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Joint production and subcontracting planning of unreliable multi-facility multi-product production systems ☆

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A B S T R A C T

This article addresses the problem of joint optimization of production and subcontracting of unreliable production systems. The production system considered presents a common problem in the pharmaceutical industry. It is composed of multiple production facilities with different capacities, each of which is capable of producing two different classes of medications (brand name and generic). The resort to subcontracting is double: first, it involves the quantity of products received on a regular basis in order to compensate for insufficient production capacity in existing facilities, second, when needed, urgent orders are also launched in order to reduce the risk of shortages caused by breakdowns of manufacturing facilities. Failures, repairs and urgent delivery times may be represented by any probability distributions.

The objective is to propose a general control policy for the system under consideration, and to obtain, in the case of two facilities, optimal control parameters that minimize the total incurred cost for a specific level of the customer service provided. Given the complexity of the problem considered, an experimental optimization approach is chosen in order to determine the optimal control parameters. This approach includes experimental design, analysis of variance, response surface methodology and simulation modeling. It allows the accurate representation of the dynamic and stochastic behaviors of the production system and the assessment of optimal control parameters. Other control parameters which represent the subcontracting are introduced and three joint production/subcontracting control policies (general, urgent, regular) are compared to one another. The proposed joint production/regular subcontracting control policy involves a cost decrease of up to 20%, as compared to results obtained by Dror et al. [1], who used a simplified control policy in addition to a heuristic solution approach for a real case study. This policy offers not only cost savings, but is also easier to manage, as compared to that proposed by Dror et al. [1]. Numerical examples and a sensitivity analysis are also performed to illustrate the robustness of the proposed control policy and the solution approach.

1. Introduction

Manufacturing systems require continuous control and monitoring [2]. Their role has become essential thanks to an economic environment which is getting more and more competitive. In addition, manufacturing systems are getting more complex due to random fluctuations of production system components (demand, breakdowns, repairs, etc.). That is why the use of buffer stocks between workstations and at the end of the production cycle has proven to be an effective tool for protecting against random perturbations. These perturbations are often manifested through the stoppage of production activities. Despite its usefulness in maintaining customer satisfaction, having a high level of safety stocks has some disadvantages, such as increased operating and inventory costs. Low safety stock levels, however, increase the risk of shortage as well as customer dissatisfaction. The major dilemma then resides in determining the optimal level of buffer stocks to adopt which allows a reduction of the total incurred cost and ensures a high level of customer satisfaction.

The pharmaceutical field is characterized by increasingly fierce competition, a spectacular rise in the number of generic drugs and new discoveries in biotechnology. In response to these developments, pharmaceutical companies are continually seeking to improve the planning and control of the supply chain [3] as well as the efficiency of their production processes. They aim to thus minimize costs and successfully adapt their production activity to market needs. The U.S. Bureau of Labor Statistics (BLS) classifies

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pharmaceutical companies under three broad categories [4]: (1) producers of consumer products whose research and development activities are primarily focused on the development of new formulas, (2) producers of generic drugs who specialize in preparations derived from branded drugs that are no longer protected by patents, and finally, (3) designers of new molecules that produce two types of drugs (both brand name and generic), and which are usually engaged at all levels of the pharmaceutical chain of activities, namely, research and development, production and marketing. This work concerns this last category. Note that generic drugs are sold at lower prices, which explains the frequent use of subcontracting for such products, in order to reduce costs and increase production capacity. That is not the case with brand name drugs, for which patents have been issued. In this article, we are interested in the case of those pharmaceutical companies that not only produce both brand name and generic drugs, but must also resort to subcontracting in order to satisfy all customers and remain competitive. The goal is to find the production rate and the storage capacities required for each product type, as well as the subcontracting rate, which minimize the total incurred cost and maintain a specific customer service level. More specifically, it is about a problem of optimal control of production and subcontracting. In fact and according to Kaplan and Laing [5], it is a common problem in the pharmaceutical industry. Indeed, Booth [6] interprets the manufacturing priorities of pharmaceutical companies as the balance between the supply and the demand as well as the increase of the use of subcontracting in order to reduce costs incurred.

In the literature, several research studies have been undertaken to address the optimal control problem for different classes of manufacturing systems which are subject to random failures. Most of them have focused on manufacturing systems with states described by a Markov process. Olsder and Suri [7] exploited the formalism of Richel [8] and developed the dynamic programming equation of the optimal control policy for a manufacturing system operating in an uncertain environment according to the homogeneous Markov process. They focus on the production planning of a manufacturing system composed of a single machine that produces one part type and whose dynamics is described by the homogeneous Markov Chain (constant transition rates). The work of Kimemia and Gershwin [9] and Akella and Kumar [10] have shown that for such a system, the control policy known as the Hedging Point Policy (HPP) is optimal. The HPP policy consists of building an optimal safety stock (threshold) during periods of excess machine capacity. As a result, future failures of the system will be prevented, leading to greater customer satisfaction. Several authors have extended the HPP policy in order to consider practical aspects such as multi-state machines, random demand, preventive maintenance, quality problems, and simultaneous breakdown and quality failures [11–16].

For systems with several product types, Caramanis and Sharifnia [17] used the results of Sharifnia [11] and proposed a suboptimal production control policy based on the decomposition method transforming the complex multi-product control problem (M_1P_n) into several mono-product control problems (M_1P_1) that can be treated analytically. Sethi and Zhang [18] presented an explicit formulation of the optimal control problem of a production system which consists of a single machine capable of producing several part types with negligible setup times and costs. The same hypothesis was used by Gharbi and Kenné [19] when they studied the production control problem of a manufacturing system with multiple machines and multiple product types. Bai and Elhafsi [20] elaborated the optimality conditions described by Hamilton–Jacobi Bellman (HJB) equations for a manufacturing system involving an unreliable machine. The production machine is capable of producing two part types, with non-negligible setup times and costs. The authors then presented a suitable structure of the control policy, known as the Hedging Corridor Policy (HCP). Gharbi et al. [21] extended the results of Bai and Elhafsi [20] by proposing a near-optimal control policy called the Modified Hedging Corridor Policy (MHCP).

Insufficient production capacity with respect to customer demand forced some industrial companies from different fields (pharmaceutical, automobile, aeronautics, etc.) to seek other alternatives, including subcontracting or the acquisition of new manufacturing machinery, which are used to increase production capacity and to satisfy all customers in terms of quantity and time. Dellagi et al. [22] considered a production system composed of a single machine producing one product type to satisfy a constant demand. This system calls upon a second machine (the subcontractor) to ensure the satisfaction of the demand. In the same context, Ayed et al. [23] used subcontracting as an independent production system in order to meet a random demand. Gharbi et al. [24] studied a manufacturing cell capable of producing one product type. Its total capacity changes depending on whether or not a reserve machine (stand-by) is used; a machine with a higher production cost. The proposed control policy is called the State Dependent Hedging Point Policy (SDHPP), and is characterized by two thresholds.

Recently, Dror et al. [1] studied a common case in the pharmaceutical industry. Here, a complex production system (M_2P_2) consisting of two facilities prone to random breakdowns and repairs is examined. These facilities have different capacities and are able to produce two medication types. The brand name medication must be produced internally, while the generic medication can be produced internally or supplied by subcontractors. The brand name and the generic medications are composed of the same main chemical substances. However, the branded medication contains special chemical additives that improve its performance characteristics. The subcontracting is intended to compensate for the lack of production capacity with respect to customer demand, and to deal with failure occurrences. The subcontracting involves an amount of drugs received on a regular basis, as well as other urgent orders which are initiated, when needed, in order to reduce the risk of shortages due to possible random breakdowns. The urgent subcontracting depends on a non-negligible and random delivery time.

Based on the HPP policy, Dror et al. [1] proposed a control policy that contributes to minimizing safety stocks and storage requirements for the two medication classes in order to reach a customer service level greater than or equal to 99.5%. The authors used several restrictions and assumptions which affect the quality of the results. They proposed a heuristic approach which ignores the dynamic aspects of the production system, the random delivery times and breakdowns, and above all, it also ignores production, subcontracting, inventory carrying and shortage costs. However, the majority of the works in the scientific literature covering production systems indicate that it is important to take into consideration the incurred cost as the main decision criterion in tackling the concerns of the company's decision makers.

Our objective is to propose a better joint production/subcontracting control policy and an efficient solution approach to this complex problem for a manufacturing system composed of multiple production facilities and producing two product types (M_iP_2, $i \in \{1,\ldots,m\}$). This will be achieved by simultaneously considering costs and customer satisfaction as two decision criteria in order to deal with the concerns of decision makers. We also explain the relationship between the customer service level, the total incurred cost and the control parameters of the production system. It is important to note that no other researchers, except Dror et al. [1], have addressed the control problem presented in this work. The proposed experimental solution approach combines statistical