Int. J. Production Economics 143 (2013) 598–604

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

How many times to remanufacture?

Ahmed M.A. El Saadany [a], Mohamad Y. Jaber [a,*], Maurice Bonney [b]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Ont., Canada M5B 2K3
[b] Nottingham University Business School, University of Nottingham, Nottingham NG8 1BB, UK

ARTICLE INFO

Article history:
Received 9 September 2010
Accepted 13 November 2011
Available online 23 November 2011

Keywords:
Reverse logistics
Remanufacturing
Design for remanufacturing.

ABSTRACT

A common finding in inventory models for reverse logistics found in the literature, from the earliest to the most recent work, is that the inventory policy shifts between two extremes, i.e., 'dispose all' or 'recover all'. These models also share a common and unrealistic assumption that an item can be recovered indefinitely. Material degrades in the process of recycling losing some of its mass and quality making the option of 'multiple recovery' somewhat infeasible. This paper develops a model where an item is recovered a finite number of times. A mathematical expression is developed that estimates the number of recovery times, which is later incorporated into two prominent models from the literature to compare the behaviour of these models with different recovery assumptions. The results suggest that as the number of times an item is recovered increases, the percentage of available used units that are recoverable plateaus. The results also suggest that there is an optimal number of times to recover a product that balances the investment and remanufacturing costs. The study also found that as the percentage of used units collected increases, the significance of ignoring the finite remanufacturing case becomes more important.

1. Introduction

Protecting the environment has become a priority for most countries in recent years. Recycling material and remanufacturing used products are inevitable options to reduce waste generation and the exploitation of natural resources. Accordingly, the management of recycling, remanufacturing and production processes became an area of interest to both practitioners and academics and became known as reverse logistics (RL). Readers may refer to Pokharel and Mutha (2009) and Ilgin and Gupta (2010) for reviews.

Continual changes in customers' demand and the dynamics of the market quicken the flow of products along supply chains and results in waste being generated faster than many economies can handle and societies can tolerate. Managing waste to protect the environment is high on the agendas of many politicians, legislators and governments around the world. Reducing waste can be attained through product recovery, which takes one of the following forms: repair, refurbishing, remanufacturing, cannibalization and recycling (e.g., Thierry et al., 1995). Product recovery has substantial gains. A study of Xerox photocopiers confirmed that over the life cycle of a photocopier, remanufacturing can reduce waste generation up to one third (Kerr and Ryan, 2001).

Managing inventories for processes that involve the collection of used items, their recovery and the production of new items are as important as those of a forward chain (e.g., Fleischmann et al., 1997; Minner, 2001). The inventory models which tackle the product reverse flow are surveyed in the next section. They have two primary limitations. First, collected used items are recovered to as good a working condition as possible and/or acceptable quality (e.g., Teunter, 2001; Hedjar et al., 2005; Rubio and Corominas, 2008). Second, the number of times that an item can be recovered is indefinite. The first assumption was addressed in Jaber and El Saadany (2009). This paper addresses the second assumption, i.e., the question of how many times a firm can recover a given product. A mathematical expression is developed that estimates the finite number of times an item can be recovered. This expression is then incorporated into two prominent models (Richter, 1997; Teunter, 2001) that were selected from the literature. Then the results from these models are compared with those derived using the original assumption of recovering an item indefinitely. The remainder of this paper is organized as follows. The next section (Section 2) provides a literature review which supports the contribution of the paper. Section 3 develops the mathematical expression and the investment function associated with it. This is followed by Section 4 which incorporates the developed expression into the selected production and remanufacturing models. Section 5 provides numerical examples, and then discusses the results to shed some light on the behaviour of the model and to draw some managerial insights. The paper summarises and concludes the work in Section 6.

* Corresponding author.
E-mail addresses: mjaber@ryerson.ca, myjaber@gmail.com (M.Y. Jaber).

0925-5273/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpe.2011.11.017

2. Literature review

The earliest reported work in the literature is that of Schrady (1967) who developed a deterministic EOQ model for repaired items, with instantaneous manufacturing and recovery rates. He assumed an inventory system to consist of two stocks of serviceable and repairable items. Nahmias and Rivera (1979) considered the model of Schrady (1967) for the case of finite repair rate and limited storage in the repair and production shops. Mabini et al. (1992) extended the work of Nahmias and Rivera (1979) by considering a demand-dependent collection rate of used products (returns). Richter (1996a,b) investigated a modified version of the model of Schrady (1967) by assuming multiple production and multiple repair cycles within a time interval. In a later study, Richter (1997) showed that the models he investigated earlier are governed by two extreme (bang-bang) strategies; i.e., 'dispose all' or 'recover all'. In a similar work to Richter (1996a,b, 1997), Teunter (2001) examined a deterministic EOQ inventory model with disposal option where recoverable and manufactured items have different holding costs and obtained a general finding similar to Richter (1997).

In an advanced step, Dobos and Richter (2004) raised the question of how many used units should be collected by a system, and generalized the work of Richter (1997) to consider finite production and repair rates. The question that Dobos and Richter (2004) raised about the behaviour of the inventory policy was addressed in El Saadany and Jaber (2010) who considered the collection (return) rate of used items to be dependent on the quality and the corresponding price of these items. Their results showed that a mixed (production+remanufacturing) strategy, rather than a bang-bang strategy, is optimal.

The usual description of a production–remanufacturing system in the literature considers the situation where demand is satisfied from the serviceable stock, which represents the inventory of produced and remanufactured items. Returns (used items) are collected in the repairable stock at a rate, which is a percentage of the demand. A portion of returns is fed back into the system to be remanufactured, while the system disposes the rest. The recovery rate is assumed to be constant over time as it is a percentage of the constant demand rate, and those items that meet the remanufactuarability requirements are assumed to be recovered for an indefinite number of times (e.g., Schrady, 1967; Nahmias and Rivera, 1979; Cohen et al., 1980; Mabini et al., 1992; Richter, 1996, a,b; Richter, 1997; Dobos and Richter, 2004, 2006; Teunter, 2001, 2002, 2004; Minner, 2001; Minner and Lindner, 2004; Kleber, 2006; El Saadany and Jaber, 2008, 2010, 2011; Jaber and El Saadany, 2009, 2011; Jaber and Rosen, 2008).

Many researchers acknowledge that a product cannot be remanufactured or repaired an indefinite number of times (Ferrer, 1997). Newell and Field (1998) accounted for the material degradation in recycling processes as an exponential function and calculated the differences between the mass (of raw material and components) that was originally used to manufacture a product and each of the subsequent recycled generations. Shu and Flowers (1999), whose study was based on industrial cases, noted that 'remanufacturing' activities are more appropriate for products that are either technologically mature or designed for upgrades, and showed that a 'design for remanufacture' option requires additional investment not only to increase the strength of a product's components and extend their service lives, but also to avoid the failure of these components during disassembly and reassembly operations.

This paper develops in the next section a mathematical expression that models the percentage of returns as a function of the number of items to be remanufactured.

3. Mathematical expression for recovery times

The paper assumes a production and recovery (remanufacturing or repair) inventory system for a single product with unlimited storage capacity, infinite planning horizon, constant demand rate, no shortages and zero lead-time. The input parameters and decision variables used are as follows:

d	demand rate (units/year)
β	proportion of used units returned for recovery purposes when an item is recovered an indefinite number of times, where $0<\beta<1$
α	proportion of used units returned and disposed, where $0<\alpha<1$
ζ	number of times an item is recovered
β_ζ	proportion of used units returned for recovery purposes when an item is recovered a limited (ζ) number of times, where $0<\beta_\zeta<1$

Other parameters and decision variables will be introduced at a later stage as needed. The percentage of collected units for a generation of products decreases over time due to usage, obsolescence and other factors. Accordingly, as the number of times a product can be recovered increases, the return rate increases, i.e., $d\beta_\zeta/d\zeta< 0$ and $d^2\beta_\zeta/d\zeta^2>0\ \forall\zeta\geq 0$, where $\beta_\zeta<\beta$, and subsequently the percentage of available used units that are recoverable plateaus at a constant value, i.e., as $\zeta\to\infty$, $\beta_\zeta\to\beta$, which is what has been assumed in the literature.

This paper considers the production, remanufacturing and disposal model described in Fig. 1 (which is the same as the one described in the literature except for replacing β with β_ζ), where a manufacturing environment (production, remanufacturing and collection of used items) consists of two stocks. Produced (new) and remanufactured items of a product are stored in the serviceable stock, while used items collected (returned) from the market are stored in the repairable stock. Unlike what has been assumed in the literature, this paper assumes that the number of times a single item can be recovered (ζ) is finite.

The paper starts by analyzing the production–remanufacturing system for the case when $\zeta=1$, i.e., a product is remanufactured once; then a general case will be formulated.

In the production–remanufacturing system described in Fig. 1, demand in the first time interval (when a product is produced for the first time) is satisfied from production only, as nothing has been returned to be remanufactured (El Saadany and Jaber, 2008), and therefore, the annual production quantity is d. In the second time interval, the annual remanufactured quantity is βd (i.e., returns of what was produced in the previous period), and the remaining demand i.e. $(1-\beta)d$ is satisfied from production. In the third time period, the remanufactured quantity is $(\beta-\beta^2)d$, and the remaining demand is produced, i.e., $(1-\beta+\beta^2)d$, and so on.

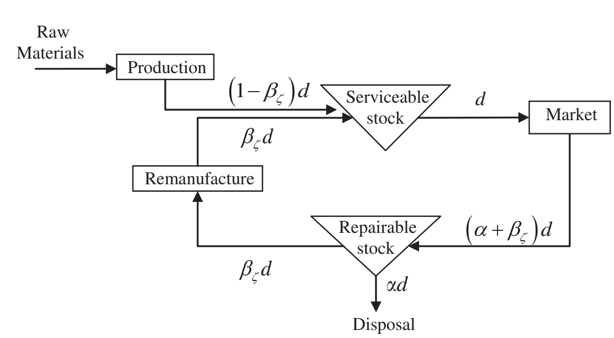

Fig. 1. Material flow for a production and remanufacturing system.