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Performance characterization of complex manufacturing systems with general distributions and job failures

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ABSTRACT

In optoelectronics assembly, the first few stages of the assembly line are dedicated to build the product and the later stages are dedicated for calibration and testing. The assembly line is arranged in a flow shop environment with multiple processors at each stage. When a product (or job) fails at a stage, it is routed back to one of the previous stages or to the same stage (depending upon the nature of the failure). Consequently, the product could circulate between the current stage and the previous stage(s) before it is transferred to the next stage. Estimating the performance measures of such complex manufacturing systems, while considering multiple product classes, random job failures, and resource sharing, is not trivial. This paper presents the approximations used to estimate the performance measures of such complex manufacturing systems with general arrival and service distributions. The analytical approximations have been validated using discrete event simulation and the source of error between them is identified. These approximations can be used by operations managers to estimate the performance measures such as WIP and flow time.

1. Introduction

In optical assembly and test operations, products are assembled through one or more stages (e.g. fiber splicing and fiber management) and tested at one or more stages (e.g. calibration, burn-in, etc.). En route to the final stage the jobs could fail at different stages either due to product or process related issues. The failed jobs are rerouted to any one of the previous stage(s) or to the same stage depending upon the nature of the failure. Consequently, the jobs can circulate between the current stage and the previous stage(s) several times before moving on to the next stage.

Fig. 1 presents the schematics of a typical optoelectronics assembly line. The first stage is the splicing stage where the product is assembled. Stages subsequent to the first stage are the testing stages such as calibration (stage 2), qualification (stage 3), and burn-in (stage 4). If a job fails at the qualification stage, it could be routed to the calibration stage for retesting, or to a splicing station for a rework. Irrespective of whether the job is routed to the first or second stage, it has to follow the regular sequence (splicing – calibration – qualification – burn-in) until it passes all the tests. Yield fallouts introduce some level of uncertainty in predicting the throughput and other performance measures.

Job circulation is also observed in integrated circuit (IC) manufacturing. The primary difference between optoelectronic assembly and IC manufacturing is in the process route. In IC manufacturing, the wafers can visit a stage multiple times, but the route is fixed (i.e. deterministic). However, in optoelectronics assembly line, random job failure at a stage leads to job circulation (in a probabilistic manner).

2. Problem description

The layout of an optoelectronics assembly line is identical to a flow shop. Analyzing such lines is easier when the yield is 100% at each stage. However, in practice the yield is seldom 100% – especially when a new product is introduced or when a product changeover takes place. All the jobs which fail at a stage will have to be reworked and/or retested (at anyone of the previous stages or the same stage) before they can move to the next stage. Consequently, the original sequence of the failed jobs is disturbed and they circulate. Estimating the performance measures, such as the average flow time and work in process (WIP), for such environments remain a challenge for planners and managers. Their task is further complicated when the facility deals with multiple product classes, which may share some resources. A tool to estimate the performance measures of such complex manufacturing systems can aid operations managers and planners to provide accurate commitment (or promise) dates to the end customers; thereby

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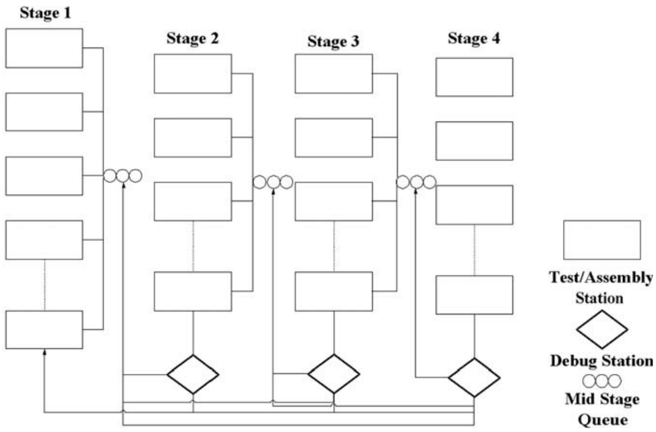

Fig. 1. Process flow in optical assembly operations.

the customers are satisfied with the service provided and unnecessary penalties (and loss of customer goodwill) can be avoided by the manufacturer for being tardy.

The manufacturing system under study has the following characteristics (1) the assembly line is a flow line, (2) jobs circulate due to random failures, and (3) multiple product classes in the system can share some resources. The primary objective is to (1) develop analytical models to predict the performance measures (such as WIP and flow time) of the system under study, and (2) to verify the analytical models by comparing the results obtained with a simulation model. The analytical methods can (1) help the operations planners to estimate the systems performance measures accurately, (2) help to cut down the time and resources required to build and analyze a simulation model, and (3) be used in conjunction with a capacity planning model to determine the optimum number of resources required at each stage to minimize a performance measure of interest.

The remainder of the paper is organized as follows. Literature pertinent to the problem under study is presented in Section 3. The analytical model proposed is presented in Section 4. The performance estimates from the analytical models (for several random problem instances) were compared to a simulation model to evaluate its accuracy. The experimental details are presented in Section 5. Experimental results are discussed in Section 6. Our conclusions and future scope for research is presented in Section 7.

3. Literature review

In IC manufacturing (a.k.a reentrant lines), jobs may visit the same processing center multiple times in a deterministic manner. Reentrant lines have been extensively studied in the past by Kumar (1993), Narahari and Khan (1995), Morrison and Kumar (1998), Yao (1994) and many other researchers to predict the performance measures. Most of them used queuing network theory as the principal tool for performance estimation.

Narahari and Khan (1995, 1996) studied the performance of reentrant lines using mean value analysis (MVA) for open (WIP is not constant) and closed queuing (WIP is constant) networks. Park et al. (2000) used the MVA technique to analyze closed reentrant flow shops with single job and batch machines. Exact solutions can be obtained when the job arrivals are Poisson and their processing times at different stations are exponentially distributed. Performance measures of a reentrant line are also estimated using simulation models (e.g. Nazzal et al., 2006; Ramírez-Hernández and Fernandez, 2005; Sivakumar and Chong, 2001). Govil and Fu (1999) conducted an extensive survey on queuing models for manufacturing applications. More recently, queuing models have been used for predicting performance measures in manufacturing (e.g. Souza et al., 2001), healthcare (e.g. Goddard and Tavakoli, 2008), electronics testing (e.g. Omar and Kumar, 2008) and several other applications. Li et al. (2007) proposed a graphical approach to evaluate the performance of a single station in semiconductor manufacturing.

Pradhan et al. (2008) proposed analytical models to estimate performance measures for the problem under study when the job arrivals and service times were exponentially distributed. This paper relaxes the Markovian assumptions made in Pradhan et al. (2008). If one wishes to analyze a large network with several servers and queues, calculation of the normalization constant that is required in the computation of system probability $p(n)$, where n is the number of jobs in the system could be very complex or almost impossible (Gelenbe and Pujolle, 1987). Thus, an exact procedure is not possible when the Markovian assumptions are relaxed. If the system states are not Markovian, the system is converted to a Markovian system by defining additional states using the concepts of hidden Markov chains as in M/G/1 and G/G/1 queues. Some of the approximation methods found in the literature are parametric decomposition, fluid models, and MVA.

In the decomposition method, the queuing network is divided into several nodes, where every node is represented by a G/G/c queue (e.g. Vandaele et al., 2002; Yang et al., 2005). This method allows for estimating the mean number of customers at each station in the network and the response time. Every queue is analyzed separately. The distribution of arrivals and service times are characterized by their first moments, or more exactly by their rates and the square of the coefficient of variation. G/G/c approximations are used to obtain the performance measures of each node and to estimate the characteristics of the output process.

In flexible production systems, the objective is to determine methods to use the tooling and other operations such that multiple products can be produced efficiently. The focus is on automating almost everything possible – from material handling to machining. Optoelectronics assembly is a flow line with some resource sharing. In optoelectronics assembly and testing, the test procedures are typically unique to a customer and a product(s). Hence it is impractical for a contract manufacturer to buy these testing equipments. Consequently, the testing equipment is provided by the original equipment manufacturer (or customer). The same resource (or testing equipment) is shared for building and testing similar products typically for the same customer. Failures and recirculation could stress these critical resources.

In summary, the MVA and decomposition techniques have been extensively utilized in telecommunication industry and for relatively simple manufacturing systems. To our knowledge, performance analysis of complex and realistic manufacturing systems (multiple classes, shared nodes, probabilistic routes, and general distributions) has not been dealt in the literature systematically. The findings reported in this paper would serve as a decision making tool for planners and managers to analyze the performance measures of complex manufacturing systems with multiple product classes, shared nodes, and probabilistic routes.

4. Flow shops with job failures

In the following sections, the analytical models for a multi-product manufacturing system with general distributions and stochastic flow of jobs between stations are presented. The underlying assumptions are as follows:

- arrival and processing times follow a general distribution;
- there exists an infinite buffer at each station in order to accommodate the WIP;