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Technical Paper

Optimal production scheduling for hybrid manufacturing–remanufacturing systems with setups

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ABSTRACT

Hybrid systems that use both raw materials (manufacturing mode) and returned products (remanufacturing mode) in their production process are considered. The system consists of one facility and necessitates setup for switching from one production mode to another. Since the flow rate of returned products is limited (fixed percentage of the demand rate is considered), switching from one mode to another is unavoidable, and so production and setup scheduling becomes critical for meeting customer demand and manufacturing cost optimization. Analytical solutions for production and setup strategies are obtained, feasibility conditions are derived, and the sensitivity of obtained results over system parameters is investigated. It is demonstrated that there exist two types of systems: *mainly manufacturing systems* with a relatively low rate of return, and *mainly remanufacturing systems* with a relatively low use of raw materials. Quantitative criteria distinguishing these two types of systems are developed, and it is shown that systems of different types obey different feasibility conditions and exhibit different optimal behavior.

1. Introduction

The integration of reverse logistics into the production environment has been attracting increasing interest among the researchers over the last two decades. In [1], the authors identified specific activities (such as distribution planning, inventory management and production planning) inherent to remanufacturing and recycling, and proposed quantitative approaches to problems that may arise. A state of the art survey focused on the production planning and control methods for remanufacturing systems developed in the nineties was presented in [2]. Several industrial case studies in reverse logistics and remanufacturing were described and compared in the survey [3]. Optimization models for supply chains with returned products recovery systems have been studied extensively with particular attention paid to production planning and inventory management. In most works covering reverse logistics, the production environment is modeled using discrete time. For example, in [4], the authors extended the results of [5] and presented an effective approach to determine the optimal control policy (in discrete time) for a recovery system. In their model, the recovered product can be remanufactured, disposed of, or held in stock for later use. Also less frequently used, a continuous time model can be found in [6], where optimization is performed in a deterministic dynamic environment, taking into account production, remanufacturing and disposal; customer demand is known and the return of recovered products is a percentage of this demand. Recently, [7] and [8] proposed a stochastic optimization model (in discrete time) to address various uncertainties that arise in hybrid manufacturing–remanufacturing systems, and [9] developed a stochastic dynamic control model (in continuous time) to optimize the global performances of the closed-loop manufacturing system that consists of two machines working in manufacturing and remanufacturing modes, respectively. Production planning problems specific for steel industrial enterprises employing closed-loop supply chains with both manufacturing and remanufacturing "branches", were addressed in [10].

Various important factors respecting reverse logistics, and the coordination of manufacturing and remanufacturing in particular, are addressed in the recent book by [11]. The coordination of different operations is considered in [12] as an essential part of efficient decision making in hybrid manufacturing–remanufacturing systems. While using the same facility for both manufacturing and remanufacturing may seem attractive as it enhances system flexibility, it may nevertheless increase the coordination complexity. An example of a concrete industrial system that uses the same production line for both manufacturing and remanufacturing operations

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is described in [13]. A case study was performed, with a company producing car parts, and an analysis was carried out specifically for a water pump production line by extending the economic lot scheduling technique to the case of return. In the scheduling policy implemented in the case study company, the setup times and costs were not considered, and the authors proposed an optimal solution which accounts for both setup times costs, and uses a mixed integer-linear programming technique. In a recent paper by Flapper et al. [14], the optimal scheduling problem for hybrid manufacturing remanufacturing systems is considered, using a stochastic steady state approach: random exponential lead time, demand and return. The production schedule that minimizes the average discounted long-term cost was determined, but no system dynamics or setup times and costs were taken into account. Classical results on son optimal scheduling for a single machine can be found in [15]. Multi-objective optimization of supply chains with returned products and related decision making problems are addressed in [16] and [17]. This brief overview shows that systems switching from manufacturing to remanufacturing mode and undergoing setups have rarely been considered in the literature, and none of those considered (to the best of our knowledge) has taken the production dynamics into account.

Manufacturing systems which can be viewed as machines operating in two possible production modes, namely manufacturing (1) and remanufacturing (2), are studied. In both modes, the system produces the same product, and the production is therefore driven by the same demand. However, the production source is different in two modes, namely: in mode 1 (manufacturing), a raw material is used, but in mode 2 (remanufacturing), the products returned from the market at the end of their life are used instead. The return level is assumed to be proportional to the demand level. Manufacturing/remanufacturing systems that consist of two machines respectively devoted to manufacturing and remanufacturing have recently gained substantial interest due to their importance for industry in the context of environmental constraints and green manufacturing (see[9] citeGupta and references therein). In this paper, we consider the situation when both production modes reside on the same facility (machine), but are separated in time, and develop an optimal scheduling policy for such systems. In this sense our paper is in line with [13] and [14].

Manufacturing systems consisting of a machine producing two part types and necessitating setup for switching between these two production modes received substantial attention from the research community in the 90s ([18,19]), and several related studies have been completed since then. Both setup cost and time were usually taken into account ([20,21]), although some interesting results were obtained when one of these factors was omitted [22].

Systems with setups often exhibit periodic behaviors with the typical production cycle (production run) consisting of the following phases: manufacturing for product 1, setup for product 2, manufacturing for product 2, and setup for product 1; this pattern is then repeated continuously. The conditions for switching between producing two products are often called *corridor policies* since they are defined with the barriers delimiting the area (corridor) in the product inventory space. Within the corridor, the maximum production rate is usually considered [19,23]. We show that for the system under consideration, it is sometimes advantageous to use the production rate below its upper limit, that is, to produce at the demand rate during a certain period of time while the system is in the main production mode. We first explore the simplest situation, where only the instantaneous setup cost is taken into account, the setup time is neglected, and the production process is deterministic (no machine failures are considered). We compute the cyclic production run and show that there are two possible structures of cyclic behaviors, corresponding to two alternative classes of systems: *mainly manufacturing systems* (MMS), with the remanufacturing mode playing an auxiliary role, and *mainly remanufacturing systems* (MRS), with the manufacturing mode playing an auxiliary role. We develop the feasibility conditions for each class of systems and express them as an upper bound (lower) on the return level for MMS (MRS) respectively. The production run contains an on-demand production period in manufacturing (remanufacturing) mode for MMS (MRS), respectively. Finally, we generalize the results obtained, taking into account the setup times, and also analyze the behavior of the system in the vicinity of the limit cycle in order to understand how the system converges to the limit cycle from the states that do not belong to it due to initial settings or as a result of a perturbation.

2. Problem formulation

We consider a hybrid manufacturing/remanufacturing system consisting of one machine capable of working in two modes: manufacturing mode (1) and remanufacturing mode (2). A comprehensive analysis of manufacturing/remanufacturing systems was presented in [9], where the model of the system similar to a model used below was proposed.

Let x_1 be the serviceable inventory, x_2 – the return inventory, u_1 and U_1 – the production rate and maximal production rate in manufacturing mode, u_2 and U_2 – the production rate and maximal production rate in remanufacturing mode, D – the customer demand rate, i – the production mode index ($i = 1$ for manufacturing and $i = 2$ for remanufacturing), T_{ij} and S_{ij} – are respectively the setup time and setup cost while switching from mode i to mode $j (i \neq j)$. The schematic of the system is shown in Fig. 1.

The evolution of the system can be described by the following equations:

$$\begin{aligned} \dot{x}_1(t) &= u_1(t) + u_2(t) - D \\ \dot{x}_2(t) &= -u_2(t) + \alpha D \end{aligned} \tag{1}$$

The production rates satisfy the constraints $0 \leq u_i(t) \leq U_i \sigma_{ii}(t)$, where $\sigma(t) = (\sigma_{ij}(t))$ is the setup indicator function defined below

$$\begin{aligned} \sigma_{11} &= \begin{cases} 1 & \text{the system is in manufacturing mode 1} \\ 0 & \text{otherwise} \end{cases} \\ \sigma_{12} &= \begin{cases} 1 & \text{the system is being setup from mode 1 to mode 2} \\ 0 & \text{otherwise} \end{cases} \\ \sigma_{21} &= \begin{cases} 1 & \text{the system is being setup from mode 2 to mode 1} \\ 0 & \text{otherwise} \end{cases} \\ \sigma_{22} &= \begin{cases} 1 & \text{the system is in remanufacturing mode 2} \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{2}$$

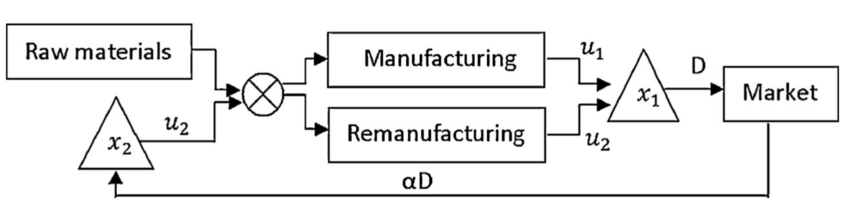

Fig. 1. System structure.