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Supply chain design for unlocking the value of remanufacturing under uncertainty

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ABSTRACT

Owing to the technological innovations and the changing consumer perceptions, remanufacturing has gained vast economic potential in the past decade. Nevertheless, major OEMs, in a variety of sectors, remain reluctant about establishing their own remanufacturing capability and use recycling as a means to satisfy the extended producer responsibility. Their main concerns seem to be the potential for the cannibalization of their primary market by remanufactured products and the uncertainty in the return stream in terms of its volume and quality. This paper aims at assisting OEMs in the development of their remanufacturing strategy, with an outlook of pursuing the opportunities presented by the inherent uncertainties. We present a two-stage stochastic closed-loop supply chain design model that incorporates the uncertainties in the market size, the return volume as well as the quality of the returns. The proposed framework also explicitly represents the difference in customer valuations of the new and the remanufactured products. The arising stochastic mixed-integer quadratic program is not amenable to solution via commercial software. Therefore, we develop a solution procedure by integrating sample average approximation with the integer L-shaped method. In order to gather solid managerial insights, we present a case study based on BSH, a leading producer of home appliances headquartered in Germany. Our analysis reveals that, while the reverse network configuration is rather robust, the extent of the firm's involvement in remanufacturing is quite sensitive to the costs associated with each product recovery option as well as the relative valuation of the remanufactured products by the customers. In the context of the BSH case, we find that among the sources of uncertainty, the market size has the most profound effect on the overall profitability, and it is desirable to build sufficient expansion flexibility in the forward network configuration.

1. Introduction

Despite the increasing awareness concerning the benefits of recovering the remaining economic value in the end-of-use and end-of-life products, recycling the material content of the returns continues to be a more prevalent form of product recovery. Remanufacturing the returned products so that they perform as good as their new versions constitutes a higher form of recovery that is not used to the extent desired by the policy makers in many cases (Atasu, Van Wassenhove, & Sarvary, 2009). In Europe, for example, the Waste Electrical and Electronic Equipment (WEEE) Directive of 2002 has been widely criticized as a "recycling law", and consequently its recast in 2012 aims at increasing the remanufacturing levels, among other improvements.[1] The firm has an option of using the third-party or developing in-house capability for remanufacturing. The extent of OEMs' voluntary involvement in remanufacturing, however, often depends on the economic benefits they expect directly (or indirectly) out of this activity (Guide, Teunter, & Wassenhove, 2003b). An important factor that clouds the OEMs' capability to assess the potential benefits of engaging in remanufacturing is the uncertainty in the volume, quality and timing of the returns. Particularly, for the economic viability of in-house remanufacturing, which we study in this paper, the firm needs to ascertain that there would be sufficient volume of returns eligible for remanufacturing. In Section 6, we discuss one firm (BSH Bosch und Siemens Hausgeräte GmbH), which is currently investigating the possibility of developing in-house remanufacturing capability for their commercial returns. Other examples of firms that

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[1] Available at http://ec.europa.eu/environment/waste/weee/index_en.htm.

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do not use third-party remanufacturing services include Caterpillar, Hewlett-Packard and Xerox.

Understanding the difference in the customers' valuation of the new and the remanufactured products is crucial for assessing the profit potential of remanufacturing. Though customers differ in how much they are willing to pay for the remanufactured goods, the initial (and often uninformed) perceptions of products containing used components are generally negative (Ferrer & Whybark, 2000).[2] In addition, the OEMs constantly introduce new products in an effort to sustain/increase their market share, which pronounces the customers' depreciation of the value of the remanufactured products. For example, the introduction of energy-efficient appliances undermines the market value of remanufactured merchandise. Thus, OEMs usually have poor knowledge of their potential secondary market demand.

A firm's product recovery strategy specifies its level of commitment to each recovery option; particularly, remanufacturing and recycling. This decision is intertwined with the configuration of the firm's closed-loop supply chain (CLSC) under the extended producer responsibility laws. Atasu and Wassenhove (2012) point out that the e-waste network design problem is strongly restricted by environmental legislations, such as recycling technology standards and landfill bans. In this paper, we focus on return streams with both a healthy secondary market for remanufactured products and a profit potential in the recycling market. Such return streams typically include end-of-use and commercial returns. In this context, CLSC design is a complex problem that comprises determining the optimal number and location of the distribution centers (DCs) and the return centers (RCs), as well as the extent of the OEM's involvement in remanufacturing and recycling activities.

The primary objective of this paper is to develop an integrative, yet practical, decision support tool for the formation of a product recovery strategy under the variety of uncertainties faced by the OEM's top management. We utilize a profit-maximization framework so as to incentivize the OEM's voluntary engagement in remanufacturing under uncertainty. This requires the estimation of the potential revenues from the primary and secondary markets as well as the costs of the development and operation of the firm's CLSC. Traditionally, the marketing aspects mentioned above have been studied through stylized models, whereas the network design problems have been represented by mathematical programming formulations. In this paper, we integrate these two modeling approaches by incorporating a stylized representation of the firm's primary and secondary markets in the mathematical programming formulation developed for CLSC design under uncertainty. Without this integration one would fail to consider the potential profitability of remanufacturing in making the strategic product recovery and CLSC design decisions.

We seek answers to the following primary research questions: *How do uncertainties influence the profitability of closed-loop supply chains?* and *How does variable cost structure as well as consumer valuation of remanufactured products influence the product recovery strategy in uncertain business environments?* In addition, we explore the robustness of the CLSC configuration under uncertainties. We propose an integrated stochastic CLSC design model (IS-CLSC) that explicitly considers different sources of uncertainty as well as the difference in customer valuation of new and remanufactured products. The proposed model enables us to optimize the extent of an OEM's involvement in each product recovery option and to determine the most appropriate facility network configuration for supporting this strategy.

One of the main contributions of our work is the incorporation of both primary and secondary markets as well as the product recovery choices in a detailed network design model under uncertainty. As we summarize in the next section, to the best of our knowledge all the prevailing work on CLSC design under uncertainty focuses on cost minimization, and hence ignores the impact of the product markets. The literature that explicitly represents the market segments for the new and remanufactured products and the recovery options, however, mostly comprises stylized models based on broad assumptions and lacking a detailed representation of the dynamics of the network design decisions. The arising stochastic mixed integer quadratic formulation is not amenable to solution by commercial software. As a methodological contribution, we propose an integration of the integer L-shaped decomposition with sample average approximation that enables us to use a large number of scenarios in our analyses.

We also developed a new case based on BSH Bosch und Siemens Hausgeräte GmbH's operation in Germany so as to illustrate the proposed methodology and develop managerial insights. BSH is currently the largest manufacturer of home appliances in Europe and one of the leading companies in the sector worldwide. The case study is inspired by a real-life problem encountered by BSH concerning the decision whether or not to offer remanufactured products within Germany's unique WEEE take-back scheme. The results provide a solid understanding of the impact of different sources of uncertainty on the CLSC configuration. Also, we shed light on the conditions under which BSH needs to develop in-house remanufacturing capabilities in response to the trend of tightening environmental regulations.

The remainder of this paper is organized as follows. In the next section, we position our research in the context of the relevant literature. In Section 3 the IS-CLSC model is presented. We describe the proposed solution method in Section 4 and report on its performance in Section 5. In Section 6, we present the BSH case study in order to highlight the features of the proposed model and show the impact of uncertainties on the performance of a real supply chain. Unlike a significant majority of the earlier papers, this new case study is presented at a level of detail that would enable the readers to reconstruct the problem instances. In Section 7, we analyze the impact of uncertainties on network structure, overall profitability and recovery strategy. The computation experiments reported in this section enable us to provide substantial answers to the research questions stated above. The paper ends with managerial insights and our concluding remarks in Section 8.

2. Overview of the literature

Our research draws on two separate streams of literature: remanufacturing and CLSC network design. In this section, we provide a review of the prominent research in each stream and position our research at the point of their intersection. We begin with an overview of the relevant remanufacturing literature.

Remanufacturing has received attention in the academic literature for more than a decade. The existing literature has addressed a variety of problems spanning from strategic to tactical level issues. In order to satisfy the immediate need for firms, the operational aspects of remanufacturing such as inventory control (Ahiska & King, 2010; DeCroix & Zipkin, 2005; Toktay, Wein, & Zenios, 2000), production planning (Ferguson, Guide, Koca, & Souza, 2009; Guide, Jayaraman, & Linton, 2003a) and logistic network design (Fleischmann, Beullens, Bloemhof-Ruwaard, & Wassenhove, 2001; Salema, Barbosapovoa, & Novais, 2007) have received the most attention. Other research efforts have considered remanufacturing from a more strategic perspective. Significant portion of these papers adapted a game-theoretic approach. For instance, Majumder and Groenevelt (2001) model the competition between an OEM and a local remanufacturer in a two-period game setting. Ferrer and Swaminathan (2006) expand the above model and characterize the optimal strategies in monopoly and duopoly environments for two-period, multi-period and infinite-period settings. They prove the existence of a remanufacturing threshold policy in the second period based on

[2] Some exceptions are retreaded tires for commercial fleet companies and Kodak's single-use camera (Atasu, Guide, & Wassenhove, 2010; Esenduran, Kemahlioğlu-Ziya, & Swaminathan, 2012; Souza, 2008).