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Resilient procurement planning for supply chains: A case study for sourcing a critical mineral material

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ABSTRACT

This study develops a multi-stage stochastic program to determine optimal selection of suppliers, sourcing strategy, and order allocation in a multi-period supply chain planning under operational and disruption risks. Option contract and spot market are considered as two alternatives for sourcing a critical raw material under an uncertain decision-making environment. Final products' demand and the material's market price are stochastic, and capacity of unreliable suppliers varies randomly because of possible disruptions. For uncertainty modeling, discrete scenarios are generated via a simulation approach and then, a scenario reduction technique is used to construct a suitable scenario tree. To obtain a resilient planning, fortification of suppliers and option contract are exploited as mitigation strategies. Further, the level of supply chain's risk is quantified through a risk measure and limited by risk constraints. Computational results are presented on a real-life supply chain including multiple mines as suppliers and zinc-smelting plants that produce zinc ingots and powder. Using the computational studies and sensitivity analysis, the applicability of the stochastic model, the performance of risk-measurement policies, and the importance of mitigation strategies are investigated to drive some managerial insights.

1. Introduction

In today's complex and uncertain business markets, industries are forced to identify efficient procurement strategies for enhancing their cost management and productivity. In manufacturing companies, procurement cost has a significant part in their supply chain costs and hence a procurement strategy plays a main role in their competitive advantages (Inderfurth and Kelle, 2011). Furthermore, the optimal selection of a supply base, a set of suppliers from which a supply chain purchases its required materials, services and goods, affects a supply chain's success, significantly (Bhutta and Huq, 2002). The goal of this study is to extend an optimization-based resilient procurement strategy to minimize the cost of supply chains and hedge well against exiting uncertainties. The proposed approach can apply to a company that operates a set of manufacturing plants that supply their required material from different suppliers, and two sourcing alternatives including option contract and spot market are possible for them.

Many uncertainty sources in supply chains such as spot market price of raw materials and resources, demand of final products, and availability of suppliers can affect the performance of a procurement strategy and its associated decisions. As mentioned by the European Commission report, a group of materials for deployment of new technologies and sustainable production has become critical because of their high economic importance and supply uncertainty (Lapko et al., 2016). Therefore, well-informed procurement decisions should be viable to function well under an uncertain environment and requires risk analysis, control and mitigation.

In accordance with the presented definition by Tang (2006), supply chain risks are classified into operational and disruption risks. Disruption risks, caused by disruption events such as external natural disasters or intentional/unintentional human actions, may have undesired influences on supply chain's functionality, goals, and performance. Moreover, the operational risks are rooted in recurrent and inherent uncertainties of a supply chain, such as existing uncertainty in demand, supply, market price, and costs. Both of these risk types can affect a procurement strategy for a supply chain. The importance of disruption risks in supplier selection and procurement decisions is highlighted by Berger et al. (2004), Norrman and Jansson (2004), Tang (2006), Snyder et al. (2016), and Ivanov et al. (2016).

Different kinds of supply contracts are introduced as mitigation strategies against uncertainties related to demand and spot market price of required materials or resources. Buy back, wholesale, quantity flexibility, and revenue sharing contract are applicable to deal with demand uncertainty (Cachon, 2003). Further, option and time flexibility contracts have been usually used in face of price uncertainty (Tang, 2006). To hedge against disruptions of suppliers, two types of sourcing strategies including routine sourcing and contingent rerouting can be exploited as disruption-mitigation strategies (Snyder et al., 2016). In

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the routing sourcing strategy, multiple suppliers can be used to simultaneously place supply orders and in contingent rerouting one, it is possible to buy from backup suppliers when the primary ones are not available. Recently, as another disruption-mitigation strategy, some suppliers are chosen in order to fortify them against various disruption events in many research studies.

This paper considers a supply chain including multiple manufacturing plants in which required material can be supplied through multiple suppliers with or without option contract. Suppliers are categorized into reliable and unreliable suppliers, and unreliable ones are not resistant against disruption events. Demands for multiple products and the spot market price of the raw material are stochastic, and unreliable suppliers' capacity varies randomly because of possible disruptions. To obtain a procurement strategy over a multi-period planning horizon, a risk-averse multi-stage stochastic program is developed for the first time in this area. Furthermore, option contract, routing sourcing, and fortification strategies are applied to obtain a resilient strategy. To demonstrate the applicability of the proposed optimization model, the performance of risk-measurement policies, and impacts of mitigation strategies on the resiliency of the procurement planning, a real-life case study is examined. In the case study, a mineral material is considered as a critical resource for a supply chain's productivity. As pointed out by Massari and Ruberti (2013), supply of many critical mineral resources has become a main challenge for many manufacturing companies in the globe.

The remainder of this paper is organized as follows. A selective literature review is presented in Section 2. Characteristics, assumptions, and features of the studied problem are explained in Section 3. In Section 4, the multi-stage stochastic program is formulated. Uncertainty modeling approach related to existing uncertainties in the stochastic problem is explained in Section 5. In Section 6, a real-life case study is explored. In Section 7, numerical experiments are provided. Derived managerial insights from this study are presented in Section 8. Finally, conclusions and future research directions are presented in Section 9.

2. Literature review

Decisions related to supplier selection have a major role in a procurement strategy for supply chains. Many review papers such as Verma and Pullman (1998), Aissaoui et al. (2007), and Karsak and Dursun (2016) investigated the supplier selection problem, and discussed about different decision-making environments, constraints, and objectives in this area.

Scenario-based stochastic programming models can be successfully applied for supply chain planning under uncertainty, and are suitable for providing managerial insights. In the area of supplier selection or/and order allocation, several studies such as Xu and Nozick (2009), Sawik (2011), Sawik (2013), and Torabi et al. (2015) developed stochastic models. However, generation of scenarios and obtaining their related probabilities is a challenging issue, especially in real-life case studies. This study is exploited a scenario tree construction approach, developed by Dupačová et al. (2003) and Heitsch and Römisch (2009), to obtain an appropriate set of scenarios.

Xu and Nozick (2009) developed a two-stage stochastic programming model to optimize supplier selection for a supply chain including multiple plants with deterministic demand and multiple unreliable suppliers. They considered the option contract as an alternative sourcing strategy in face of disruption events. Bilsel and Ravindran (2011) proposed a chance constraint programming model with multiple objectives for supplier selection under uncertainty. Their model used backup suppliers as a mitigation strategy against disruptions. In this area, using dual/multiple suppliers or backup suppliers is a common mitigation strategy in face of operational and disruption risks (see e.g., Ayhan and Kilic, 2015; Dada et al., 2007; Yu et al., 2009; Berger and Zeng, 2006; Meena and Sarmah, 2013; Firouz et al., 2017).

Risk-averse models and supplier fortification strategy are relatively scarce in the area of supplier selection and sourcing problem. Many risk measures such as conditional value at risk (CVaR), standard deviation, variance, and absolute deviation, firstly developed in the area of finance and insurance, can be exploited to propose a risk-averse procurement strategy based on the risk attitude of a decision maker (Heckmann et al., 2015). Value-at-risk (VaR) and CVaR, as two well-known risk measures, are used by Sawik to present risk-averse stochastic models for the integrated supplier selection and order allocation problem (Sawik, 2011, 2013, 2014). Resilient supplier selection with fortification strategy is also addressed by Sawik (2013) and Torabi et al. (2015).

Supply contracts between different supply chain members are usually used as risk-mitigation strategies in the presence of demand or/and price uncertainty. The interested readers can be referred to several survey studies on supply contracts such as Tsay et al. (1999) and Anupindi and Bassok (1999). Recently, Sluis and De Giovanni (2016) empirically identified key drivers for companies in choosing a contract in their supply chains. A few studies including Keyvanloo et al. (2014), Keyvanloo et al. (2015), and Van Delft and Vial (2004) used stochastic programing approaches to address a sourcing problem with supply contracts. Recently, option contracts are gradually exploited in several modern industries to supply their critical resources and raw materials. Based on an option contract mechanism in a multi-period planning horizon, at the beginning of the horizon, a supply chain buys R units of option for each period at reservation cost r. Then, in each period, the supply chain can exercise the option up to the R units with a known exercise price (Keyvanloo et al., 2015). Option contract is used for a sourcing problem under demand or/and price uncertainty by Inderfurth and Kelle (2011), Li et al. (2009), and Barnes-Schuster et al. (2002). However, there are a few papers that captured price uncertainty in a market over multi-period planning horizon. Keyvanloo et al. (2015), such as this study, used Geometric Brownian motion stochastic process with drift to deal with price uncertainty over multiple periods.

This paper presents a resilient procurement strategy, including supplier selection, sourcing strategy, and order allocation decisions, for a supply chain network with multiple plants and reliable/unreliable suppliers. In this study, the demand for multiple products and the spot market price of the raw material are stochastic over a multi-period planning horizon, and the capacity of unreliable suppliers varies randomly because of possible disruptions. In accordance with the presented literature review and introduction section, it can be concluded that this study addresses some critical aspects that have been gained less attentions by previous studies. The major contributions of the paper can be summarized as follows:

- A novel risk-averse multi-stage stochastic program is developed as a mixed-integer linear programming for the integrated supplier selection, sourcing, and order allocation problem.
- Both operational and disruption risks are considered in the problem. To model the related uncertainties, demand of multiple products and the raw material's spot market price follow time-dependent stochastic processes.
- To obtain a resilient procurement policy, different mitigation strategies including the fortification of unreliable suppliers, option contract, and multiple sourcing are simultaneously developed and their impacts on the risk reduction are investigated.
- Some managerial and practical insights are derived by implementing the proposed optimization tools in a real-life case study for sourcing a critical mineral material.

3. Problem description

In this paper, the basic setting of the supply chain network is defined by: *Manufacturing plants* and *suppliers*, and the network is centralized such that there is not any competition among manufacturing plants. A planning horizon divided into multiple tactical periods is