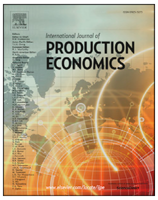
International Journal of Production Economics 197 (2018) 330–341

Contents lists available at ScienceDirect

International Journal of Production Economics

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



# Optimizing a recover-and-assemble remanufacturing system with production smoothing

Seyed Mehdi Zahraei [a,*], Chee-Chong Teo [b]

[a] School of Business, Singapore University of Social Sciences, 463 Clementi Road, 599494, Singapore
[b] School of Civil & Environmental Engineering, Nanyang Technological University, Nanyang Avenue, 639798, Singapore

ARTICLE INFO

Keywords:
Remanufacturing
Recover-and-assemble
Production smoothing
Safety stocks

ABSTRACT

We consider a recover-and-assemble remanufacturing system in which an upstream stage recovers components from used products before a downstream stage performs assembly using the recovered components. In such systems, the inventory variances of the recovered components depend significantly on the production variabilities of the recovery and assembly processes. The production variabilities, in turn, are functions of the uncertain arrivals of used products (at the recovery) and demand for remanufactured products (at the assembly). We study how best to employ production smoothing to mitigate the uncertainties. We first build a network model that incorporates the inter-stage material and demand flows. We then derive the safety stock formulae as functions of the smoothing behavior and uncertainties. We embed the variables characterized by the model into an optimization procedure that optimizes the smoothing and the safety stocks. Through numerical examples, we demonstrate the application of the model, the value of production smoothing in this context and related managerial insights.

## 1. Introduction

There has been heightened interest in product recovery in recent years. One of the most widely practiced forms of product recovery is remanufacturing, which is commonly referred to as the process of restoring used, end-of-life or defective products to like-new condition. Hagerty and Glader (2011) report that the U.S. market for remanufactured goods is estimated to be worth more than $100 billion per year. A recent survey by Parker et al. (2015) shows that the remanufacturing activities within the European Union generate about €30 billion in turnover. The sector is widely expected to grow rapidly due to its economic benefits as well as increased regulatory pressure to enhance environmental performance. The operational challenges unique to remanufacturing have been well documented. The challenges are mainly driven by uncertainties in timing, quantity and quality of returned products, which subsequently leads to difficulty in balancing the returned items with the stochastic demands (see e.g., Fleischmann et al., 1997; Guide, 2000 for a discussion).

In this paper, we consider a *recover-and-assemble* remanufacturing system. In this configuration, the upstream stage recovers components from returned products (widely known as *cores*), which typically involves disassembling, cleaning, inspection and restoration. Subsequently, the downstream stage assembles the product using the recovered components, usually together with other components that could be externally sourced or in-house built. In the recover-and-assemble system, the inventories of recovered components are replenished by the recovery process and are consumed by the assembly. Hence the inventory variability (and thus the safety stocks) depends considerably on the production variabilities at the recovery and assembly processes, which in turn are respective functions of the stochastic arrivals of returned products and demand for assembled products. The intent of this research is to study how best to manage the uncertainties in the recover-and-assemble systems by the use of production smoothing. Production smoothing is the leveling of production output across time, usually to ease capacity loading when faced with variable demand. In this paper, we first develop a model that optimizes the amount of smoothing at the recovery and assembly processes. Additionally, we characterize the optimal safety stocks that correspond to the smoothing tactic, for both the recovered components and the finished remanufactured products.

The recover-and-assemble configuration is extensively employed in a large variety of industries. One example is the remanufacturing of consumer electronics. The worn-out components are replaced, whereas durable components are recovered and reused in the assembly of the remanufactured products. Electronics remanufacturing has been in the

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* Corresponding author.
*E-mail addresses:* zahraei@suss.edu.sg (S.M. Zahraei), teocc@ntu.edu.sg (C.-C. Teo).

https://doi.org/10.1016/j.ijpe.2018.01.016
Received 24 June 2017; Received in revised form 14 December 2017; Accepted 17 January 2018

**Table 1**
List of notations.

| | |
|---|---|
| $i$ | index for stage |
| $L_i$ | risk period for inventory of component $i$ |
| $\widehat{L}$ | maximum value of $L_i$'s among components |
| $\varphi_{i0}$ | number of units of component $i$ needed for every unit of product processed at ASSEMBLY |
| $\varphi_{i1}$ | number of units of components restored at RECOVERY for every unit of returned item |
| $n_i$ | control parameter (planned lead-time) at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) |
| $m_i$ | nominal production capacity at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) per period |
| $c_{Pi}$ | expediting cost per unit of capacity shortages at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) |
| $c_{Ii}$ | expediting cost per unit of inventory shortages at stage $i$ |
| $h_i$ | unit holding cost at stage $i$ per period |
| $z_i$ | safety factor at stage $i$ |
| $N_{0t}$ | demand at processed inventory of ASSEMBLY at start of period $t$ |
| $N_{1t}$ | number of returned items at RECOVERY at start of period $t$ |
| $\mu_i$ | expected $N_{it}$ at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) |
| $\sigma_i$ | standard deviation of $N_{it}$ at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) |
| $P_{it}$ | production requirements at ASSEMBLY ($i=0$) and RECOVERY ($i=1$) and order quantity for component $i$ ($i=2, \ldots, q$) in period $t$ |
| $Q_{0t}$ | inventory shortfall at ASSEMBLY at start of period $t$ after demand observation |
| $Q_{1t}$ | inventory level of returned items at RECOVERY at start of period $t$ |
| $D_{it}^{rp}$ | demand (net demand) over risk period for orders placed at period $t$ for single-source (dual-source) component $i$ |
| $B_i$ | base stock level at stage $i$ |
| $EI_i$ | expected inventory level at stage $i$ |
| $q+1$ | number of stages in the network |
| $\mathbf{D}$ | diagonal matrix with elements $1/n_i$ ($i=0, 1, \ldots, q$) |
| $\mathbf{\Phi}$ | square matrix with $\varphi_{ij}$ as its elements |
| $\boldsymbol{\mu}$ | column vector with $\mu_i$ ($i=0$ for ASSEMBLY and $i=1$ for RECOVERY) as only non-zero elements |
| $\mathbf{\Sigma}$ | covariance matrix consisting of covariance of $N_{it}$ |
| $\mathbf{P}_{\mathrm{t}}$ | column vector with $P_{it}$ as its elements ($i=0, 1, \ldots, q$) |
| $\mathbf{A}_{\mathrm{t}}$ | column vector with $A_{it}$ as its elements ($i=0, 1, \ldots, q$) |
| $\mathbf{N}_t$ | column vector that comprises $N_{0t}$ and $N_{1t}$ as the only non-zero elements |
| $\mathbf{I}$ | identity matrix |

limelight lately due to the rapid growth of e-waste (electronic waste). In the U.S. alone, as much as 4.5 million tons of old consumer electronic goods have been disposed (Minter, 2013). It is projected to increase due to shortening of life-cycles of consumer electronics. In order to reduce the e-waste and to recover material cost, many manufacturers have begun to collect used products from consumers and explore the value-added product recovery. Sony has created the Green Fill Program that provides its retailers collection kiosks for used electronics. LG Electronics establishes the LG Electronics Recycling Program that offers drop-off sites and free shipping for returning end-of-life products. Product take-back legislation has also been prevalent in recent years. For example, the European Commission had passed the Waste Electrical and Electronic Equipment (WEEE) Directive such that European Union members are required to establish e-waste collection schemes. In the U.S., more than 25 states have enacted product take-back legislations (Electronics Take-back Coalition, 2011), mandating state-wide e-waste collection and recycling.

The remanufacturing of automotive parts, which has been in existence for decades, is also mostly based on the recover-and-assemble operation. The useful parts (such as engine housings) are recovered, and the worn-out or defective parts are either restored or disposed. After the usual processes of cleaning and inspection, the recovered parts are then assembled with other parts to form the completed product. The APRA (Automotive Parts Remanufacturing Association) approximates that there are more than 15,000 companies in the U.S. alone that remanufacture motor vehicle parts and the industry is estimated to hire more than 350,000 employees (U.S. International Trade Commission, 2012). Besides the automotive industry, the U.S. International Trade Commission (2012) reported several other examples from diverse industries that operate with the recover-and-assemble configuration. Examples are aerospace parts, medical devices, office furniture and restaurant equipment. Clearly, the recover-and-assemble operation is prevalent in practice and the aforementioned examples are certainly far from exhaustive. The importance of remanufacturing has also given rise to the concept of *Design for Remanufacturing* (*DfRem*) in which the products are designed to facilitate the remanufacturing process, particularly in the form of the modular product architecture where modules can be easily dissembled, restored and re-assembled (see Yang et al., 2014). The *DfRem* trend will lead to more widespread adoption of the recover-and-assemble systems.

Despite the prevalence of the recover-and-assemble configuration, there have been limited studies on such configuration as compared to other remanufacturing settings. In most literature, the remanufacturing activities are modeled aggregately as a single step, without considering the individual processes and their interplay (See Akcah and Cetinkaya, 2011 for a review of models categorized according to network configurations.). Readers interested in the remanufacturing literature can refer to an abundance of review papers such as Junior and Filho (2012) and Steeneck and Sarin (2013) (on production planning and control), Morgan and Gagnon (2013) (on scheduling of remanufacturing operations), Pourghadim et al. (2014) (on inventory management), Schenkel et al. (2015) (on value creation through the recovery of returned products), and Lin et al. (2015) (on plant selection in multi-plant remanufacturing environment). Like our paper, there are others that study the recovery of components. Ferrer and Whybark (2001) characterize the production planning for the fundamental problem of uncertain return rate of used components and the stochastic demand for remanufactured products. Under similar problem setting, DePuy (2007) include the considerations of the quality variation of the returned components and uncertainty of the processing times. DeCroix and Zipkin (2005) consider a single-product, multi-component assembly system where some of the components in the returned products can be recovered and returned to inventory; they establish conditions under which the component recovery is equivalent to a serial system and develop heuristics that can be employed when these conditions are not satisfied. The main contrast of our paper to the aforementioned works is that our model explicitly incorporates the downstream assembly process and inventories, as our focus is to capture the system-wide interactions and trade-offs in the recover-and-assemble setting. To our knowledge, there are very few papers in the research stream on component recovery that characterize the

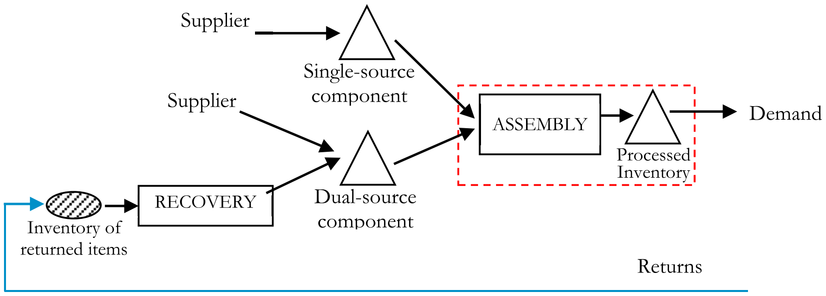

**Fig. 1.** An example of the recover-and-assemble production network.