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Managing component reuse in remanufacturing under product diffusion dynamics

Wenyuan Wang [b], Yue Wang [a,*], Daniel Mo [a], Mitchell M. Tseng [b]

[a] *Hang Seng Management College, Hong Kong*
[b] *Hong Kong University of Science and Technology, Hong Kong*

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ABSTRACT

Rapid changes in technology have precipitated the disposal of increasing amounts of used products and components. To mitigate the side effects of product disposal and decrease the associated costs in the overall value chain, remanufacturing has been advocated as an important approach given its formation of a closed-loop value chain. The key to fully achieving the benefits of remanufacturing lies in the efficient and cost-effective reuse of components from end-of-life products. In this paper, we attempt to model the economic benefits of component reuse in the remanufacturing supply chain and examine how product diffusion dynamics in the market affect the volume of components reused in the single-generation life cycle of a product. We use the Bass model to model the product diffusion process and facilitate analysis of the economic benefits of component reuse and remanufacturing. We then derive the optimal component reuse volume and the corresponding acquisition costs. We present analytical results and case study to show the merits of the proposed methodology and gain insights that can be applied to component reuse decisions in remanufacturing.

1. Introduction

The traditional product life cycle in manufacturing typically starts with raw material extraction, followed by component production, assembly, testing and distribution to customers for use and disposal at end-of-life. An increasing amount of end-of-life products are being dumped as waste. The increase in the amount of end-of-life products is projected to accelerate even faster due to rapid technological evolution and intensive global competition. According to the US Environmental Protection Agency, 47.4 million computers, 27.2 million televisions and 141 million mobile devices reached their end-of-life in 2009. The total weight of these end-of-life electronic products was 2.37 million tons, an increase of more than 120% over 1999 levels (Environmental Pretention Agency, 2009). Under these circumstances, the traditional disposal of end-of-life products as waste in landfills or by incineration cannot be maintained due to land scarcity and the concomitant environmental pollution.

However, it has been observed that many discarded products remain well within their physical lifespan and contain significant amounts of residual value. Many of the components in discarded products can be reused to manufacture products with original functionality. It is tempting to apply a remanufacturing strategy and replace the traditional produce-consume-discard paradigm with a closed-loop supply chain, as this may bring economic benefits and promote environmental sustainability (Das and Posinasetti, 2015). A considerable number of successful business cases have demonstrated the economic viability of implementing a remanufacturing strategy in the office equipment, electrical and electronics, household appliances and automobile industries. For example, Xerox is one of the most widely cited corporations for successfully managing to remanufacture used photocopiers and toner cartridges from around the world, and it has saved millions of dollars while boosting its image as an environmentally conscious company (Kerr and Ryan, 2001). Other examples include Mercedes-Benz and Ford, which have begun collecting and disassembling their end-of-life vehicles to recover valuable components as spare parts for both consumers and commercial customers (Toffel, 2003).

From a company's point of view, one of the key questions to be answered is how many end-of-life products or components should be collected for reuse. If the collected components are excessive, then unnecessary expense on remanufacturing will be incurred. Otherwise, the economic benefit of component use is not fully utilised. Once the optimal component reuse volume is known, companies can make better decision by collecting the appropriate amount of end-of-life products. As components may become

* Corresponding author.
E-mail addresses: wywang@ust.hk (W. Wang), yuewang@hsmc.edu.hk (Y. Wang), danielmo@hsmc.edu.hk (D. Mo), tseng@ust.hk (M.M. Tseng).

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obsolete across multiple product generations, the scope of this paper is confined to component reuse for remanufacturing within a single-generation product life cycle, i.e., from product launch to market withdrawal (Geyer et al., 2007). A typical product life cycle contains introduction, growth, maturity and decline stages. Correspondingly, a product's diffusion curve increases at first and then decreases to zero gradually across its life cycle. As a result, the potential component reuse volume also changes in different stages of product diffusion. Research must focus on how to link product diffusion dynamics with component reuse decisions and particularly the component reuse volume.

To address this issue, we aim to investigate how product diffusion dynamics in the market affect the component reuse volume in remanufacturing. In particular, we focus on the optimal component reuse volume at different stages of the product life cycle. We derive a closed-form mathematical expression based on the Bass model, a classic model proposed by Frank Bass to quantify product diffusion dynamics in the market. Drawing on this closed-form expression, we extend the work of Wang et al. (2015b) by generating propositions to obtain managerial insights and investigate the effects of the return rate and time delay on component reuse in remanufacturing. Through numerical analysis, we demonstrate that the effects of product diffusion dynamics on component reuse in remanufacturing are significant and sensitive in relation to the coefficients of innovation and imitation in the Bass model. Moreover, both the return rates of end-of-life products and the time delay in remanufacturing play important roles in determining the total component reuse volume in remanufacturing under product diffusion dynamics.

The remainder of this paper is organised as follows. In Section 2, we review the literature related to component reuse and remanufacturing. In Section 3, we examine component reuse in manufacturing across a single generation under product diffusion in detail. In Section 4, we present a numerical example to illustrate the ideas proposed in this paper. Section 5 concludes the paper.

2. Literature review

Product end-of-life management has attracted increasing attention in recent decades. Numerous studies of this issue have been published. A number of review papers have addressed different characteristics of end-of-life management, including from operations (Guide and Van Wassenhove, 2009; Tang and Zhou, 2013) and integrated design (Ramani et al., 2010) perspectives. Research papers have addressed issues such as the closed-loop supply chain (Savaskan et al., 2004; Östlin et al., 2008; Kenné et al., 2012; Lundin, 2014), reverse logistics (Dobos, 2003; Kumar and Putnam, 2008; Das and Chowdhury, 2012; Cannella et al., 2016) and marketing positions for remanufactured products (Debo et al., 2005). In this section, we consider the remanufacturing literature with a particular focus on design for remanufacturing and economic benefit analyses.

In the area of design for manufacturing, Kimura (1998) established a basic methodology for evaluating product deterioration after use and indicated the economic benefits of component reuse after minimal repair. The study aimed to establish a basic methodology for evaluating product deterioration during product operations and parts reuse in maintenance to develop a closed-loop, environmentally conscious manufacturing approach. Studies have proposed optimal life cycle designs for a closed-loop manufacturing framework by considering component reuse and functional upgrades in the product life cycle. Mangun and Thurston (2002) applied a product portfolio approach to integrate long-range planning for component reuse into product design. Their model can be used to determine end-of-life strategies for different components, including reuse, recycling and disposal. Georgiadis and Athanasiou (2010) studied the capacity planning problem of a remanufacturing network in a two-product-type joint life cycle scenario. In particular, they focused on how the entry time of the second product type to the market and the used product return patterns affected the optimal policies of a company's remanufacturing capacities by applying a dynamic systems model. Jin et al. (2013) addressed the problem of manufacturing system operations with uncertainty in end-of-life product returns. In particular, they developed assemble- and reassemble-to-order systems performance measures for end-of-life products, and proposed a systematic reassemble-to-order methodology to facilitate remanufacturing. Shi and Min (2013) modelled the cost of remanufacturing using a geometric Brownian motion and then constructed and analysed the product remanufacturing problem using the real option model. They examined how remanufacturing decisions are affected by cost uncertainty and other factors. They also derived a cost threshold for exercising the remanufacturing option. Subramanian et al. (2013) studied how one company's remanufacturing operations affected its component commonality decisions. Their results indicated that remanufacturing decisions in the product design stage and customers' preferences for new and remanufactured products determined component commonality decisions.

Relevant studies have also been conducted to quantify the economic benefits of component reuse in remanufacturing. Geyer et al. (2007) quantified the economic benefits of component remanufacturing under the constraints of limited component durability and finite product life cycles. They also studied how the constraints interacted with each other and how different remanufacturing decisions affected the cost-savings potential of the production system. As a follow-up work, Atasu et al. (2008) considered the characteristics of remanufactured products and identified profitable opportunities for remanufacturing. They mainly considered three factors, including direct competition between OEMs, the existence of a green segment and changes in market size, and provided guidelines for manufacturers to make remanufacturing decisions. Subramanian et al. (2009) studied how extended producer responsibility (EPR) affected product development decisions. They considered the environmental effects of products during and after use in their analytical framework. They derived an optimal product design criterion and showed that financial costs could be used to motivate companies to design environmentally friendly products. Plambeck and Wang (2009) studied the effects of EPR on the profitability of remanufacturing under two regulations: 'fee upon sale' and 'fee upon disposal'. By applying a duopoly model, they showed that the 'fee upon disposal' regulation encouraged companies to adopt product remanufacturing because it was more profitable. He (2015) studied remanufacturing decisions with uncertain demand and supply in a closed-loop supply chain. In particular, the author derived acquisition prices for centralised and decentralised cases. Wang et al. (2015a) considered the relative cost-effectiveness of the insourcing and outsourcing of certain remanufacturing components. Their model also incorporates the quality of the collected products, the consumer's willingness-to-pay for remanufactured products and the market share of remanufactured products to predict a retailer's propensity to remanufacture.

Overall, the research has indicated immense reuse potential due to the remarkable amount of physical life remaining in end-of-life products (Mazhar et al., 2004, 2005). Moreover, based on a number of successful case studies related to remanufacturing, the economic feasibility and environmental benefits of remanufacturing have been asserted and analysed for manufacturing companies, and managerial insights have been provided (Ayres et al., 1997; Kerr and Ryan, 2001). Based on our review of the

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