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Production Policy Optimization in Flexible Manufacturing-Remanufacturing Systems

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Abstract: Hybrid systems that use in their production process both raw materials (manufacturing mode), and returned products (remanufacturing mode) are considered. The system is supposed to be fully flexible and able to share its production time between manufacturing and remanufacturing. The system performance is evaluated using a piecewise linear function of serviceable and return inventories. Limited flow rate of returned products results in the state constraint on the return inventory and imposes additional limitations on the system feasibility. Such systems, to the best of the authors knowledge, were not previously considered in the literature. After characterizing manufacturing-remanufacturing strategies analytically, we propose some heuristics that approximate optimal policies in case of systems without failures, and then extend them to the case of failure-prone systems. We present the numerical study based on the solution of Hamilton-Jacobi-Bellman equations, that complements analytical results and allows to validate the proposed sub-optimal policies.

Keywords: Manufacturing, remanufacturing, feasibility, failures, optimal policy.

1. INTRODUCTION

The integration of reverse logistics into the production environment is gaining an increasing interest of the research community over the last decades. Specific activities inherent to remanufacturing (distribution planning, inventory management, production planning, etc.) were identified Fleishman et al. (1997), and quantitative approaches to arising problems were first outlined. Optimization models for the systems with returned products recovery have been studied extensively in Kiesmuller and Scherer (2003) with particular attention paid to production planning and inventory management. Recently, Kenne et al. (2012) developed a stochastic dynamic control model in continuous time to optimize the global performance of the closed-loop manufacturing system that consists of two machines working in manufacturing and remanufacturing modes, respectively.

Various issues relevant to reverse logistics, and the coordination of manufacturing and remanufacturing in particular, are addressed in the recent book by Gupta (2014). 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 can be found in Tang and Teunter (2006). A case study was performed, with a company producing car parts, and specifically, a water pump production line was analyzed by extending the economic lot scheduling technique to the case of return. Authors proposed an optimal solution based on a mixed integer-linear programming technique. In a recent paper by Flapper et al. (2014), the optimal scheduling for hybrid manufacturing remanufacturing systems is considered. The production schedule that minimizes the average discounted long-term cost was determined using a stochastic steady-state approach without taking into account the system dynamics. Dynamics and optimal control of the hybrid systems with setups was considered in Polotski et al. (2015).

We study in this paper the systems that are fully flexible (no setup needed for switching from one mode to another), but have an upper bound on their integrated (manufacturing plus remanufacturing) production capacity. We essentially follow the line of analysis proposed in Srivatsan and Dallery (1998) and Presman et al. (1998) for a flexible machine producing (simultaneously) two part types. In our case, however, the flexibility of the machine serves to combine two production processes instead of two parts produced. Such hybrid systems with the explicit upper bound on the production capacity have been rarely considered in the literature, and none of those considered has taken the production dynamics into account.

After formulating the problem in section 2, we explore in section 3 the simplest situation, when the production process is deterministic (no machine failures are considered). We classify the systems according to the parameter combination related to the system feasibility. In section 4 we consider the failure-prone systems and develop the optimality conditions in the form of Hamilton-Jacobi-Bellman (HJB) equations. Next, we propose some heuristics for a

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particular case of rare failures, generalize them to failure-prone case and study this general case numerically. Our analysis is focused on the systems with following characteristics: relatively low return rate, manufacturing capacity exceeds the demand, backlog is (much) more expensive than inventory, holding cost of return inventory exceeds the serviceable inventory cost. Some results for the systems with different characteristics are briefly presented in section 5, followed by conclusions.

2. PROBLEM FORMULATION

We consider a hybrid manufacturing/remanufacturing system that consists of one flexible machine capable of working (simultaneously) in two modes: manufacturing mode (1) and remanufacturing mode (2). In mode (1) the production uses raw materials that are supposed to be unlimited, while in mode (2) the production source is the limited return inventory. The machine is subject to (random) failures followed by (random) repairs. The times between failures and the repair times are exponentially distributed with rates p and r respectively.

The state of the system consists of discrete and continuous components: discrete state is described with the binary random variable ξ: $\xi = 1$ when the machine is operational and $\xi = 0$, when it is under repair; continuous state is described with the two-dimensional vector $(x_1,\ x_2)$ where x_1 is the serviceable inventory, x_2 is the return inventory. The decision variables are: the production rate in manufacturing mode u_1 and the production rate in remanufacturing mode u_2. We further introduce μ_1 (respectively μ_2) - the maximal production rate in manufacturing (respectively remanufacturing) mode in case of full dedication to manufacturing (respectively remanufacturing), D - the customer demand rate, R - the return rate.

The schematic of the system is shown in Fig. 1. State transitions can be conventionally described by a state transition matrix G:

$$G = \begin{pmatrix} -p & r \\ p & -r \end{pmatrix} \tag{1}$$

The system temporal evolutions can be described by the following equations:

$$\begin{aligned} \dot{x}_1(t) &= u_1(t) + u_2(t) - D \\ \dot{x}_2(t) &= R - u_2(t) \\ x_2(t) &\geq 0 \end{aligned} \tag{2}$$

The last inequality asserts that the system evolves in the half-plane $x_2 \geq 0$, because the return inventory can not be negative.

Production capacity satisfies the following constraint imposed on the production rates:

$$\frac{u_1}{\mu_1} + \frac{u_2}{\mu_2} \leq \xi \tag{3}$$

Also, the state constraint $x_2 \geq 0$ implicitly imposes additional limitations on the production capacity: near $x_2 = 0$, we must have $u_2 \leq R$. Alternatively, the return inventory gets negative, which is meaningless. For $\xi = 0$ expression (3) leads to $u_1 = u_2 = 0$, saying that there is no production when the machine is down. For $\xi = 1$ expression (3) defines the triangle in (x_1, x_2) plane shown as shaded area in Fig. 2. We call this triangle the *capacity domain.*

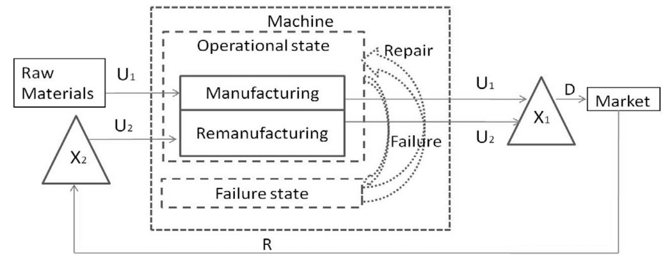

Fig. 1. System structure

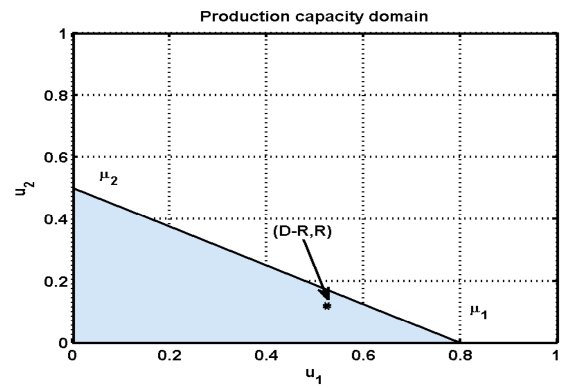

Fig. 2. Production capacity domain

We define the instantaneous cost $h(\cdot)$, containing production, inventory and backlog components:

$$h(x(t)) = c_1^+ x_1^+ + c_1^- x_1^- + c_2 x_2,$$

where c_1^-, c_1^+, c_2 are unit costs for backlog, serviceable inventory and return inventory respectively; $x^+ = \max(0, x)$, $x^- = \max(0, -x)$.

The production optimization problem is to chose the production rates that minimize the long average cost. This objective can be expressed as follows:

$$\min_{u_1, u_2} (\limsup_{T \to \infty} \frac{1}{T} E \int_0^T h(x(t)) dt\ ) \tag{4}$$

were averaging (E) is performed over all random failure/repair sequences.

For the numerical analysis we will consider another objective function

$$\min_{u_1, u_2} (E \int_0^\infty e^{-\rho t} h(x(t)) dt\ ) \tag{5}$$

This function represents the discounted cost over infinite horizon and is known to give a smooth approximation to (3) when ρ is small enough (Presman et al. (2002)). Also, the powerful computational methods exist for its minimization Kusner and Dupuis (1992).

At this stage we would like to formulate the following assumptions:
1. The production policy $u_1 = D - R$, $u_2 = R$ belongs to the capacity domain (as shown in Fig. 2).

The rationale behind this assumption is that it must be possible to maintain both return and serviceable inventories at the constant levels (under such policy equations (1) become $\dot{x}_1 = 0$, $\dot{x}_2 = 0$). Also, this policy corresponds to the very natural regime of remanufacturing *on-return* rate and manufacturing with the rate that results in overall