Optimal production planning of hybrid manufacturing/remanufacturing systems under deteriorations

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Abstract
The system studied consists of two parallel factories subject to production rate-dependent failure rates. The factories are subject to random non-operational periods considered herein as governed by a failure/repair process, and respond to a single product type demand. The main objective here is to propose production policies that will minimize the total cost (inventory and backlog costs), over an infinite planning horizon. The failure rate of the first factory depends on its production rate, while that of the second factory is constant. The proposed model is based on a non-homogeneous Markov decision process, and the stochastic dynamic programming approach is used to obtain optimality conditions.

Keywords
Manufacturing, Remanufacturing, Optimal Control, Stochastic processes, Dynamic programming, Numerical methods.

1. Introduction
Due to the constant search for increased productivity and a better service to clients, the number of scientific publications in the field of deteriorating manufacturing systems has been growing steadily. For example, Hu and Xiang (1995); Dehayem et al. (2011) and Kazaz and Sloan (2013) studied semi-Markov processes, where the assumption is that the system deteriorates with age or number of failures. While this is a reasonable assumption, which in some cases provides simple and appealing mathematical solutions, the authors did not address the question of what happens if the machine is used to its maximum production capacity for a long period. The problem becomes more realistic if the failure rate depends on the production rate. The most important accomplishments of the research of Hu et al. (1994) was the investigation of the necessary and sufficient conditions for the optimality of the hedging point policy for a single machine, single part-type problem, when the failure rate of the machine is a function of the production rate. They showed that hedging point policies are only optimal under linear failure rate functions. Based on their discussion, numerical results in the general case suggest that as the inventory approaches a hedging level, it may be beneficial to decrease productivity in order to realize gains in system reliability. This conjecture was confirmed by the numerical results reported in Martinelli (2007; 2010), and Nourelfath and Yalaoui (2012). Kouedeu et al. (2014) extended these preceding works to manufacturing systems consisting of two machines subject to a non-homogeneous Markov failure/repair process with production rate-dependent failure rates. The authors showed that the hedging point policies are optimal within a four-threshold feedback policy, and that the reliability of the machines is also enhanced. They also studied the case of manufacturing systems involving multiple failure rates. However, their results were limited to manufacturing systems with a constant demand rate and exponential failures and repair time distributions. From a practical point of view, random demand and a non-Markovian process are more suited to model manufacturing systems. In this case, the analytical models combined with simulation can be used to determine the effects of the factors considered on the incurred cost and to obtain a near-optimal control policy. For the application of such a method to a homogeneous non-Markovian process, we refer our readers to Dhouib et al. (2010), Gharbi et al. (2011), Rivera-Gomez et al. (2013), and Bouslah et al. (2014).

Generally, remanufacturing has been used within the sole domain of the automotive and aeronautical sectors, with Rolls-Royce, MTU (Motoren- und Turbinen-Union) aero Engines, General Electric, Caterpillar and Cummins Engine being but a few prominent examples of remanufacturers (Jian et al. (2010)). For example, Hashemi (2014) studied an integrated system of manufacturing and remanufacturing using a capacitated facility in the aerospace industry, where products are returned after certain flight hours or cycles for overhaul. The authors developed a mixed integer linear programming model developed to maximize profit considering manufacturing, remanufacturing set-up, refurbishing, and inventory carrying costs. In recent decades, however, remanufacturing has spread to other sectors as in Sundin et al. (2012) where the authors explored how manufacturers can develop automatic end-of-life (EoL) processes facilitated by product design methods, e.g., design for disassembly, recycling and remanufacturing. They illustrated such a product and EoL process development while maintaining economic and environmental values, with a focus on toner cartridges and liquid crystal displays (LCDs).

This paper investigates a deteriorating hybrid manufacturing/remanufacturing system consisting of two parallel factories (manufacturing factory and remanufacturing factory) subject to production rate-dependent failure rates (non-homogeneous Markov process). The stochastic nature of the system is attributable to factories that are subject to random non-operational periods considered herein as governed by a failure/repair process. The factories produce one type of product, namely, laser printer cartridges. The objective is to find the production rates of the different factories so as to minimize a long-term average expected cost, including inventory and backlog costs. To solve the optimization problem, we propose a stochastic programming formulation of the problem and obtain the optimal production policies numerically. Control policy parameters are obtained by combining analytical modelling, simulation experiments and response surface methodology. To the best of our knowledge, no other research has studied this problem governed by non-Markovian processes.

The remainder of this paper is organized as follows. After the industrial context is developed in Section 2, Section 3 presents the problem formulation. Section 4 deals with the optimality conditions and results analysis. The paper is concluded in Section 5.

2. Industrial context

The formulation and the approaches developed in this paper have been tested in the case of a printer cartridge company in France operating throughout Europe. Its activity is based on the combined manufacturing of new cartridges and the remanufacturing of used ones. For the sake of confidentiality, this company will be referred herein as the Manufacturing/Remanufacturing Company (MRC). Although, non-homogeneous Markov processes have been used in many operational management problems, their application to the printer cartridge industry is still quite rare. This work is intended to make a contribution in that regard.

MRC is the European leader in compatible consumables for inkjet, laser, fax and impact printing, offering remanufactured and new patent-compliant cartridges. It invests and innovates to offer new solutions that meet increasingly significant economic and ecological requirements. MRC is active in about 20 countries, has about 25 industrial and commercial sites, and a yearly turnover of more than €200 million. It is headquartered in France and employs close to 2000 people world-wide. It operates in several production facilities for new or remanufactured inkjet or laser cartridges in Eastern Europe and North Africa. We limit ourselves to the production chain, and so issues concerning administration, control, quality management, etc., are not addressed in this study.

For the considered control problem, the manufacturing and the remanufacturing factories produce the laser printer cartridges. At the end of their usage, products are collected for possible reuse. However, the manufacturing factory makes new products from raw materials, while the remanufacturing factory produces "like new" parts from used products returned from the market. It is interesting to note that the returned products come from the MRC's markets as well as from markets of competitors such as Armor, HP, Canon, Dell, Epson, Brother, Lexmark, Samsung, Sharp, Toshiba, Xerox, etc. Thus, we assume that the returns like raw materials are not starved. The factories are subject to random non-operational periods considered herein as governed by a failure/repair process. Finished parts (both manufactured and remanufactured) are stored in the serviceable inventory.

The manufacturing factory is the main factory characterized by a higher production rate. Its failure rate depends on its production rate. This means that when the manufacturing factory works at a faster rate, it is more likely to fail and be unavailable. In that case, we cannot use it to its maximum production rate all the time. Thus, we introduce another production rate called the economical production rate. The failure rate of remanufacturing factory and the repair rates of both factories are assumed constant. The maximum production rates of the factories and the economical production rate are known. The demand process for the finished products process is deterministic. Backorders of unsatisfied demands are permitted.

3. Problem formulation

The manufacturing/remanufacturing system illustrated in Figure 1 consists of two parallel factories denoted as M_1 (manufacturing factory) and M_2 (remanufacturing factory) capable of producing one product type. These factories are subject to random failures and repairs that can generate stock-outs. M_1 is called the main factory given that its production rate is higher than that of M_2. When M_1 works at a faster rate, it is more likely to fail. The system availability can be described at each time t by a stochastic process $\xi_i(t),\ i=1,2$ taking values in $B_i=\{1,2\}$ with $\xi_i(t)=1$, if the factory is operational at time t, and $\xi_i(t)=2$, otherwise. The system dynamics can be described by the stochastic process $\xi(t)\in B=\{1,2,3,4\}$. The transition probabilities are given by:

$$\mathrm{P}\left[\xi(t+\delta t)=\beta \mid \xi(t)=\alpha\right]=\begin{cases}\lambda_{\alpha\beta}(.)\delta t+o(\delta t) & if\ \alpha\neq\beta\\ 1+\lambda_{\alpha\beta}(.)\delta t+o(\delta t) & if\ \alpha=\beta\end{cases} \quad (1)$$

where $\lambda_{\alpha\beta}$ is the transition rate from mode α to mode β. $\lambda_{\alpha\beta}\geq 0$ and $\lambda_{\alpha\alpha}=-\sum_{\beta\neq\alpha}\lambda_{\beta\alpha}$ with $\alpha,\beta\in\{1,2,3,4\}$.

$$\lim_{\delta t}\frac{o(\delta t)}{\delta t}=0$$

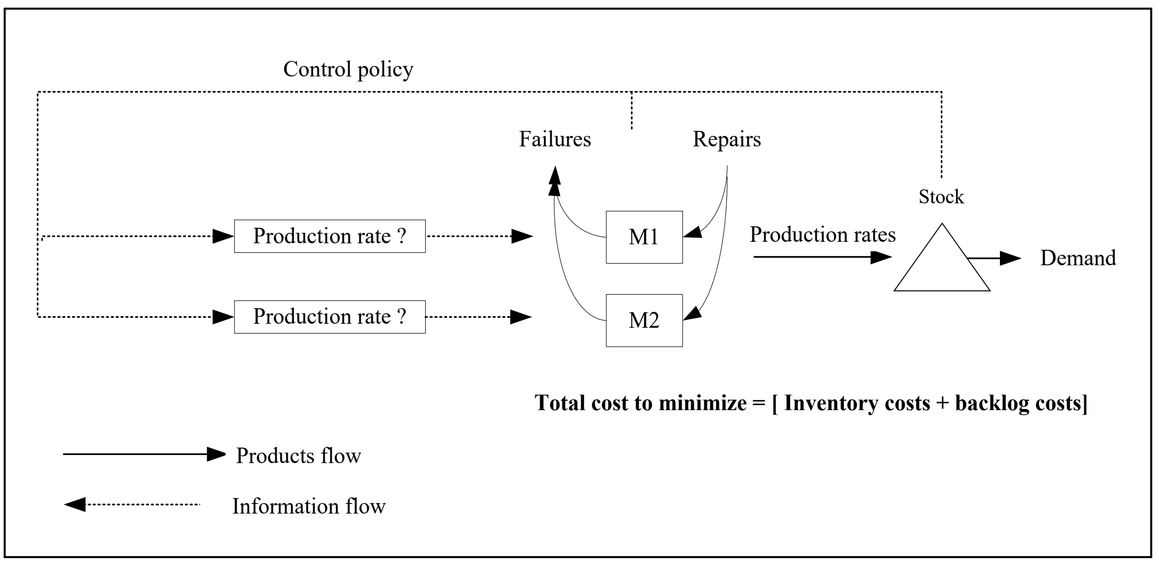

Figure 1. Manufacturing system considered

For failures/repairs processes described by exponential time distributions and a constant demand rate, the process is modeled by a continuous time Markov chain with a transition rate matrix given by $Q=\lambda_{\alpha\beta}$. It is a 4×4 irreducible stochastic matrix.

Let $u_1(t)$ and $u_2(t)$ denote the production rates of M_1 and M_2, respectively. The production rates are nonnegative. The stock of Figure 1 is the inventory of finished products (serviceable inventory), and it is defined by the variable $x(t)$. Thus, the continuous system dynamics evolves according to the following differential equation:

$$\frac{dx(t)}{dt}=u_1(t)+u_2(t)-d,\quad x(0)=x_0 \quad (2)$$

where x_0 and d are the given initial stock level and demand rate, respectively.

The set of the feasible control policies A, including $u_1(\cdot)$ and $u_2(\cdot)$, is given by:

$$\mathrm{A} = \left\{ \left(u_1(\cdot), u_2(\cdot) \right) \in \Re^2, 0 \le u_1(\cdot) \le u_{1\max}, 0 \le u_2(\cdot) \le u_{2\max} \right\} \quad (3)$$

where $u_1(\cdot)$ and $u_2(\cdot)$ are known as control variables, and constitute the control policies of the problem under study. The maximal productivities of the main factory and the second factory are denoted by $u_{1\max}$ and $u_{2\max}$, respectively.

Let $g(x)$ be the cost rate defined as follows:

$$g(x) = c^+ x^+ + c^- x^- \quad (4)$$

where constants c^+ and c^- ($ per product per unit of time) are used to penalize inventory and backlog, respectively. $x^+ = \max(0, x)$ and $x^- = \max(-x, 0)$. The problem objective lies in determining the optimal control policy so as to minimize the expected discounted cost given by:

$$J(\alpha, x, u_1, u_2) = E\left\{ \int_0^\infty e^{-\rho t} g(\alpha, x) dt \,\middle|\, x(0) = x_0, \xi(0) = \alpha \right\} \quad (5)$$

where ρ is the discount rate and E is the mathematical expectation. The value function $v(\cdot)$ of such a problem is given by:

$$v(\alpha, x) = \inf_{(u_1(\cdot), u_2(\cdot)) \in \mathrm{A}(\alpha)} J(\alpha, x, u_1, u_2), \ \forall \alpha \in B \quad (6)$$

where A is the set of the feasible control policies given by:

$$\mathrm{A} = \left\{ \left(u_1(\cdot), u_2(\cdot) \right) \in \Re^2, 0 \le u_1(\cdot) \le u_{1\max}, 0 \le u_2(\cdot) \le u_{2\max} \right\}.$$

4. Optimality conditions and results analysis

Assuming that $v(\alpha, x)$ is differentiable, the optimality conditions are described by:

$$\rho v(\alpha, x) = \min_{(u_1, u_2) \in \mathrm{A}(\alpha)} \left[g(\alpha, x) + \sum_{\beta \in B} \lambda_{\alpha\beta} v(\beta, x) + (u_1 + u_2 - d) \frac{\partial v(\alpha, x)}{\partial x} \right] \quad (7)$$

The expression of equation (7) is commonly called a Hamilton-Jacobi-Bellman (HJB) equation. Further details about how HJB equations are obtained can be consulted in Gershwin (2002).

The objective of this paper is not to solve equation (7) analytically, but rather, to experimentally determine the optimal parameters of the hedging point policy, which give the best approximation of the value function $v(\alpha, x)$.

c^+	c^-	h	U	u_{1max}	u_{2max}	d	$MTBF_1$	$MTBF_2$	$MTBF_3$	$MTTR_1$	$MTTR_2$	ρ
4	100	0.025	0.27	0.30	0.26	0.28	80	100	60	1	1	0.09

Table 1. Numerical data of the considered system

For the date presented in table and for infinite supply of returns, the production rates of the manufacturing/remanufacturing system are illustrated in Figures 2, 3 and 4.

The results of Figures. 2 and 3 show that the optimal production control policy of M_1 consists of one of the following three rules:

Set the production rate of M_1 to its maximal value when the current stock level is under the first threshold value z_1 (both factories are operational) or z_3 (only M_1 is operational);

Reduce the production rate of M_1 to its economic value (U) when the current stock level approaches the second threshold value z_2 (Figure. 2) or z_4 (Figure. 3);

Set the production rate of M_1 to zero when the current stock level is greater than the second threshold value.

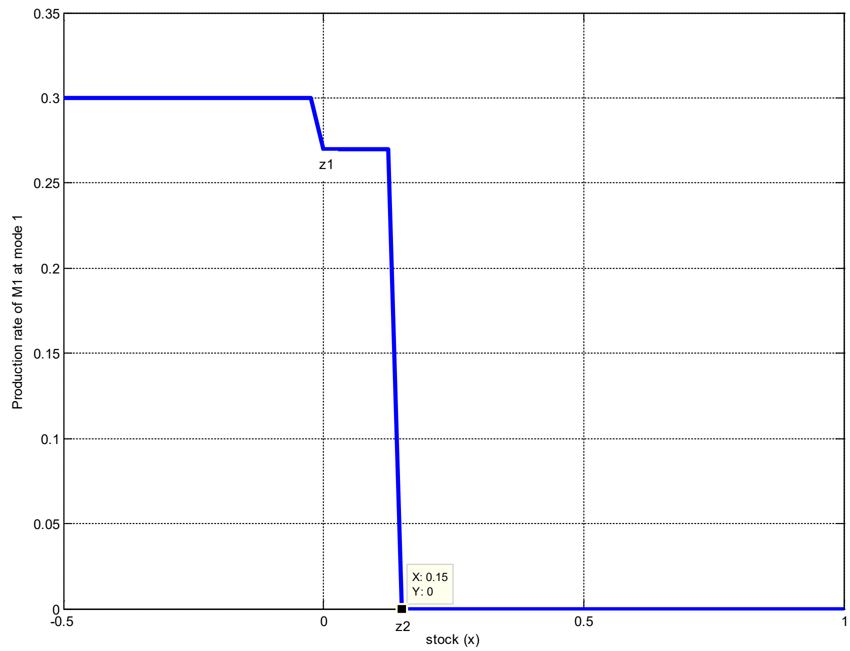

Figure 2. Production rate of M_1 when both factories are operational

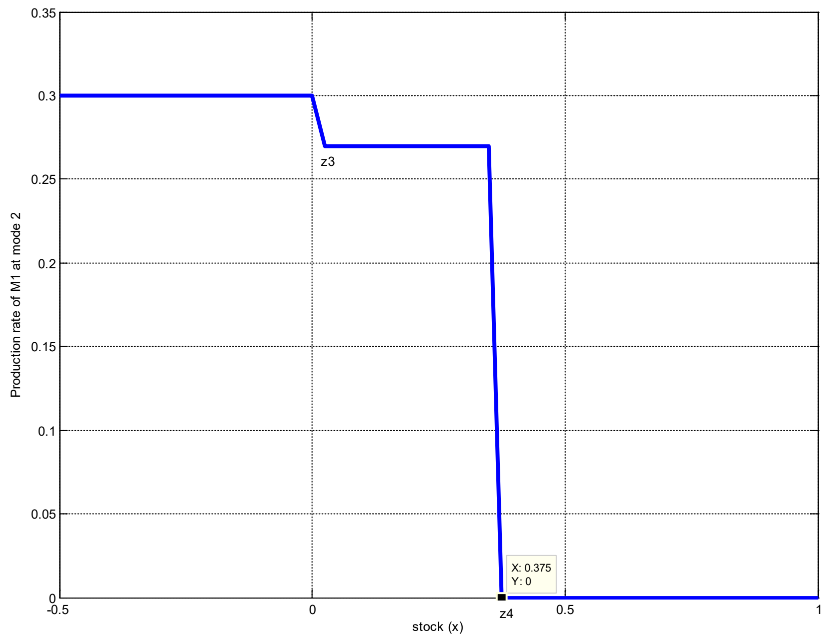

Figure 3. Production rate of M_1 when M_2 is non-operational

The optimal production control policy of M_2 (Figure. 4) consists of one of the two following rules:

(1) Set the production rate of M_2 to its maximal value when the current stock level is under the threshold value z_2;

Set the production rate of M_2 to zero when the current stock level is greater than the threshold value z_2.

This gives rise to the following control policies:

$$u_1(\cdot) = \begin{cases} u_{1\max} & \text{if } x < z_1 \\ U & \text{if } z_1 \le x < z_2 \\ 0 & \text{if } x > z_2 \end{cases} \quad \text{or} \quad u_1(\cdot) = \begin{cases} u_{1\max} & \text{if } x < z_3 \\ U & \text{if } z_3 \le x < z_4 \\ 0 & \text{if } x > z_4 \end{cases} \tag{8}$$

$$u_2(\cdot) = \begin{cases} u_{2\max} & \text{if } x < z_2 \\ 0 & \text{if } x > z_2 \end{cases} \tag{9}$$

The implementation of the control policies is illustrated in Figure. 5. This illustration shows the actions that should be taken by the manager when both factories are operational (mode 1), and when the second factory is non-operational (mode 2). At mode 3, M_1 is non-operational and M_2 cannot satisfy the customer demand alone. Both factories are under repair at mode 4.

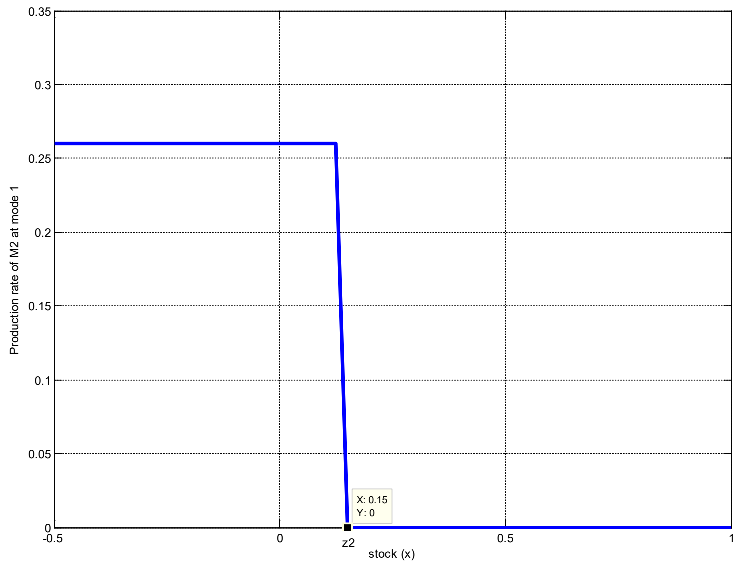

Figure 4. Production rate of M_2 when both factories are operational

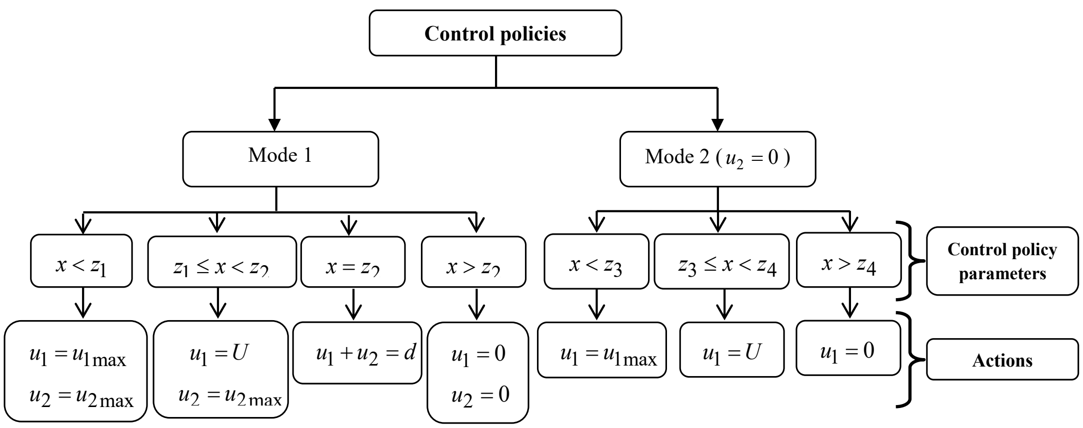

Figure 5. Model implementation diagram

5. Conclusion

In this paper, we showed that the hedging point policies of a non-homogeneous Markov failure/repair manufacturing/remanufacturing system (in which the failure rate of the factory depends on its production rate) are optimal among feedback policies, and that the reliability of the factories is enhanced. Applying stochastic optimal control theory, we have developed the optimality conditions described by Hamilton-Jacobi-Bellman (HJB) equations; that we solved numerically with Kushner's approach. The results showed that optimal policies depend on system degradation in a closed loop supply chain context. The model presented in this paper could be extended to the case of more complex systems (subject to random perturbations described by general distributions) using simulation and experimental design.

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