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Robust sustainable bi-directional logistics network design under uncertainty

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ABSTRACT

Reverse logistics networks are often implemented to ensure a sustainable product or material recovery and to improve a company's sustainability footprint. The most common approach for designing bi-directional networks is the independent design of reverse and forward networks. The joint integration of both networks is rarely considered. Here we study a strategic capacitated facility location problem with integrated bi-directional product flows through a network of multiple supply stages, including production allocations, uncertain data development, facility locations and flexible capacity adjustments. We extend the location and capacity problem by including the decision on the type of depot to install. Forwarding or collecting depots only process one designated direction. Hybrid sites process products of both flow directions. We first introduce a detailed deterministic model assessing the impact of incorporating reverse logistics into a forward-oriented supply chain. This is then extended to a robust capacitated facility location model, which minimizes the expectations of relative regrets for a set of scenarios over a multi-period planning horizon, while considering uncertainty regarding supplying and collecting goods. Example settings show the superior performance of the robust model compared to the deterministic model. The resulting network design mitigates the risks of higher costs and of not being able to fully satisfy demand. This is achieved at costs not significantly higher than the individual optimal solution and with solution times that are promising for applications in practice. The approach supports practitioners in assessing the flexibility of their supply chain, independent of its product flow direction, when operating under uncertainty.

1. Introduction

Sustainability is a topic of growing interest (Pagell and Wu, 2009) especially for companies and their operations. Consumers tend to purchase products according to environmental responsible production of the producing company. The members of the European Union have committed themselves to enforce upcoming legislation to push environmental responsibility of collection and disposal to producers of electrical and electronic equipment (Neto et al., 2008). But the successful adaptation of sustainability in companies and the compliance to the external pressure requires the integration of sustainability aspects in their corporate strategies and their operationalization accordingly. One aspect of corporate strategy and thus target for activities related to sustainability is the long-term logistics network planning. This is considered as part of Sustainable Operations Management (SOM), which also includes green supply chain, green procurement and reverse logistics. The latter comprises the adoption of collection, treatment, recycling and disposal of goods into supply chain operation. An activity conceived as part of the SOM is the integration of reverse logistics into existing, forward-oriented supply chain operations. Lee and Wilhelm (2010) observed that environmental regulations, such as the collection of disposed products, significantly influence facility location planning. Pure reverse logistics networks are claimed to be more complex than pure forward flows because of more uncertainties associated with quality and quantity of returned products (Kara et al., 2007). Thus, the incorporation of returning goods into existing supply chains can account for a significant part of the logistics costs (Min and Ko, 2008; Hameri and Paatela, 2005) and add tremendous complexity (Matos and Hall, 2007) in optimizing the integrated forward and reverse supply chains. This makes optimization methodologies important for the decision-making process (Rastogi et al., in press).

Decision makers of manufacturing companies will be confronted to adjust the supply chain in a way that inbound products will not compromise the outbound activities, customer demand is satisfied and costs minimized. Adjustments need to be viable over longer time periods and flexible enough to cope with the uncertainty of e.g. the amount of demanded and returned products over time.

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On the other side, Hameri and Paatela (2005) observed that the integration of reverse logistics into the forward logistics operations provides a potential for competitive differentiation. Their examined company is thus continuously developing this part of its supply chain service offering. Neto et al. (2008) claim an emerging change of company objectives in supply chain design from cost minimization only, to simultaneous cost and environmental impact minimization. However, the majority of companies are not paying respective attention to the reverse logistics (Min and Ko, 2008; Hameri and Paatela, 2005).

With our paper, we aim to raise awareness for planning over long-term time horizons under extreme uncertainty and provide a robust approach. We propose a mixed integer linear programming (MILP) model formulation for the holistic integration of reverse logistics into existing forward supply chains. Our intent, however, is not to optimize the network design explicitly in terms of sustainability aspects, but in terms of cost minimization. Cost minimization is up to now the typical approach of North American and European companies. Improving sustainability issues is in many cases a very welcome side effect of this approach. The Sustainable Capacitated Facility Location Problem (SuCFLP) incorporates many aspects of the before mentioned complexity like capacity, location and distribution decisions in order to minimize supply chain costs over multiple periods. In particular, we focus on the question how a company with a given set of plants and distribution centers should adapt its supply network to incorporate reverse logistics and contribute to future supply and demand uncertainty.

Aghezzaf (2005) outlines that due to the uncertainty in predicting unstable market factors it is not viable and unrealistic to take capacity and location decisions based on only deterministic solutions. We reckon volatile demand and supply as key driver for concluding capacity adjustment and site location plans and thus as mainly accounting for uncertainty (see also, Aghezzaf, 2005; Poojari et al., 2008; Lee et al., 2010). Hence, to account for the uncertainty of a long-term planning horizon in a volatile demand and supply market, we also implemented a robust model formulation of the deterministic SuCFLP. By this, an optimal solution for a set of scenarios is concluded which is also robust to uncertain future developments. To obtain these robust solutions we use the concept of robust optimization introduced by Mulvey et al. (1995). Our robust approach is able to deal with different supply and demand scenarios and provides solutions which allow a corporate decision maker to evaluate the costs of uncertain developments. Furthermore, by proposing a multi-period model in which location, capacity and customer-facility assignment decisions can be adjusted over time, we enable a decision maker to adjust his decisions from period to period and react according to the realized situations.

The remainder of the paper is organized as follows: first we review the relevant literature on sustainability in supply chain design, robust supply chain design, facility location planning and reverse logistics. Next, we present a deterministic SuCFLP when the demand and supply are known with certainty. We then extend the deterministic model to include uncertainty inherent in predicting volatile market demands and returns (and thus transportation costs and required capacities) via a robust model formulation (RSuCFLP). We present a numerical example and computational results. Finally, we discuss the results of the different approaches and close with our conclusions.

2. Literature review

In the operations management literature several approaches to incorporate sustainability into supply chain design can be found (see Pagell and Wu, 2009 for an overview). Neto et al. (2008) developed a framework for the design and evaluation of sustainable logistics networks for main activities, like transportation and testing, affecting environmental performance and cost efficiency. Neto et al. (2010) study issues regarding the transition from closed-loop to sustainable supply chains and provide extensions of existing models to become sustainable. They further discuss varying definitions and perceptions of sustainable supply chains. We reckon that by including reverse logistics into existing supply chains not necessarily a sustainable supply chain will emerge. However, incorporating reverse logistics is for sure an important first step to built truly sustainable supply chains. The focus of our work, the supply chain design in terms of facility location and their capacities are not part of the above-mentioned studies.

Facility location problems have been studied extensively in the literature. Comprehensive surveys are given by Aikens (1985), Brandreau and Chiu (1989), Owen and Daskin (1998) and Melo et al. (1997). Reviews exclusively concerning stochastic location problems are Berman and Krass (2002), Louveaux (1986) and Snyder (2006). Bhutta et al. (2003) and Thanh et al. (2008) which propose comprehensive deterministic forward flowing models for the design and planning of a production–distribution system with extendable capacities. The works of Gutierrez et al. (1996), Carrizosa and Nickel (2003), Aghezzaf (2005), Chen et al. (2006) and Nagurney (2010) focus on the optimal network design for forward distribution flows but do not consider backward flows of returned goods. A generic framework for dynamic location problems is provided by Melo et al. (2004). In contrast, our approach combines dynamic capacity adjustments and location decisions simultaneously for each echelon over time. This allows the handling of realistic capacity and location decisions, regarding current technology advances in location scalability.

A growing body of literature in operations management also addresses reverse logistics problems for returning products (see Fleischmann et al., 1997; Amin and Zhang, 2012 for a systematic overview). The importance of reverse logistic activities has been described by Stock (2002) and Sasikumar et al. (2010). French and LaForge (2006) study re-use issues and practices in the process industries and show that the differences in comparison to discrete industries call for specific solutions. Lau and Wang (2009) investigate external and internal factors affecting reverse logistics implementation in developing countries like China and identify the major drivers and obstacles faced by the industry. A generic conceptual framework for reverse logistics systems is developed by Lambert et al. (2011). Their framework covers the important elements of reverse logistics systems and assists managers to structure their reverse logistics activities. However, reverse logistics activities are not limited to operations management. Mollenkopf et al. (2011) analyze the functional integration at the marketing–operations interface and show that the coordination of their activities is imperative to a successful returns management.

Another approach to reverse logistics problems, with yet relatively few papers (see Sbihi and Eglese, 2010 for an additional overview), is facility location models, as presented by Jayaraman and Srivastava (1999), Fleischmann et al. (2001), Realff et al. (2004), Listes and Dekker (2005), Salema et al. (2007), Kara et al. (2007), Steinborn et al. (2008), Demirel and Gökçen (2009) and Cruz-Rivera and Ertel (2009). They consider the problem of finding the optimal locations for the processing facilities in order to minimize the costs of the collection of the returned products. The models include forward and backward flows of products in the network but separate them by strictly dedicated distribution facilities that can either function as distribution or collection centers. Zarandi et al. (2011) identify the need of an integrated assessment of both flow directions and propose a closed-loop model for both flows where only facilities are allowed to collect