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Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty

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ABSTRACT

Considering economic, environmental and social impacts, this paper presents a new sustainable closed-loop location-routing-inventory model under mixed uncertainty. The environmental impacts of CO_2 emissions, fuel consumption, wasted energy and the social impacts of created job opportunities and economic development are considered in this paper. The uncertain nature of the network is handled using a stochastic-possibilistic programming approach. Furthermore, for large-sized problems, a hybrid meta-heuristic algorithm and lower bounds are developed and discussed. Finally, a real case study is provided to demonstrate the applicability of the model in real-world applications, and several in-depth analyses are conducted to develop managerial implications.

1. Introduction

The traditional definition of supply chain management (SCM) is a process of planning, implementing and controlling the operations from a supplier to a set of customers based on efficiency (Zahiri et al., 2014). In the recent years, several important reasons highlighted the need for reverse logistics and designing closed-loop supply chains (CLSCs), including economic aspects, customers' expectations and government legislations such as the directive on Waste Electrical and Electronics Equipment (WEEE) (Melo et al., 2009). In contrast to the forward logistic, a reverse logistic starts from end users (i.e., consumers), where used products are collected, and then attempts to manage end-of-life products through different decisions such as remanufacturing, repairing and disposing (Govindan et al., 2015). The integration of traditional forward supply chain management and reverse logistic results in a CLSC, which has recently gained significant importance. In a CLSC, the distribution system forms a closed-loop where returned damaged products, unsold products or end-of-life products are remanufactured to refurbished products or sold as spare parts or new products to a secondary market (Diabat et al., 2015).

Recently, companies have noticed that the spare parts and after-sales service markets have a huge profit potential. These markets are worth more than $200 billion (Bacchetti and Saccani, 2012). A study of more than 80 multi-national companies in different industries reported that more than 50% of the total revenue of many high tech companies are gained through

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spare parts and after-sales services (Koudal, 2006). As a result, designing a CLSC with spare parts consideration can help meet the requirements and expectations of governments and customers as well as increase the total revenue of the supply chain.

In addition to the need to design a CLSC, incorporating operational decisions alongside the strategic decisions is of crucial importance in supply chain network design (SCND) (Govindan et al., 2014). In today's competitive business environment, companies should make operational decisions alongside strategic decisions to optimize and manage their logistic system more efficiently. Reducing costs and improving customer service are the two main challenges for each company in a competitive business environment. In the literature, there are two important operational decisions, vehicle routing and inventory management, which are known as the main tools for coping with such challenges (Govindan et al., 2014; Asl-Najafi et al., 2015). A vitally important operational decision concerns finding optimal vehicle routes to transfer the products through the network efficiently (Govindan et al., 2014). Although finding optimal vehicle routes can significantly reduce costs and improve customer service, many of the studies in the area of CLSC did not consider this important operational decision. Inventory management is another important operational decision that is known as one of the main tools for reducing costs and improving customer service (Asl-Najafi et al., 2015). Indeed, inventory decisions enable firms to offer improved responsiveness at lower cost (Daskin et al., 2002). There are a limited number of studies in SCND that are entirely incorporated in such operational planning levels of analysis. Traditionally, the three sets of decisions (i.e., location-allocation, vehicle routing and inventory management) are made at different levels of management and are generally analyzed separately. However, integrating these decisions leads to better network design because it enables a firm to efficiently manage their logistic system processes (Govindan et al., 2014; Gzara et al., 2014).

Regardless of the system's cost efficiency, sustainability is becoming a growing interest due to the concern about the environmental impacts (EIs) and social impacts (SIs) of business activities (Pagell and Wu, 2009). The World Summit of Sustainable Development (WSSD) defines sustainability as a balance between economic benefits, environmental protection and social developments. Following the WSSD, environmental impacts are a significant pillar of sustainability. Transportation networks have an important role in the design of a sustainable supply chain because they affect the environment through GHG emissions, particularly carbon dioxide (CO_2) (Dekker et al., 2012; Elhedhli and Merrick, 2012; Pan et al., 2013). In this respect, many countries, including both developed and developing countries have set national targets to reduce their CO_2 emissions in the near future. For instance, according to the "Eleventh development plan of China," the country must reduce its carbon emissions by 10 percent (Wang et al., 2011).

Another pillar of sustainability is social responsibility (SR), which has rarely been addressed in the literature (Pagell and Wu, 2009). This aspect of sustainability is related to the force of Non-Governmental Organizations (NGOs) to take responsibility for the SIs of their actions. Because SR includes a wide variety of aspects, considering all of them in SCND would result in a non-optimal network (Pishvaee et al., 2014). Community involvement and development is considered as one of the main aspects of SR because researchers believe that the communities around the workplace should be respected and enhanced economically and socially (Dehghanian and Mansour, 2009; Pishvaee et al., 2012). Indeed, increasing employment opportunities and providing balanced economic development for local communities are the main goals of this aspect of SR. Recently, governments have paid significant attention to this aspect of SR, especially in developing countries (Lakin and Scheubel, 2010). For instance, according to the "Fifth development plan of Islamic Republic of Iran," the issues of job creation and balanced economic development that belong to the community involvement and development aspect of SR have been significantly addressed. Therefore, developing a decision framework to design a sustainable supply chain considering employment opportunities and economic development alongside the environmental aspects of the designed network can be a great help in mitigating the worldwide concerns regarding sustainability.

Due to the dynamic nature of supply chain networks, different parameters such as demand, cost, distances and other relevant parameters may change due to the uncertain circumstances. Because it will greatly affect the design of the network, uncertainties must be addressed in the SCND (Snyder, 2006; Zahiri et al., 2014). To address the uncertainties, three types of modeling techniques have been introduced in the literature: stochastic programming, fuzzy programming and robust optimization; recently, researchers have attempted to combine these techniques to address uncertainties more efficiently (see Snyder, 2006; Mohammadi et al., 2014; Vahdani and Mohammadi, 2015).

This paper develops a sustainable CLSC model, in which routing and inventory decisions are integrated with location-allocation decisions in a multi-period, multi-product CLSC under mixed uncertainty. In this way, a new multi-objective, mixed-integer, nonlinear mathematical programming (MOMINLP) model is proposed to minimize the total investment cost, transportation cost, inventory cost and EIs of a transportation network. Additionally, the proposed mathematical programming model aims to maximize the positive SIs of designing a supply chain network. The main contributions of this paper that differentiate our efforts from related studies are as follows:

- designing a new sustainable multi-period, multi-product closed-loop supply chain that incorporates routing, inventory and location-allocation decisions and addresses the fluctuations in demand, costs, etc.;
- proposing a new environmental objective function to minimize the EIs of CO_2 emissions and fuel consumption (i.e., regarding different factors of vehicles, roads and air conditions) and wasted energy in the transportation network;
- utilizing an M/M/c queueing model to address the waiting time of vehicles in the remanufacturing facilities;
- applying SIs as an objective function to maximize the positive impacts of CLSC network design;
- applying a two-phase approach including an efficient stochastic-possibilistic programming method and a modified game theory approach to cope with the uncertainty;