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A carbon-constrained stochastic optimization model with augmented multi-criteria scenario-based risk-averse solution for reverse logistics network design under uncertainty

Hao Yu*, Wei Deng Solvang

Department of Industrial Engineering, UiT—The Arctic University of Norway, Lodve Langesgate 2, 8514 Narvik, Norway

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A B S T R A C T

With the increase of the concern from the public for environmental pollution and waste of resources, the value recovery through reuse, repair, remanufacturing and recycling from the end-of-use (EOU) and end-of-life (EOL) products have become increasingly important. Reverse logistics is the process for capturing the remaining value from the EOU and EOL products and also for the proper disposal of the non-reusable and non-recyclable parts. A well-designed reverse logistics system will yield both economic and environmental benefits, so the development of an advanced decision-making tool for reverse logistics system design is of significant importance. The paper presents a novel multi-product multi-echelon stochastic programming model with carbon constraint for sustainable reverse logistics design under uncertainty. Compared with the previous stochastic optimization models in reverse logistics system design, which mainly focuses on the expectation of the optimal value, this paper, however, emphasizes on both optimal value expectation and its reliability in decision-making. Due to this reason, a multi-criteria scenario-based risk-averse solution method is developed based on a latest research in order to obtain the optimal solution with high level of confidence. Later in this paper, the application of the model and the augmented solution method is illustrated and the managerial implications are discussed through the numerical experiment and sensitivity analysis. The result of the study shows that the model can be used for providing decision-makers with a deep insight into the relationship between profit and carbon emission requirement, understanding and resolution of the infeasibility caused by capacity limitation, the use of flexible manufacturing system in reverse logistics, and proper use of the government subsidy as a leverage in reverse logistics design.

1. Introduction

Logistics and supply chain network design is a complex decision-making problem in operational research, which aims mainly at determining the locations of different facilities and the material flows and transportation strategy among those facilities (Lee and Dong, 2009). Due to the complicated nature of the logistics and supply chain network design problem, it has never lost its appeal to both academic researchers and practitioners. In recent years, with the increasing focus on sustainable development and circular economy, the value recovery from the end-of-use (EOU) and end-of-life (EOL) products has been adopted by many enterprises all over the globe due to the economic incentives and stringent environmental regulations enforced. For example, the EU Directive 92/62/CE has set a compulsory requirement for the manufacturing companies to recover a percentage of the EOL, EOU as well as the packaging materials from the market (Gonzalez-Torre et al., 2004). Therefore, the design of an economically efficient and sustainable reverse logistics network has been increasingly focused in the recent literature (Nikolaou et al., 2013).

Reverse logistics is the entire process for effectively managing the material, information and cash flow in order to re-generate value from EOU and EOL products through repair, reuse, remanufacturing, recycling and re-introduction to the market, besides, it also involves the proper treatment of the non-reusable and non-recyclable parts (Rogers and Tibben-Lembke, 2001; Yu and Solvang, 2016a). Reverse logistics network design is a long-term decision at strategic level, and when the supply chain network is

* Corresponding author.
E-mail addresses: hao.yu@uit.no (H. Yu), wei.d.solvang@uit.no (W.D. Solvang).

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configured, it could be extremely difficult and costly to alter it. A well-planned reverse logistics system will yield both economic and environmental benefits. However, an improperly designed reverse logistics system may reduce the profitability of the business while simultaneously cause more serious environmental and/or social impact. Due to this reason, it is of great importance to develop the advanced methods for resolving the complex decision-making problem of reverse logistics network design.

This paper formulates a new carbon-constrained mathematical model under stochastic environment for sustainable reverse logistics network design, and an augmented multi-criteria scenario-based risk-averse solution method is also developed for resolving the model. The remainder of the paper is organized as follows: Section 2 presents a comprehensive literature review of the recent research works in reverse logistics network design. Section 3 formulates the stochastic optimization model. Section 4 develops the augmented multi-criteria scenario-based risk-averse solution method based upon the research work given by Soleimani et al. (2016). The existed problems of the original method and the solution in the augmented method are explicitly discussed in this section. Section 5 presents the numerical experiment of the model and solution method. Section 6 summaries some generic managerial implications, i.e, the relationship between profit and carbon emission requirement, the use of flexible manufacturing system in reverse logistics, and proper use of the government subsidy as a leverage, etc. Section 7 concludes the paper and proposes directions for future research.

2. Literature review

During the past decade, reverse logistics network design problem has been extensively focused in operational research and mathematical optimization. Comprehensive literature review are given in Pokharel and Mutha (2009), Govindan et al. (2015), Agrawal et al. (2015), Mahaboob Sheriff et al. (2012) and Govindan and Soleimani (2017), and from the perspectives of sustainable development and uncertainties of decision-making, this paper presents a brief overview of some of the recent publications in this field.

The primary target of reverse logistics is the value recovery form EOU and EOL products, so economic benefit and sustainability have been widely formulated and emphasized in literature. Alumur et al. (2012) propose a mixed integer programming for a multi-period reverse logistics network design problem. The model aims at maximizing the total profits generated in the reverse logistics system through optimally locating different facilities and allocating the materials follows over several continuous periods. Demirel et al. (2016) develop a mixed integer linear programming for minimizing the reverse logistics costs for recycling the EOL vehicles in Turkey. Li and Tee (2012) formulate a mathematical model for reverse logistics network design with the consideration of both formal and informal channels. Sasikumar et al. (2010) formulate a mixed integer programming for reverse logistics network design, and a case study of truck tire remanufacturing is given in the paper.

Alshamsi and Diabat (2017) formulate a multi-period location-allocation model for reverse logistics network design, and a genetic algorithm is developed for resolving the large-scale optimization problems in an effective and efficient manner. Diabat et al. (2013b) combine both genetic algorithm and artificial immune system in the optimization problem of a product return system. Kumar et al. (2017) develop a mixed integer model for maximizing the profits generated in an integrated forward-reverse logistics system on a multi-period basis, and an evolutionary algorithm is developed for resolving the optimization problem. Das and Chowdhury (2012) propose an optimization model for the reverse logistic network design considering the collection and recycling of multiple types of EOU and EOL products. Zhou and Zhou (2015) formulate a cost-minimization model for the design of a multi-echelon reverse logistics network. Demirel and Gökçen (2008) propose a mathematical programming for designing a remanufacturing system.

Introduced in 2005 World Summit of the United Nations, sustainability framework includes economic, environmental and social dimensions (Chopra and Meindl, 2007). In order to account those dimensions simultaneously, reverse logistics network design becomes a complex decision-making problem which involves several objectives or criteria. Some research works focus on the optimal tradeoff among those conflicting objectives or criteria in decision-making. Diabat et al. (2013a) formulate a bi-objective optimization model for the optimal design of an integrated forward/reverse logistics system, and the model aims at simultaneously minimizing the costs and CO_2 emissions. Yu and Solvang (2016a) develop a bi-objective mixed integer linear programming for reverse logistics design considering both economic benefits and environmental impact, and in this paper, the environmental impact is evaluated by carbon emissions.

With the consideration of economic, environmental and social sustainability, Govindan et al. (2016a) investigates a multi-objective mixed integer programming of the design of a multi-product multi-period integrated forward/reverse logistics system. In this research, the environmental sustainability is measured by both cost saving from material recovery and CO_2 emission, while the social sustainability is evaluated by four indicators regarding the welfare, responsibilities and employment. Govindan et al. (2016b) formulated a fuzzy mathematical model for sustainable design of reverse logistics system. The model aims at simultaneously balancing the economic efficiency, environmental impact and social benefits in a sustainable reverse logistics system, and a customized multi-objective particle swarm optimization algorithm is developed to find out the optimal solution.

In the real world, decision-making is seldom done with all parameters exactly known in advance, but many important decisions have to be made even though the knowledge or information of some parameters is limited at the point of decision-making (King and Wallace, 2012). Reverse logistics network design is a long-term decision that involves great uncertainties, so some literature focuses on the uncertainty issues associated with reverse logistics network design. Lee and Dong (2009) develop a two-stage stochastic programming for designing a multi-period integrated forward-reverse logistics system under demand uncertainties. El-Sayed et al. (2010) formulate a stochastic optimization model for the design of a multi-period forward-reverse logistics network with the consideration of risk. Ramezani et al. (2013) develop a multi-objective stochastic optimization model for the optimal planning of an integrated forward-reverse logistics network, and the responsiveness and quality level of the EOU and EOL products are accounted in this model. Chu et al. (2010) propose a fuzzy chance-constrained model for the design of a reverse logistics system for household appliances recovery.

Considering both forward and reverse directions of the supply chain planning, De Rosa et al. (2013) formulate a robust optimization model for the network planning under supply uncertainties. Roghanian and Pazhoheshfar (2014) develop a stochastic programming for minimizing the opening and operating costs of a multi-period and multi-echelon reverse logistics system, and the capacities, customer demands for recycled products, and quantity of EOU and EOL products generated are considered as stochastic parameters. Soleimani and Govindan (2014) develop a multi-level multi-product two-stage stochastic programming for reverse logistics network design with the consideration of the risk