deterministic if it does not vary from one part to another; and stochastic if it varies randomly from part to part. This randomness may be due to random processing times, random failure and repair events, or both [1]. The production line dealt with in this research work is asynchronous in nature, and failures and repairs are random with operation dependent failures. Parts are transferred to the next workstation via the intermediate buffer on a unit-by-unit basis.

There exist many different metrics that can be applied as measure of performance in a manufacturing system. Production rate, average number of parts stored in intermediate buffers, and throughput time are among the most commonly used measures of performance in the literature. In this paper we will introduce and use Total Cycle Time as the ultimate performance measure. A definition will be provided later.

* Corresponding author.

http://dx.doi.org/10.1016/j.apm.2014.11.059

Nowadays, with the help of low cost automated machines and material handling systems, many small and medium sized companies are equipped with automated serial production systems capable of producing many different product types without major changes in the system configuration. A good example of such systems is packaging lines in pharmaceutical or food industries that produce a large variety of product types.

However, in such systems analyzing the performance will become complicated due to product types variety. Most of the existing studies in the area of manufacturing performance evaluation have been focused on classic production lines that are traditionally assumed to produce single product type. In this study, we will present an approach to tackle performance evaluation problem in multi-product production lines.

The remainder of this paper is organized into the following sections. Section 2 presents a review of previous works based on modeling techniques. Section 3 introduces notation, description of the research problem, assumptions, and develops a methodology to approximate Total Cycle Time as the ultimate performance measure. It tackles the complexity of product type variation by introducing general performance measures that are independent of product type changes. It employs GI/G/1/N queuing model and decomposition method to approximate the general production rate as a key performance measure. Section 4 presents the application of the proposed analytical approximation method on several cases to demonstrate its accuracy, strength and limitations. The method is compared with the results obtained by simulation. Finally, conclusions and future research directions are discussed.

2. Literature review

This section is organized based on model development techniques. We can categorize models by their computational form. With this taxonomy, models are analytical or experimental [2]. Analytical models represent a more mathematical abstraction of the real system, and are mainly divided into two major sub-categories: exact models and approximation models. Simulation models, on the other hand, are experimental. In addition to these categories, hybrid models may also be used. More explanation of each model development method and the related literature review is given below.

2.1. Exact models

Johri [3] developed a Linear Programming model in order to measure the cycle time in an automated serial production line where each workstation is prone to failure. Buzacott [4] presented some simple models of production–inventory systems and demonstrated how production capacity and flexibility are enhanced with the use of inventory banks.

A linear programming model was proposed by Abdul-Kader [5] by exploiting Johri's [3] multi-product model, and further modified by replacing machines' repair and downtime with the insertion of fictive products to address the issue of capacity estimation/ improvement of a multi-stage unreliable serial production line with finite buffers. The line can process a variety of products in batch environment according to a predefined sequence.

Gaver [6] considered a single server queue with Poisson arrival and general independent service time where the server is subject to random failure, and the repair time is generally and independently distributed. Alexandros and Chrissoleon [7] proposed an exact solution to a two stage one buffer flow line in which each stage consists of parallel servers.

Among other related exact methods, Zipkin [8], Gupta and Banik [9], Albores-Velasco and Tajonar-Sanabria [10], Asmussen and Moller [11] and Xu and Zhang [12] have investigated single or multi-server queuing models.

Unfortunately, most of the models in the area of queuing theories have only addressed servers in parallel, and not in series. In theory, systems can be modeled via Markov chains for any number of stages. But in practice, it is very difficult to obtain exact analytical solutions of transfer lines with more than two machines. The reason is the number of system states in the Markov chain, which increases exponentially with the increase of machines and the inter-stage buffer capacity. For example, a production line with four machines and inter-stage buffers of capacity 3 gives rise to a Markov chain with 19,402 states [13]. Therefore, to cope with the complexity of exact mathematical solutions, approximation methods are used widely in the literature.

2.2. Approximation models

Gershwin [14] presented a decomposition technique for the approximate evaluation of tandem queues with finite storage space and blocking. The efficiency of Gershwin [14] algorithm was improved upon by Dallery et al. [15] who proposed an efficient algorithm known as DDX algorithm that converges in substantially less time. Gershwin [16] made an attempt to treat three-parameter continuous material systems where he combined two equal processing rate machines together. The concept was: one machine would be accountable for the failure rate and the other would modify the machine speed. But this idea was proved unrealistic after the simulation experiments.

Tempelmeier and Burger [17] proposed a decomposition method in order to analyze the performance of non-homogeneous asynchronous Flow Production Systems (FPSs). They considered characteristics such as general processing time, unreliable stations, and scrapping for the studied FPSs. De Koster [18] used repeated aggregation to multi-stage continuous flow lines of several unreliable machines separated by buffers for the prediction of line efficiency. Haskose et al. [19] developed an