Computers & Industrial Engineering 64 (2013) 109–121

Contents lists available at SciVerse ScienceDirect

Computers & Industrial Engineering

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

Estimating customer service levels in automated multiple part-type production lines: An analytical method ☆

C.D. Senanayake, V. Subramaniam *

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 21 September 2011
Received in revised form 29 August 2012
Accepted 1 September 2012
Available online 22 September 2012

Keywords:
Multiple part-type
Production line
Machine setup
Decomposition
Analytical method

ABSTRACT

We develop an approximate analytical method to estimate the customer service levels in automated multiple part-type production lines. The production line consists of several processing stations in series with finite intermediate buffers, one for each part-type. The main contributions include the analysis of multiple part-type systems with machine setups, bypass routings and stations having combinations of shared and dedicated machines. This research is motivated by observations of real production lines. We use the continuous material approximation in modeling the system behaviour and develop a new approximate decomposition method to analyze the performance of the system. Validation experiments conducted on production lines with different configurations show good accuracy in the estimation of customer service levels compared to simulation. We use an example case study to demonstrate the application of the model in the performance improvement of a system that is based on a real production line. The analytical model is proposed as a reliable and fast performance analysis tool for the optimization of automated multiple part-type production lines with complex configurations.

1. Introduction

Modern-day industrial production lines are generally designed to produce multiple part-types (Goyal & Netessine, 2007). Examples are found in automotive assembly (Patchong, Lemoine, & Kern, 2003), semiconductor manufacturing (Jang, 2007), packaging lines and bottling plants (Colledani, Gandola, Matta, & Tolio, 2008). Manufacturers who operate multiple part-type production lines often aim to achieve high customer service levels for all part-types, while minimizing inventory and other related costs (Christou, Lagodimos, & Lycopulou, 2007). Therefore, it is essential that the production system is designed such that these performance requirements can be fulfilled.

In designing any production system, various alternate configurations are often evaluated before selecting the configuration that best meets performance objectives. Analytical methods are increasingly used for evaluating the performance of production systems (Patchong et al., 2003; Burman, 1995). Compared to simulation, analytical methods are faster and can provide greater insights to the dynamics of the manufacturing system (Colledani et al., 2010).

In this paper, we propose an approximate analytical method for estimating customer service levels in automated multiple part-type production systems. The system consists of several interconnected stations with each station having processing machines that may be shared among several part-types (*shared machines*) or dedicated to a particular part-type. Processing operations and material transportation between stations are automated. An example production system consisting of five stations producing four part-types is shown in Fig. 1, where rectangles represent machines and circles represent inter-station buffers. As shown in the figure, each part-type has its own buffer (*homogeneous* buffers). This is commonly observed in food product packaging lines and bottling plants (Colledani et al., 2008).

Several researchers have contributed to the analysis of automated multiple part-type production systems (Jang, 2007; Colledani et al., 2008; Nemec, 1999). A literature review is provided in Section 2. These studies mainly focused on estimating the production rate of systems where each station consisted of a single shared machine with negligible setup times.

In this paper, we extend the analytical methods to multiple part-type systems with stations having combinations of shared and dedicated machines where shared machines require a setup each time production is switched between part-types. In addition, part-types may also have bypass routings. This work has been particularly motivated by discussions with the authors of a simulation study (Zhou, 2009) of an electrical component production line that involved all of the system characteristics mentioned above.

Machine setups are quite common in the production of multiple part-types (Gershwin, 1994). Setup operations may include tool changes, machine calibration, fixture adjustments, cleaning, etc. Although setup times are being constantly reduced through

☆ This manuscript was processed by Area Editor Manoj Tiwari.

* Corresponding author. Tel.: +65 6516 6555; fax: +65 6779 1459.
E-mail addresses: cds@nus.edu.sg (C.D. Senanayake), mpesubra@nus.edu.sg (V. Subramaniam).

0360-8352/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cie.2012.09.002

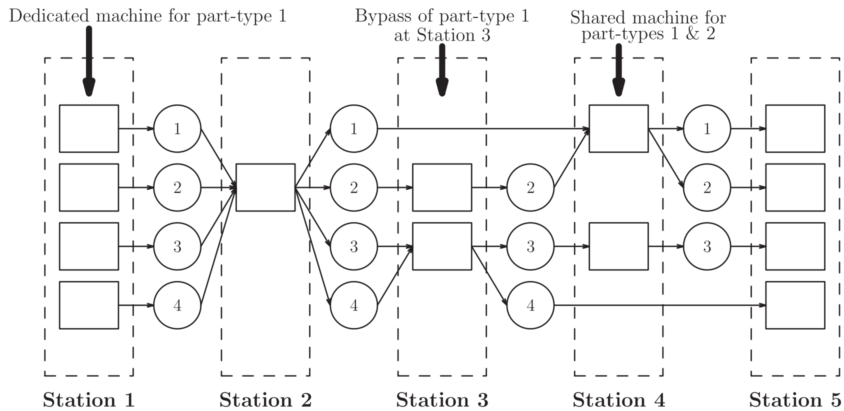

Fig. 1. A five station, four part-type production system.

technological advances (e.g. automatic tool changes) and continuous improvement activities, most production systems will still require non-negligible setups (McIntosh, Culley, Mileham, & Owen, 2001).

In industrial multiple part-type manufacturing systems, a single shared machine station is primarily used when the machine is too costly to be duplicated (Hopp & Spearman, 2008). However, certain stations may have both dedicated and shared machines, as described by Zhou (2009). In addition, part-types may not require processing at all stations as assumed in previous studies (Jang, 2007; Colledani et al., 2008; Nemec, 1999). Bypass routings are frequently encountered in multiple part-type production (Diponegoro & Sarker, 2003) and industrial examples include sheet metal fabrication (Diponegoro & Sarker, 2003), electrical component assembly (Zhou, 2009), and garment packing plants.

In our analytical approach, we first develop a new building block model of a two-machine system (2M1B model) using the continuous material flow approximation (Alvarez-Vargas, Dallery, & David, 1994). In this model, it is assumed that both machines have equal deterministic processing times and are subject to failures. This is a common assumption in the modeling of automated systems (Li, Blumenfeld, & Huang, 2009). The continuous flow approximation provides the flexibility to later extend the analysis to asynchronous systems, where machines at each stage have different processing times. We then incorporate this new 2M1B building block in the approximate decomposition analysis of automated multiple part-type production lines with general configurations of the characteristics studied in this paper.

Numerical results show that the decomposition method provides good accuracy in estimating customer service levels for a range of production line configurations. We also apply the methodology to estimate the customer service levels of a production system with a configuration similar to an existing industrial production line described in the simulation study of Zhou (2009). Using this system as a case study, we demonstrate how the model can be used to identify system improvements that will best enhance system performance.

The remaining sections of the paper are organized as follows: Section 2 provides a review of the relevant literature. The system description and modeling methodology is then detailed in Section 3. Section 4 presents results for the model validation and experimental case study. Finally, the conclusions and future research directions are presented in Section 5.

2. State of art

2.1. Analysis of automated production lines

Analytical models of automated production lines usually assume unreliable machines, deterministic processing times and finite intermediate buffers (Li et al., 2009). An automated system consisting of two unreliable machines and a finite intermediate buffer is analyzed in Gershwin (1994) using the continuous flow approximation (*continuous* 2M1B model). Studies have shown that the continuous flow model provides a good approximation to high volume discrete part flow automated systems (Alvarez-Vargas et al., 1994). Recently, Tan and Gershwin (2009) developed a general methodology using level crossing analysis for solving continuous 2M1B models with any number of machine states. An alternative solution method based on an inverse Laplace transform approach was proposed by Cao and Subramaniam (2010).

The exact analysis of long production lines is not feasible because the state space increases exponentially with each additional machine/buffer component (Gershwin, 1994). Therefore, approximate methods such as decomposition were proposed by several authors (Gershwin, 1987; Tolio & Matta, 1998; Dallery, David, & Xie, 1989). In this approach, the analysis of a production line with k machines is approximately 'decomposed' into a set of $k-1$ tractable 2M1B building block models. Several decomposition methods based on the continuous model have been developed in the literature (Burman, 1995; Dallery et al., 1989; Levantesi, Matta, & Tolio, 2003). Typical performance measures that are calculated using decomposition include the average production rate, mean flow time and the average work-in-process (WIP). Further, by approximating the demand and supply processes as additional machine models (Dallery & Gershwin, 1992), it is also possible to estimate customer service levels.

In the following section, we discuss the analytical methods developed for multiple part-type systems. Since most researchers have focused on systems with homogeneous buffers, we too shall restrict our review to these studies.

2.2. Analysis of multiple part-type automated production lines

Several authors have analyzed multiple part-type systems by assuming reliable machine models (Krieg & Kuhn, 2004, 2008; Gurgur & Altiok, 2007, 2008). In these studies, the processing times were assumed to be either exponential or Erlang distributed. However, it has been empirically shown that the assumptions of reliable machines and Erlang distributed processing times are not suitable for the analysis of automated production lines (Inman, 1999). Senanayake and Subramaniam (2011) and Diamantidis and Papadopoulos (2006) have proposed building block models with unreliable machines for the analysis of multiple part-type systems. However, exponential processing times was still assumed and approximate methods to analyze longer production lines were not developed.

The research specific to automated multiple part-type production systems has almost exclusively assumed negligible setup