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A disruption recovery plan in a three-stage production-inventory system

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ABSTRACT

This paper proposes a recovery plan for managing disruptions in a three-stage production-inventory system under a mixed production environment. First, a mathematical model is developed to deal with a disruption at any stage while maximizing total profit during the recovery-time window. The model is solved after the occurrence of a disruption event, with changed data used to generate a revised plan. We also propose a new and efficient heuristic for solving the developed mathematical model. Second, multiple disruptions are considered, where a new disruption may or may not affect the recovery plans of earlier disruptions. The heuristic, developed for a single disruption, is extended to deal with a series of disruptions so that it can be implemented for disruption recovery on a real-time basis. We compare the heuristic solutions with those obtained by a standard search algorithm for a set of randomly generated disruption test problems, and that show the consistent performance of our developed heuristic with lower computational times. Finally, some numerical examples and a real-world case study are presented to demonstrate the benefits and usefulness of our proposed approach.

1. Introduction

Batch production is a very common and popular technique in manufacturing systems in which products are produced in batches to minimize the overall production cost while maximizing utilization of the available capacity. Sometimes, the batch size and processing time can be constant, depending on the nature of the process, as well as on the capacity of the equipment. In some cases, the processing time can be either dependent or independent of the batch sizes. For example, the mixing time of raw materials is independent of the batch size because a quantity of them which does not use the full capacity of the equipment can be mixed. In real-life production lines, it is very common to process materials or products in a series of stages, one after another, to obtain the final products. There are numerous industries, such as pharmaceutical, textile and manufacturing that produce products using multiple stages, during which the production environment can be either similar or different, and processes such as batch or continuous production or a combination of both. Even if the production environment is continuous, a product may be produced in batches due to there being higher production capacity than demand. In these real-life situations, production disruptions are common events which occur for different reasons and, moreover, may take place at any time and in any stage of the system. As an organization can face a huge financial, as well as goodwill, loss due to a disruption in its system [33], it is important to develop a suitable recovery plan to minimize the effects of such a disruption. This research has been motivated by the disruption scenarios observed in a real-life pharmaceutical production line. That production line consists of three sequential processes (known as mixing, compression, and packaging) which can easily be defined as three stages of the production process. The production process starts with a discrete batch production in the mixing stage and is followed by two continuous production processes in the compression and packaging stages. The production line is sometime disrupted, mainly due to machine breakdowns that occur at any stage of the line without having any prior knowledge. Although management repairs the machines as soon as possible, it is not easy to reschedule the production line to minimize the overall loss with a minimum effect on customer goodwill. This is a common problem in many industrial units, and hence it requires a new real-time problem solving approach, such as the disruption recovery method proposed in this paper.

Over the last few decades, one of the most important research topics, in operations research and computer science, has been production-inventory systems. During the early stage, researchers focused on developing inventory models under ideal conditions; for example, the development of the basic economic order quantity (EOQ) model ([12] (reprinted from 1913) and [37]) and basic

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economic production quantity (EPQ) model [34] which was an extension of the EOQ model. Later, many researchers used these models in their studies; for example, Cheng [40] considered production process reliability in a single-stage imperfect production process to develop an EPQ model. Goyal [9] also applied the basic concept of the EPQ model to determine optimal lot sizes in a two-stage production system that minimized the sum of all costs. Other such extensions of EPQ models in single-stage production-inventory systems were developed by Ishii and Imori [16], Graves [11], Biskup et al. [2], Chan and Song [3], Dave [6], Chiu et al. [5], Pentico et al. [29], Paul et al. [24], Sarkar and Moon [31], and Kiesmüller et al. [17].

However, the above studies focused mainly on either single- or two-stage production systems whereas, on many production lines, products are processed in multiple stages [10]. A few researchers analysed multiple-stage production systems that included: (i) the determination of optimal production policies for single-item and multi-stage production systems [35,22], (ii) the modification of the single end-item production lot sizing model considering work-in-process inventories [1], (iii) the determination of safety stocks in multi-stage inventory systems with normally distributed demands [15], (iv) the consideration of reworking options in a multi-stage production inventory to minimize the inventory cost of work-in-process and finished goods [32]. Some additional studies of multi-stage production-inventory systems were those by Konak et al. [19], Glock and Jaber [8], and Kim and Glock [18].

Past studies of single- or multiple-stage production-inventory systems were conducted in ideal production environments but there is very little research work in the literature on managing disruptions in production-inventory systems. However, the impacts of machine breakdowns have been analysed in several studies. Some examples are: the development of a (s,S) production-inventory policy with random disruptions and exponential times between breakdowns in an unreliable bottlenecked system [23], the analysis of the impact of machine breakdown on an EPQ model for deteriorating items in a single-stage production system considering a fixed period of repair time [20], the extension of the model of Lin and Gong [20] for deteriorating items with random machine breakdowns and stochastic repair times with uniform and exponential distributions [36], the development of an EPQ model with a Poisson-distributed machine breakdown for determining an optimal production run-time [5], and the development of a robust plan for a machine breakdown and reworking failure [4].

Recently, a mathematical model for a single disruption recovery within a single-stage, single-item production system was developed by Hishamuddin et al. [13]. They proposed a heuristic for solving the disruption recovery problem that considered back orders and lost sales costs. An extension of that problem which included demand uncertainty and process reliability for a single-stage production-inventory system was investigated by Paul et al. [25]. Recently, Hishamuddin et al. [14] introduced concepts for managing a single transportation disruption in a two-echelon serial supply chain system involving both the producer and retailer. Interested readers can refer to Qi et al. [30], Xia et al. [38], Mohebbi [21], Eisenstein [7], Yang et al. [39] and Paul et al. [26] for other disruption recovery models within the context of production-inventory systems.

Existing studies considered either single- or two-stage batch production-inventory systems, with disruption recovery policies for only a single disruption. In this paper, we consider a three-stage production system and deal with single as well as multiple disruptions on a real-time basis. We consider a disruption event that is not known and cannot be predicted in advance. We first develop a mathematical model for coping with a single disruption in any stage. In our experimental study, we use a uniformly random probability distribution to generate disruption parameters, such as disrupted stage, and pre-disruption and disruption periods. Then, we solve the mathematical model after the occurrence of a disruption and use the estimated recovery time to develop a revised plan. We assume that the batch size in the first stage is limited by the capacity of the equipment, and that the processing time is constant and independent of the batch size but that, in the second and third stages, the processing time is proportional to the batch size. After processing in the first stage, the whole batch is transferred to the second stage for further processing and may then be split into smaller lots depending on the capacity of the transfer bucket between the production stages.

In this paper, we propose a new and efficient heuristic for solving the developed mathematical model, with its results compared with the solutions obtained from a pattern search using a set of randomly generated disruption test problems. We also consider multiple disruptions, one after another in a series, that occur in any stage at any point in time and may or may not affect the plans amended after previous disruptions. If a new disruption occurs during the recovery-time window of another, a new revised plan which considers the effects of both disruptions must be derived. Accordingly, as this is a continuous process, we extend the heuristic to deal with a series of disruptions on a real-time basis by incorporating a modified version of that developed for a single disruption. This is the first quantitative model that develops a disruption recovery model for both a single and multiple disruptions, on a real-time basis, in a three-stage mixed production-inventory system. Finally, we show how the proposed methodology can be applied to real-time disruption recovery planning, with randomly generated test problems, as well as a real-world case problem from the aforementioned pharmaceutical company.

The main contributions of this paper can be summarized as follows:

(i) Development of a mathematical model for disruption recovery in a three-stage production-inventory system. As a disruption scenario is not known in advance and not possible to predict, the recovery plan is revised for periods after the disruption occurs on a real-time basis.
(ii) Development of a new efficient heuristic for generating a revised production plan after a disruption.
(iii) Extension of this heuristic to deal with multiple disruptions on a real-time basis. As any new disruptions may or may not affect the plans revised after previous ones, their scenarios may be considered dependent and independent, both of which the extended heuristic can handle.
(iv) Application of the developed methodology to a real-world case problem from a pharmaceutical company.

The remainder of the paper is organized as follows. The problem description and recovery strategy are presented in Section 2 and the model formulation in Section 3. The solution approaches, and experimentation and results analysis, are provided in Sections 4 and 5 respectively. A real-life case study is presented in Section 6 and, finally, conclusions are drawn and future research directions suggested in the last section.

2. Problem description and recovery strategy

We consider the ideal three-stage production system, as shown in Fig. 1. In it, stage 1 processes the raw materials as a batch and the production procedures in stages 2 and 3 are continuous. As the system requires different processing techniques, we recognize it as a mixed-production environment. In Fig. 1, X_0 is the batch size in the first stage and, as it is less than or equal to the capacity of the equipment, the processing time is independent of it and, therefore,