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Modeling a two-stage supply contract problem in a hybrid uncertain environment

Wenfei Li[a], Yankui Liu[a], Yanju Chen[b,*]

[a] Risk Management & Financial Engineering Laboratory, College of Mathematics & Information Science, Hebei University, Baoding 071002, Hebei, China
[b] Key Laboratory of Machine Learning and Computational Intelligence, College of Mathematics and Information Science, Hebei University, Baoding 071002, Hebei, China

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ABSTRACT

This study examines the supply contract problem in supply chain management, in which the uncertain demand is affected by a variety of factors. Since the available historical data cannot adequately determine the exact probability distribution of future demand, the prediction of experienced experts about uncertain demand is usually required in the practical modeling process of supply contract problem. The main contributions of this study are to model the uncertain demand by both probability distribution and possibility distribution, and develop a new two-stage expected value optimization model for our supply contract problem, in which an options-futures contract is employed to reduce the risk of uncertain demand. In the first decision-making stage, the distributor signs an options-futures contract with the supplier to determine the futures and options ordering quantities. After knowing the realization of uncertain demand, the distributor takes the signed options as the recourse decision in the second stage. When the actual demand follows some common probability and possibility distributions, the proposed two-stage optimization model can be turned into its deterministic equivalent programming model so that it can be solved efficiently via commercial optimization software. To illustrate the effectiveness of the proposed optimization method, a practical natural gas supply contract problem is provided in our numerical experiments. The computational results demonstrate that the possibility distribution of uncertain demand does affect the ordering decisions, and modeling uncertain demand by both probability distribution and possibility distribution is more realistic in our natural gas supply contract problem. As a result, the proposed two-stage optimization method can guide distributors to make their informed decisions in practical supply contract problem when the probability distribution of uncertain demand is partially known.

1. Introduction

With the modern large-scale retail industry rapidly expansion, distributors have important strategic positions in the supply chain management, they hold the historical data from retailers and suppliers about sales volume (demand), market share, and other information. The available information influences the distributor's ordering quantity, which can guide production for manufacturers and reserve raw materials for suppliers. The distributor's optimal ordering quantity is not only a requirement for its own profit, but also necessary for rational production in the whole supply chain management. Therefore, optimizing the distributor's ordering decisions in supply chain management is very worthy of study. In addition, the distributor usually faces uncertain decision-making environment, and the uncertainty may be resulted from demand, supply, competition, or their combination (Yi, Ngai, & Moon, 2011). As a consequence, the corresponding order decision problem can be built as an uncertain optimization model.

This study considers the ordering decision problem under hybrid uncertain demand. In the existing literature, some researchers have addressed the case that the probability distribution of demand can be determined exactly by the available historical sales data. However, for some practical supply chain management problems, the distribution of future demand is affected by a variety of factors like the changes in consumer groups and national policies. For example, the natural gas demand in China is affected by current national policies. The Chinese Government positively promote the use of this clean energy in order to control the smog. The policy about changing fuel from the conventional coal to the natural gas was implemented in 2017, which led to sharp increase in demand for the natural gas. In this case, it is unreasonable to order the natural gas exactly according to the historical statistical data. As a result, the statistical distribution is the important reference; the experts' knowledge is necessary to predict the expansion of demand for the natural gas. The important parameter of probability distribution usually presents subjective uncertainty, and its possibility distribution

* Corresponding author.
E-mail addresses: yliu@hbu.edu.cn (Y. Liu), yanjuchen@hbu.edu.cn (Y. Chen).

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can be specified according to the experts' knowledge. Therefore, incorporating a possibility distribution into a probability distribution would be more suitable for predicting the actual demand for the natural gas. Based on the above consideration, we model the uncertain demand by a random fuzzy variable characterized by both probability and possibility distributions, in which the probability distribution reflects the objective uncertainty determined by the available historical data, while the possibility distribution reflects the subjective uncertainty prescribed by the experts' knowledge.

The supply contract can optimize the supply chain system, ensure the coordination of the supplier and the distributor, and maximize the profits of both the supplier and the distributor. Because the demand has hybrid uncertainty and commodities are provided based on the ordering decision, ordering too much will lead to an inventory backlog, while ordering too little will lead to a stockout, therefore making only one-stage decisions may lead distributors to bear high risks. To reduce risk, distributors would like to make a recourse decision in the second stage according to the realization of uncertain demand. This study employs an options-futures contract to divide the decision-making process into two stages. In the first stage, the initial decisions are to determine the amount of futures and options to order; in the second stage, the recourse decision is to determine the amount of options to exercise.

This paper differs from the existing related studies and makes the following main contributions to the current literature. First, it establishes a new two-stage random fuzzy expected value model for a distributor's supply contract problem, in which uncertain demands are characterized by both possibility and probability distributions. This integrated description of hybrid uncertainty is more realistic compared with single uncertainty. The applied options-futures contract can ensure a two-stage decision-making process. Hence, the distributor can make a recourse decision in the second stage to reduce the risk associated with hybrid uncertain demand. Second, this paper discusses the calculation process about the expected value of random fuzzy variables, which helps us to obtain the analytic expressions of the objective function in several important types of uncertain distributions. Third, to overcome the crux about the solution of the proposed two-stage supply contract model, this study derives the deterministic equivalent optimization model of the proposed original uncertain optimization model under common probability and possibility distributions. Finally, this study provides a practical natural gas supply problem as an application example to illustrate the effectiveness of the proposed supply contract model. We also compare the proposed two-stage optimization method with stochastic optimization method via numerical experiments. The computational results illustrate that the proposed two-stage random fuzzy supply contract model can guide distributors to make their informed order decisions.

The structure of this paper is as follows. Section 2 reviews the relevant literature. Section 3 builds a two-stage expected value model for the supply contract problem with hybrid demand uncertainty. Section 4 analyzes the two-stage random fuzzy programming model, and derives the optimal value expression of the second-stage programming. Section 5 transforms the proposed two-stage model into the tractable deterministic equivalent single-stage optimization model. Section 6 provides a numerical example to illustrate the effectiveness of the proposed model. This section also discusses the impacts of different fuzzy parameters on ordering decisions and profit. Section 7 concludes the paper and presents future research. All proofs are given in the Appendix.

2. Literature review

Three research fields are closely related to our study: supply contracts, uncertain programming and evaluation criteria. We briefly review the related literature in the following subsections.

2.1. Literature on supply contracts

Supply contracts have been a hot research topic in supply chain management. Contracts are comprehensive coordination mechanisms to coordinate supply chain partners. Govindan, Popiuc, and Diabat (2013) point out that contracts play an important role in transfer payment contractual incentives and inventory risk sharing, and then classify contracts accordingly. Signing a contract is an effective way to reduce risks, and scholars have studied a variety of supply contracts. Cachon (2004) studies the impact of allocating inventory risk on supply chain efficiency with three types of wholesale price contracts. A push contract can let retailer order entire supply, and bear all of the inventory risk. A pull contract lets supplier bear the inventory risk because only the supplier holds inventory while the retailer replenishes as needed during the season. Advance-purchase discounts generate the intermediate allocations of inventory risk. An option contract guarantees a needed replenishment after knowing the realization of demand, so that it makes retailer a reduction in the inventory holding cost and opportunity cost. Gomez-Padilla and Mishina (2009) analyze the impact of an option contract on supplier and retailer. A buyback contract makes the buyer can return unsold units to the seller at a unit buyback price. Becker-Peth, Katok, and Thonemann (2013) examine the effect of newsvendor behaviors on ordering decision by designing a buyback contract with the same critical ratio but different contract parameters. For the buyer, a quantity flexibility contract can be used to determine the size of orders that should be released in the current period and revise the reservation quantity from each supplier for a contracted period. Kim, Park, and Shin (2014) focus on a quantity flexibility contract. Lan, Zhao, and Tang (2015) design a contract that employs inspection, price rebate and effort simultaneously to maximize the buyer's expected payoff. A revenue sharing contract and risk sharing contract can guarantee the various cooperation units in the supply chain share revenue and risk, respectively. Avinadav, Chernonog, and Perlman (2015) employ a revenue sharing contract to circumvent the double marginalization effect that associated with vertical competition. Through combining the effect of demand uncertainty and price volatility, Ghadge, Dani, Ojha, and Caldwell (2017) develop a novel supply chain risk sharing contract to mitigate supply chain risks. Govindan, Diabat, and Popiuc (2012) evaluate the performance measures and supply chain profit behavior under buyback, revenue sharing, quantity flexibility and advanced purchase discount contracts versus no coordination and wholesale price systems. They indicate the different performances of different contracts in the aspect of gaining profit under different circumstances. Therefore, it is necessary to choose a proper contract for the actual optimization problem. A mixed-ordering contract, options-futures contract, is ordering some commodities and purchasing some options. Wang and Chen (2015) demonstrate that the mixed-ordering contract is a more optimal policy than single ordering. Li and Chen (2016) study the optimal ordering decision problems with random demand using options-futures contract.

Different types of contracts have different performances in the supply chain management. The literature review shows that designing and signing an appropriate contract in commercial activities can reduce risk and increase profit. To the best of our knowledge, there is no literature about options-futures contracts in the two-stage decision process under hybrid uncertain environment. This study examines the supply contract problem, in which the distributors are at the risk of uncertain demand, and options-futures contracts can ensure distributors make a recourse decision in the second stage after knowing the realization of uncertain demand.

2.2. Literature on uncertain programming

In the literature, stochastic programming is the initial method for modeling uncertain decision problems. Cachon (2004), Gomez-Padilla and Mishina (2009), Becker-Peth et al. (2013), Kim et al. (2014),