Available online at www.sciencedirect.com
ScienceDirect
European Journal of Operational Research 179 (2007) 424–443
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH
www.elsevier.com/locate/ejor

Stochastics and Statistics

Buffer sizing in multi-product multi-reactor batch processes: Impact of allocation and campaign sizing policies

Inneke Van Nieuwenhuyse [a,*,1], Nico Vandaele [b], Kumar Rajaram [c], Uday S. Karmarkar [c]

[a] European University College Brussels, Stormstraat 2, 1000 Brussels, Belgium
[b] Faculty of Applied Economics, University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium
[c] Decision, Operations and Technology Management, UCLA Anderson School of Management, Box 951481, Los Angeles, CA 90095-1481, United States

Received 4 March 2005; accepted 16 March 2006
Available online 3 May 2006

Abstract

This paper studies the impact of management policies, such as product allocation and campaign sizing, on the required size of the finished goods inventories in a multi-product multi-reactor batch process. Demand, setup and batch processing times for these products are assumed to be stochastic, and the inventory buffer for every product type needs to be such that target customer service levels are met. To perform this analysis, we develop a queueing model that allows us to explicitly estimate service levels as a function of the buffer size, and the allocation/campaign sizing policies. This model can be used to evaluate the service level given an existing buffer configuration, as well as to determine the buffer sizes required across products to meet a pre-specified service level. It also allows us to formulate a number of insights into how product allocation decisions and campaign planning policies affect buffer sizing decisions in symmetric production systems.

Keywords: Queueing; Campaign sizing; Product allocation; (Semi)process industries

1. Introduction

In this paper, we analyze the issue of determining the required size of finished goods inventories in a multi-product, multi-reactor batch process. The objective is to meet a predetermined customer service level, which is defined as the long-run percentage of time that incoming customer orders can be delivered from the finished goods stock.

* Corresponding author. Tel.: +32 3 220 45 42.
E-mail addresses: inneke.vannieuwenhuyse@ehsal.be, inneke.vannieuwenhuyse@ua.ac.be (I. Van Nieuwenhuyse), Nico.vandaele@ua.ac.be (N. Vandaele), kumar.rajaram@anderson.ucla.edu (K. Rajaram), uday.karmarkar@anderson.ucla.edu (U.S. Karmarkar).
[1] At the time of writing, Ms Van Nieuwenhuyse was employed as a Postdoctoral Researcher of the Fund for Scientific Research—Flanders (Belgium).

0377-2217/$ - see front matter
doi:10.1016/j.ejor.2006.03.020

Multi-product batch operations are encountered in many applications (e.g., the food processing industry). Typically, products are made to stock, and demand patterns as well as processing and setup times are stochastic. We will study the system from the perspective of a company with specific equipment at hand. Though this implies that the equipment parameters (such as the batch size of the reactors and the processing parameters) as such are given, management can influence system performance through two types of decisions: *campaign sizing* and *allocation policies*.

The term campaign size refers to the amount of product that is produced between two consecutive setups on a reactor. Setups may be needed when the reactor switches from one product type to another, e.g., for cleaning. The size of the campaigns cannot be set arbitrarily: as the reactors' batch sizes are a given, campaign sizes typically consist of a multiple of the equipment sizes (Rajaram and Karmarkar, 2004).

The allocation policy determines how replenishment orders for product types are assigned to the reactors. In this paper, we largely distinguish between two policies: one in which a given product type is always produced on the same reactor (*deterministic policy*), and one in which multiple reactors each produce a given fraction of the replenishment orders (*probabilistic policy*).

Through the allocation and campaign sizing decisions, management can influence the performance of the system: indeed, it is intuitively clear that both decisions will impact the replenishment lead times, and hence the size of finished goods inventory needed to attain a target customer service level. As both allocation and campaign sizing policies are pure management decisions, and hence can be easily adapted, quantitative insight into how these decisions affect system performance is extremely useful. To study this issue, we will regard the production–inventory system as a stochastic system, and propose a queueing model to analyze the system's behaviour. As will be shown, this approach not only allows us to evaluate the performance of any general system, but also enables us to formulate a number of insights and managerial guidelines on campaign sizing and allocation decisions in symmetric production systems.

The application of queueing theory to model a semi-process industry setting is quite unusual; apart from some earlier attempts to illustrate the potential usefulness of the methodology (e.g., Carlson and Felder, 1992), research literature in this area is almost non-existent. On the one hand, issues related to campaign sizing, campaign scheduling and product cycling have been studied quite intensively from a deterministic perspective (e.g., Rajaram and Karmarkar, 2002, 2004; Dobson, 1987; Elmaghraby, 1978; Fleischmann, 1990). On the other hand, the few research efforts aimed at modelling process industry settings from a stochastic perspective have predominantly focused on discrete-event simulation (e.g., Felder et al., 1983, 1985). The use of queueing models for analyzing demand allocation problems is more common (see, e.g., Benjaafar and Gupta, 1999; Benjaafar et al., 2004a). However, the models presented in the literature assume a Poisson arrival process to the queue, which makes them unable to adequately reflect the campaign sizing step in a process industry setting.

In this paper, we show that the body of knowledge on queueing theory can be very valuable in modelling semi-process industries, provided that adequate changes to the models are made in order to capture the specificities of this type of industry (such as batch processing, product allocation and campaign sizing). This is done in Section 2. In Section 3, we analyze the impact of the average customer order replenishment lead time on the customer service level for an arbitrary multi-product multi-reactor system. These insights enable us to further examine the impact of allocation and campaign sizing decisions in symmetric systems in Section 4, and to formulate propositions about "optimal" decisions for this type of systems. In Section 5, the findings are applied to a numerical example. Finally, Section 6 summarizes the conclusions.

2. Model formulation

2.1. Notation and assumptions

Consider a chemical plant consisting of R reactors (index $r = 1, \ldots, R$), and K product types (index $k = 1, \ldots, K$). Each product type k needs only one single operation, which can be performed on a subset V_k of the reactors ($V_k = \{r \mid \text{product type } k \text{ can be produced on reactor } r\}$). Each reactor r has a batch size B_r, which is a technical characteristic and hence is given. The processing characteristics for product type k (e.g., average and variance of setup and processing times) may differ across the reactors in V_k. For each