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Robust bi-level optimization for green opportunistic supply chain network design problem against uncertainty and environmental risk

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ABSTRACT

The main objective of this research is to introduce the concept of Green Opportunistic Supply Chain (GrOSC) and to design it in a lean and agile manufacturing setting under uncertain and risky environment. The model considers the uncertainties of the market-related information, i.e. the demand and transportation and shortage costs, under Vendor Managed Inventory (VMI) strategy. Addressing the retailer's risk aversion level through Conditional Value at Risk (CVaR) to deal with these uncertainties leads to a bi-level programming problem. The Karush-Kuhn-Tucker (KKT) conditions are adopted to transform the model into a single-level mixed integer linear programming problem. Since, the realization of the uncertain parameters is the only information available, a data-driven approach is employed to avoid distributional assumptions. The effectiveness of the model is finally demonstrated through a numerical example.

1. Introduction

Today's rapid economic growth has led to crucial environmental issues such as Greenhouse Gases (GHG) emissions. Carbon dioxide (CO_2) is one of the major GHGs that contribute to climate changes. The increasing global energy consumption, particularly in developed countries, gives rise to the increment of the contribution. Reducing CO_2 emissions therefore has become a major priority for industries and businesses, particularly in the USA, the European Union (EU) countries, and Japan. The criticality of the issue is not limited to developed countries. Developing countries such as Malaysia, China, and Asian partners of Japan are also faced with increasing amount of CO_2 emissions (Urata, Yamada, Itsubo, & Inoue, 2015). It is therefore vital for companies and businesses to obtain a balance between economic interests and environmental protection, especially because of altered consumers' behavior toward green products and services.

As a result of economies of scale, it is not logically expected that all the production processes are finished in a company and a Supply Chain (SC) needs to be designed (Pan & Nagi, 2013). It is therefore necessary to pay more attention to greenness in not only the individual companies, but also the entire SC. A SC is a network of facilities, i.e. suppliers, manufacturers, distributors, and retailers, organized to acquire raw materials, convert these raw materials to finished products, and distribute the products to consumers. Organizational relationships and strategic alliances and partnerships are vital to the success of a SC. As a result, Supply Chain Network Design (SCND) is a crucial decision affecting the future success of the business.

Given the importance of both the SCND problem and the greenness concept, Green Supply Chain Network Design (GrSCND) is emerged. It is an important strategic decision due to its impact on economic and environmental performances of the SC. However, the market needs and market-related information are not clearly known and it is realistic to expect to face uncertainties. The variation in the demand, especially for a new market, is the largest source of uncertainty since the demand stems from irregular order patterns (Lambert & Cooper, 2000). Accordingly, the transportation costs and the amount of CO_2 emissions are also uncertain (Eskandarpour, Dejax, Miemczyk, & Péton, 2015). These uncertainties reduce the predictability of the SCs performance and, consequently, increase risk (Heckmann, Comes, & Nickel, 2015). Due to the importance of the agility in such unpredictable environments, SC agility has become an important issue to enhance the performance of the chain (Hasani, Zegordi, & Nikbakhsh, 2012). A comprehensive review of the research on agility in SCs and individual enterprises has been provided in Fayezi, Zutshi, and O'Loughlin (2016). Furthermore, the literature provides several real-life

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successful agile Green Supply Chain Networks (GrSCNs) such as the networks of Zara, H&M, Oberalp group, Calida, C&A, Mango, and Puma (Turker & Altuntas, 2014). Since, it is acknowledged within the literature that manufacturers agility and partners diversity may lead to SC agility, the concept of Virtual Supply Chain (VSC) is emerged as a potential corporation of some agile enterprises (Chauhan, Proth, Sarmiento, & Nagi, 2006; Fayezi, Zutshi, & O'Loughlin, 2016). Chauhan et al. (2006) introduced a forecast-based Opportunistic Supply Chain (OSC) design approach to deal with the VSC design problem for a new market opportunity. They claimed that the approach is available for semiconductor and automotive manufacturing companies. Paradoxically, many agile companies are anything but lean, i.e. doing more with less, in their SC (Christopher, 2000). However, a demand-driven system can manage the inventory level, which in turn enhances the effectiveness of the network, and leads to lean SC through Vendor Managed Inventory (VMI) strategy (Kang & Kim, 2012).

The literature provides several real-life successful VMI partnerships such as the partnership between Wal-Mart and Procter & Gamble (P&G), among distribution systems of Dell, HP, STMicroelectronics, and Barilla distribution system in Europe (Yu, Huang, & Liang, 2009). In such a strategy, the supplier monitors inventory level of the retailer as well as demand from final customer. It determines how much to replenish its own inventory at the warehouses, and how much to deliver to the retailer. Even though, both the retailer and the supplier follow their own objective to optimize. Such a strategy can be organized through Stackelberg game theory since it is a dynamic non-cooperative game in which player 1, i.e. the leader, chooses a strategy first and then player 2, i.e. the follower, makes its decision accordingly. The corresponding mathematical model is called bi-level programming (BLP). A comprehensive review of recent applications of the Stackelberg game theory to SC management is reported in He, Prasad, Sethi, and Gutierrez (2007). The theory is applicable, especially when a number of the problem inputs are subject to uncertainty (Patriksson & Wynter, 1999), which is usually the case in real situations.

Demand uncertainty is a common cause of SCs inventory risk (Chopra & Sodhi, 2004). The costs resulting from such uncertain demand, e.g. the transportation and shortage costs, are also uncertain. Tang (2006) and Heckmann et al. (2015) reported market demand and cost uncertainties as the operational risks of a SC. Regulatory, competitive, and social pressures to reduce environmental pollution risks magnify the risk arising from these uncertainties. Robust Optimization (RO) approach is therefore needed to deal with vulnerability of the SC in presence of such undeniable uncertainties and risk considerations. The idea to use RO in response to uncertainties of the input data has been studied by several researchers. Ben-Tal and Nemirovski (1999), constructed a robust counterpart of the uncertain problem using ellipsoidal uncertainty sets. Bertsimas and Sim (2004) adopted polyhedral uncertainty sets to keep the linearity of the initial problem. Natarajan, Pachamanova, and Sim (2009) integrated the uncertainty sets into Risk Measures (RMs). A given function μ is called a RM if satisfies the axioms of Monotonicity and Translation in Variance. Bertsimas and Brown (2009) constructed uncertainty sets according to Coherent Risk Measures (CRMs) for robust linear optimization problems. A particular RM is called CRM if satisfies the additional axioms of Convexity and Positive Homogeneity. Thus, a robust counterpart of an uncertain problem can result from CRMs. This approach relies on Decision Maker's (DMs) risk preferences based on a class of CRM, called distortion RMs. A finite number of Conditional Value-at-Risk (CVaR) measures generates such class of RMs. Bertsimas and Brown (2009) introduced CVaR as a controllable means of multiple chance constraints that is tractable in the RO context. Based on the consistency of CVaR with the second order stochastic dominance, minimizing the CVaR is a strong alternative to maximizing the expectation of any risk-averse utility function (Abdel-Aal & Selim, 2017).

In order to better define the aforementioned concepts, consider that a risk-averse DM would like to satisfy the constraint $\mathbf{u}^t\mathbf{x} \geqslant \psi$ with at least $(1-\alpha)$ level of confidence, i.e. chance constraint. Of course, the DM could enforce $p(\mathbf{u}^t\mathbf{x} \geqslant \psi) \geqslant 1-\alpha$ for sufficiently small values of α (Gotoh & Takano, 2007). CVaR is an effective approach that allows DM to obtain any given degree of confidence without missing convexity (Xu, Meng, & Shen, 2013). It transform the problem into the form $\max_x CVaR_\alpha(\mathbf{u}^t\mathbf{x})$ where $\alpha \in (0,1]$ reflects the risk aversion level of the DM (Wu, Zhu, & Teunter, 2013b). α sets a quantitative balance between mean profit and the variance, called risk. In financial point of view, $1-\alpha = 0$ reveals that only the mean profit function is maximized. The DM is therefore risk-neutral, and the CVaR is equal to traditional expected profit (Xinsheng, Zhiqing, Rui, Min, & Ping, 2015). The DMs readiness to sacrifice the mean profit increases, while the parameter α decreases to avoid risk.

This paper formulates a SCND through the selection of prequalified companies, which in turn forms a VSC under uncertainty. The ε-constraint method, introduced by Mavrotas (2009), is employed to address the greenness in the resulting model. The risk arising from decentralized nature of the SC, on the other hand, leads to robustness against uncertainty. The resulting Green Opportunistic Supply Chain Network (GrOSCN) design model is formulated as a bi-level optimization problem using CVaR with respect to the DMs risk aversion level. Finally, an exact solution approach is proposed to solve the model based on the Karush-Kuhn-Tucker (KKT) conditions. The contributions of the paper are summarized as follows:

(a) The main objective of the paper is to introduce the idea of GrOSCN and to develop an integrated model to design the network considering leanness, agility, and robustness.
(b) Addressing the retailer's risk aversion level using CVaR integrates GrOSCN design model with hazard management in a robust manner. The model can be adapted with incoherent risks; however, it originally builds on coherent risks, according to Natarajan et al. (2009).
(c) Integrating OSC concept with VMI strategy via CVaR approach makes the SC well organized against risk. This obtains better information management within the SCs uncertain and risky environment, according to Tang (2006).
(d) Developing a BLP to adopt CRM gives rise to a strong linear relationship between the expected cost of the chain and the retailer's risk aversion level.

The rest of the paper is organized as follows. A literature review and the motivation of the study are given in Section 2. The problem is described in Section 3, and the model is formulated in Section 4. Computational results, discussion, and robust solution analysis are pointed out in Section 5. Finally, conclusions and some future directions are presented in Section 6.

2. Literature review

Integrating decisions of different functions in a single optimization model is an efficient approach to deal with the SCND problem. Some recent researches have been carried out to tackle the OSC network design through such an approach. Chauhan et al. (2006) introduced the OSC network design problem in a deterministic forecast-based situation. The objective of their research was to design a SC by selecting one prequalified partner from each tier of the chain to meet the demand. A limiting characteristic of the