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A production–repair inventory model with time-varying demand and multiple setups

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ABSTRACT

In this paper, we proposed a model for an inventory system that satisfies a continuous time-varying demand for a finished product over a known and finite planning horizon by supplying both new and repaired items. New items are fabricated from a single type of raw material procured from external suppliers, while used items are collected from the customers and then repaired to a condition that is as-good-as-new. During each time interval, new items and used items are produced from multiple production and repair runs. The problem is to determine a joint policy for raw materials procurement, new items fabrication, and used items repair such that the total relevant cost of the model is minimized. We also proposed a numerical solution procedure and we tested the model with some numerical examples and a simple sensitivity analysis.

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1. Introduction

Globally, urbanization and competitive markets drive the rise in consumption of manufactured products, resulting in faster and faster depletion of natural resources and accumulation of solid waste. The composition of solid waste is more complex than before due to the diffusion of plastics and electronic consumer products. The environmental problems posed by these phenomena led governments around the world to legislate laws that require some manufacturers to recycle used items that have reached the end of their useful lives. Thus it is desirable for these manufacturers to adopt recycling policies that economize their operating costs.

In the literature of inventory management, the study of inventory models that incorporate recycling started with authors modifying the economic order quantity (EOQ) model by Harris (1913), as the simple mathematics of the EOQ model makes it an appropriate base. Schrady (1967) proposed an EOQ model with instantaneous order and repair rates. His model treated the serviceable and recoverable inventories as interdependent parts of a single system, and jointly determined the optimal order and repair quantities for $(1, R)$ policies – policies that alternate one order batch with R repair batches – using expressions whose derivations are similar to the classical EOQ formula. The work of Schrady (1967) was extended for the case of finite repair rate (Nahmias and Rivera, 1979), and for the case of multiple products (Mabini et al., 1992). Koh et al. (2002) also extended the work of Schrady (1967) for the case of finite repair rate, but they allowed the repair rate to be less than or equal to the demand rate, and they considered $(P, 1)$ policies – policies that alternate one repair batch with P production batches – as well. They found the optimal setup numbers using exhaustive search procedures. Later, Teunter (2004) generalized earlier works by considering the case of finite production rate, but he used a semi-heuristic procedure to ensure the discreteness of P and R. In follow-up works, Konstantaras and Papachristos (2008a) proposed exact solution procedures for the model by Koh et al. (2002), and Konstantaras and Papachristos (2008b) and Wee and Widyadana (2010) proposed exact solution procedures for the model by Teunter (2004).

The above works assumed that all returned items are recovered. Richter (1996a), Richter (1996b) studied an EOQ waste disposal model, in which some returned items are scrapped. He assumed instantaneous production and repair rates, and multiple production and repair setups during each cycle. Richter (1997) extended the cost analysis of his earlier works and obtained an extremal result: the pure strategy of total repair or the pure strategy of total disposal dominates any mixed strategy of repair and disposal. Richter and Dobos (1999) and Dobos and Richter (2000) extended the works of Richter (1996a), Richter (1996b), Richter (1997) by considering part of the problem as an integer programming problem to secure the discreteness of the setup numbers. In a similar work, Teunter (2001) examined an EOQ waste disposal model with different holding costs for recovered and manufactured items. Dobos and Richter (2003) relaxed the

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assumption of instantaneous production and repair rates by considering a finite rate waste disposal model with a single production cycle and a single repair cycle per time interval. Dobos and Richter (2004) generalized their earlier work by considering multiple production and repair cycles per time interval. The results of these works reiterated the dominance of pure strategies vis-a-vis mixed strategies. El Saadany and Jaber (2008) extended the works of Richter (1996a), Richter (1996b) by proposing a modified model that does not ignore the first time interval when no repairing occurs. Their unit time cost is lower than Richter′s, because Richter took unnecessary residual inventory into account, resulting in the holding costs being overestimated.

Dobos and Richter (2004) raised the question about the quality of returned items and the party to control this quality. This question was addressed when Dobos and Richter (2006) found that the decision to control the quality of returned items inhouse or to outsource it depends on whether the non-EOQ costs are taken into account or not. El Saadany and Jaber (2010) considered the case of a variable return rate that depends on the purchasing price and the quality level of the returned items, and they showed that pure strategies are no longer optimal against mixed strategies.

The above works assumed that recovered items are of a quality that is as-good-as-new. Jaber and El Saadany (2009) addressed this limitation by assuming that the demand for remanufactured items is different from the demand for newly manufactured ones, i.e., there is a quality difference between remanufactured items and new items. Konstantaras et al. (2010b) assumed that returned items are either refurbished, sold at a secondary market, and never collected again, or remanufactured to a condition that is as-good-as-new.

Most of the above works do not account for shortages, which can be economical in some situations. Konstantaras and Papachristos (2006) obtained an optimal production and recovery policy analytically for an EOQ model with complete backorders. Konstantaras and Skouri (2010a) obtained sufficient conditions for the optimal policy of a model with complete backorders and variable setup numbers. Hasanov et al. (2012) extended the work of Jaber and El Saadany (2009) for the case of pure and partial backordering.

Other authors who wrote relevant works include Choi et al. (2007), who extended the work of Koh et al. (2002) for the case of (P, R) policies with the sequence of P orders and R repairs itself as a decision variable; Jaber and Rosen (2008), who extended the works of Richter (1996a), Richter (1996b) by proposing entropy costs to address the difficulty of estimating the EOQ cost parameters; Jaber and El Saadany (2011), who considered learning effects; El Saadany and Jaber (2011), who considered the case of serviceable items being manufactured from a mixture of new or remanufactured subassemblies; and El Saadany et al. (2013), who extended the works of Richter (1997) and Teunter (2001) for the case of limited remanufacturability.

Besides stationary demand, some authors have studied reuse models with time-varying demand functions. Omar and Yeo (2009) proposed an integrated production–repair model that held three types of items in stock: used items, serviceable items, and raw materials. The producer serves a continuous time-varying demand over a finite planning horizon by producing new items from raw materials as well as by repairing used items. Each time interval is divided into production and repair periods, each with multiple setups. However, they assumed that used items are not collected during the repair period. They described a numerical solution procedure to find the interval times and setup numbers that minimize the total relevant cost. Alamri (2011) presented a global optimal solution to a general reverse logistics model with time-varying rates for demand, return, production, repair, and deterioration. They considered one remanufacturing setup and one production setup per time interval, over an infinite planning horizon.

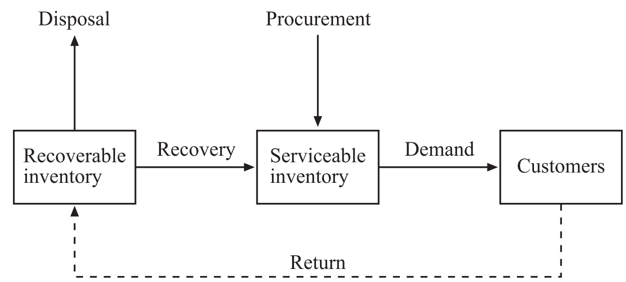

Fig. 1. Framework of material flow of the model in this paper.

In this paper, we extend the work of Omar and Yeo (2009) by relaxing the assumption that used items are not collected during the repair period. A general framework of the material flow through the relevant inventories is given in Fig. 1. The remainder of this paper is organized as follows. In Section 2, the mathematical formulation of the proposed model is developed; in Section 3, a numerical solution procedure is proposed; in Section 4, the model is tested with some numerical examples; in Section 5, a simple sensitivity analysis is performed; and finally, in Section 6, the paper is concluded.

2. Model formulation

In this paper, we make the following assumptions:

1. A single item inventory system that operates over a known and finite planning horizon of length H units of time.
2. The demand rate $D(t)$ is a deterministic and known function of time t, with $D(t) > 0$ for $0 \le t \le H$.
3. The production rate P and repair rate R are finite and constant, with $P > D(t)$ and $R > D(t)$ for $0 \le t \le H$.
4. The return rate $C(t)$ is linearly proportional to the demand rate, i.e. $C(t) = \theta D(t)$, with $0 < \theta < 1$.
5. All used items are repaired. Repaired items are as good as new.
6. Only one type of raw material is required to fabricate new items. After an order is placed, the raw materials are immediately replenished.
7. Each time interval has v $(v = 1, 2, \ldots)$ production runs and raw materials orders, and w $(w = 1, 2, \ldots)$ repair runs, with one raw materials order per production run.
8. Used items are not collected during the repair runs of the final time interval.
9. Shortages are not allowed during the planning horizon.
10. The following cost parameters are considered:

    (a) k_p, the setup cost of each production run (cost/setup).
    (b) k_r, the setup cost of each repair run (cost/setup).
    (c) k_m, the ordering cost of the raw materials (cost/order).
    (d) h_p, the inventory holding cost of the serviceable items (cost/unit/time).
    (e) h_r, the inventory holding cost of the used items (cost/unit/time).
    (f) h_m, the inventory holding cost of the raw materials (cost/unit/time).
    (g) s_p, the unit production cost of the new items (cost/unit).
    (h) s_r, the unit repair cost of the used items (cost/unit).

    Note that the unit production and repair costs may be omitted from the total inventory cost as the return portion is fixed, but

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