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Global reverse supply chain design for solid waste recycling under uncertainties and carbon emission constraint

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ABSTRACT

The emergence of concerns over environmental protection, resource conservation as well as the development of logistics operations and manufacturing technology has led several countries to implement formal collection and recycling systems of solid waste. Such recycling system has the benefits of reducing environmental pollution, boosting the economy by creating new jobs, and generating income from trading the recyclable materials. This leads to the formation of a global reverse supply chain (GRSC) of solid waste. In this paper, we investigate the design of such a GRSC with a special emphasis on three aspects; (1) uncertainty of waste collection levels, (2) associated carbon emissions, and (3) challenges posed by the supply chain's global aspect, particularly the maritime transportation costs and currency exchange rates. To the best of our knowledge, this paper is the first attempt to integrate the three above-mentioned important aspects in the design of a GRSC. We have used mixed integer-linear programming method along with robust optimization to develop the model which is validated using a sample case study of e-waste management. Our results show that using a robust model by taking the complex interactions characterizing global reverse supply chain networks into account, we can create a better GRSC. The effect of uncertainties and carbon constraints on decisions to reduce costs and emissions are also shown.

1. Introduction

Due to the rapid growth of the world population and the shortening product lifecycle, solid wastes have increased rapidly in the past 20 years (Bing et al., 2016; Sanjeevi and Shahabudeen, 2015; Wang and Nie, 2011). The worldwide economic and environmental concerns have required countries to implement various instruments for collection and recycling of solid wastes. Some solid wastes, like e-waste and household plastics, usually contain precious materials and they can be recycled economically (Ayvaz et al., 2015; Bing et al., 2015; Nagurney and Toyasaki, 2005). Hence, it is feasible and profitable to collect and process those recyclable solid wastes. However, for many developed countries, one of the main obstacles for the solid waste recycling is the high handling cost because of the high human power and environmental protection instruments (Sanjeevi and Shahabudeen, 2015; Velis, 2014). Therefore, the governments and organizations are required to develop more efficient reverse supply chain and to seek every opportunity for solid wastes recycling (Golroudbary and Zahraee, 2015). One of the promising options is to develop a global solid waste recycling system.

Due to the imbalance of trade between the developing and the developed countries, like China and the European Union, the majority of container ships heading back to developed countries are often empty (Bing et al., 2015). This fact creates opportunities for waste transportation with a relatively low cost between the continents. Furthermore, the developing countries are focusing on manufacturing industry and thus have a high demand for raw materials. There is also a need for sustainable management of natural resource in the world (Nakajima et al., 2014; United Nations Environmental Programme, 2011), for which recyclable solid wastes can be a significant source. There is also an ongoing effort to use more of the recyclable solid wastes that have been pretreated for use in the manufacturing processes (Lundgren, 2012). As a result, solid wastes have become a major trading good (European Commission, 2015), which is leading to the formation of global reverse logistic networks for waste recycling (Bing

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et al., 2016, 2015; Lepawsky, 2015; Lundgren, 2012; Velis, 2014; Willén, 2008).

However, a reverse supply chain network for waste recycling is expected to process all the wastes with minimum environmental and financial impact. Re-processing of wastes is one of the major sources of pollution and it is significant to avoid spreading pollutants overseas (Bing et al., 2016, 2015). In a global supply chain (GSC), environmental sustainability optimization addresses the overall consumption of resources and energy (Kannegiesser and Gunther, 2013). Thus, the location of facility is still the most influential factor in determining the cost and emissions (Kannegiesser et al., 2013). Most previous optimization analyses for both short-term and long-term planning for solid wastes management overlooked global warming potential impacts (Chang et al., 2012). Moreover, it is essential to incorporate the uncertainties, like currency exchange rate (Ayvaz et al., 2015; Bing et al., 2016; Hasani et al., 2015) and waste collections (Almaktoom et al., 2016; Aras et al., 2015) in the design of a global reverse supply chain (GRSC).

This research is inspired by a worldwide concern on solid wastes recycling and global carbon emissions reduction. However, the previous study did not systematically address the solid wastes collection, transportation, and recycling processes at a global scale. The interaction between the available treatment capacities in different countries, the cost and emission trade-offs of all sections are seldom considered in solid wastes management literature as well. Therefore, the development of a global multi-echelon supply chain model for solid waste recycling is highly desired.

Noting that the gap that exists in the literature, this research aims to explore managerial implications in a GRSC for solid wastes recycling in the context of uncertainties and global carbon cap (GCC) legislation. The GCC policy is the extended application of the carbon cap policy in a GSC environment. Under a GCC policy, a level of emissions allowance (called carbon cap) is provided to a set of supply chain entities which are located in different countries. This study proposes to allow market incentives to play a vital role in the solid waste recycling rather than restricting the trade of recyclable wastes. A controlled design a GRSC for solid wastes recycling can be considered with processors are running in the supply chain with similar technology and quality standards.

The contribution of the research is twofolds: (1) with both environmental and economic concerns, this paper develops a mixed integer-linear programming (MILP) model via robust optimization to capture the unique features and uncertainties in the design of a GRSC; (2) based on publicly available data, a case study of e-waste recycling is conducted to generate insights for both the governments and organizations who have engaged and would engage in wastes recycling activities at a global scale.

The remainder of this paper is as follows: the paper gives a brief overview of the reverse supply chain and GSC design in Section 2. In Section 3, the GRSC design problem is introduced. In Section 4, the robust MILP model is presented. In Section 5, the results of computational study are presented along with the insights derived from the results. Finally, the conclusions, limitation of the proposed model, and the future research directions are provided in Section 6.

2. Literature review

2.1. Reverse supply chain design

The reverse supply chain can be defined as a business strategy that acts as the driving force for putting recovery activities in action effectively for the purpose of recovering value (Ayvaz et al., 2015). A number of prior studies have focused on analysing reverse supply chain for solid wastes recycling. An optimization model is presented by Hiete et al. (2011) to understand the dynamics and planning of a construction and demolition wastes recycling network. Khadivi and Ghomi (2012) adopt a combination of analytical network process and data envelopment analysis in solid wastes facility location selection. A municipal solid wastes management system with interactive planning of transportation and inventory for optimized productivity levels under available capacities was developed by Zhang et al. (2014). A multi-period MILP model for optimizing the municipal solid wastes was developed by Tan et al. (2014) for the Islander region in Malaysia. Vadenbo et al. (2014) present a multi-objective MILP optimization model for waste and resources management in industrial networks. Gan and Cheng (2015) compare the centralized optimization model and the distributed agent-based model in construction waste management.

Among the solid wastes, the e-waste and plastic waste have received particular attention. In a general sense, e-waste consists of a set of discarded electronic and electrical devices and components, including large household appliances, cooling and freezing appliances, TV monitors, and small household appliances (Kilic et al., 2015). Ayvaz et al. (2015) present a two stage stochastic programing model for a third party e-waste recycling. Gomes et al. (2011) investigate the e-waste recovery network in Portugal using a MILP model. A multitier network equilibrium framework is developed by Nagurney and Toyasaki (2005) for e-waste recycling. Plastic waste is studied in the literature. Bing et al. (2012) develop a MILP model with scenario study approach to analyse the strategic alternatives of reverse logistics network for household plastic waste. Bing et al. (2015) model a global network optimization problem using an integer programing approach, allowing the relocation of intermediate processing plants under emissions trading restrictions in both Europe and China. Optimization results show that global relocation of re-processors leads to reduction of both the total costs and total transportation emissions.

As presented in Table 1, this literature review has identified that, the main focus of the reverse supply chain researchers has been on financial objective and a limited research incorporates the environmental impacts of the waste recycling (Bing et al., 2015; Chang et al., 2012). Using traditional cost-effectiveness principle or cost-benefit analysis with no environmental concern cannot compete with alternatives with environmental concerns especially in a carbon-regulated environment (Chang et al., 2012). Most of the existing studies are conducted in the deterministic decision environment. The impacts of the uncertain decision parameters, such as quantity of waste collection (Aras et al., 2015; Ayvaz et al., 2015) and cost of transportation on the economic and environmental performance require more extensive analysis. Furthermore, the networks for wastes handling are within regional or municipal area. The global configuration of the networks of the reverse supply chain for waste recycling has been undertaken with a limited scope (Bing et al., 2015).

2.2. Global supply chain (GSC) design

The literature related to supply chain design with global factors are also considered. The GSC is more complex and more vulnerable to risks (Bassett and Gardner, 2013; Hammami and Frein, 2014b; Hasani et al., 2015). Avoidance of the threat of potential disruptions is of great significance in a GSC design (Speier et al., 2011). A mixed-integer, non-linear robust model is developed by Hasani and Khosrojerdi (2016) who propose a six resilience strategies to mitigate the risks of correlated disruptions. Das (2011) introduces a MILP model to optimize the quality-based global supply chain design. Using variation inequality theory, Liu and Nagurney (2013) formulate the governing equilibrium conditions of the competing decision-makers under demand and cost uncertainty.

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