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Highlights

1. Studying option contracts with risk considerations in a two-echelon supply chain.
2. Constructing the mean-variance models of option contracts.
3. Investigating the channel coordination of option contracts with risk constraints.
4. Designing a new minimum option quantity commitment for the supplier.

Mean-Variance Analysis of Option Contracts in a Two-Echelon Supply Chain

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Abstract: This paper studies the implications of risk considerations for option contracts in a two-echelon supply chain. Under the mean-variance framework, we first investigate the conditions for coordinating the supply chain by using option contracts. We find that supply chain coordination is not always achieved, contrasting with the result that properly designed option contracts can always coordinate a supply chain in the absence of risk considerations. Second, we analyze the Stackelberg game for a decentralized supply chain in two cases, depending on whether the retailerôs risk aversion threshold is known to the supplier. We show that when the threshold is public information, there exists a unique equilibrium in which the supplier with a higher risk tolerance prefers to reduce the exercise price, and thus, the retailerôs order quantity increases. When the retailerôs risk aversion threshold is private information, the retailer has an incentive to pretend to be less risk averse. To curb this incentive distortion, we design a new minimum option quantity commitment for the supplier. We complement our theoretical results with numerical simulations.

Keywords: supply chain management; option contract; risk constraint; mean-variance model; supply chain coordination

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1. Introduction

Risks are pervasive in firmsô operational decisions, and thus, risk management plays a vital role in the success of firm operations. Indeed, inappropriate risk management may lead to significant financial losses. For example, rapidly weakening demand coupled with locked-in supply agreements incurred a $2.5 billion inventory write-off for Cisco Systems, Inc. in the second quarter of 2001 (Norrman and Jansson, 2004). In the third quarter of 2001, Nike lost $100 million in sales revenue due to an inventory shortage (Norrman and Jansson, 2004). Therefore, incorporating risk factors into supply chain decisions has drawn heightened attention from practitioners. For instance, Hewlett-Packard established a procurement risk management system to evaluate and control supply chain risks. Through this system, Hewlett-Packard saved at least $100 million in sourcing costs in 2008 (Nagali et al., 2008). Although firms have begun to realize the importance of supply chain risk management, determining how to make a tradeoff between profit and risk remains a significant challenge.

Previous studies have mainly focused on two types of supply chain risk: disruption risks, such as those associated with wars, earthquakes, diseases and terrorist attacks (Qi et al., 2004; Sodhi et al., 2012; Ray and Jenamani; 2016), and operational risks, such as those emanating from supply reliability and demand uncertainty (Wei and Choi, 2010; Liu and Nagurney, 2011; Xue et al., 2016, Zeng and Yen, 2017, Fan et al., 2017). Researchers have proposed various methods for managing a supply chain under risk constraints. The most widely used method is the mean-variance framework, originating from Markowitzôs portfolio theory. Markowitz originally proposed the mean-variance framework to analyze risk diversification of financial assets and to help investors design an optimal portfolio (Markowitz, 1959).

The mean-variance framework is widely explored within the realm of operational decisions to address various supply chain risks, particularly those arising from uncertain market demand (Tomlin, 2006; Choi et al., 2008a; Wu et al., 2009; Choi and Chiu, 2012; Liu et al., 2016; Chiu and Choi, 2016). Specifically, Choi et al. (2008a) carry out a mean-variance analysis for the newsvendor problem in which decision makers are risk-averse, risk-neutral, or risk-taking. They analytically investigate the effective frontiers for each case. With the same objective function, Choi and Chiu (2012) study the mean-downside-risk and mean-variance newsvendor models for both the exogenous and endogenous retail price cases. They find that the retailer orders the same stocking amounts in the mean-downside-risk and mean-variance models. Some studies have also analyzed how to achieve supply chain coordination within the mean-variance framework (Gan et al., 2004; Gan et al., 2005; Choi et al., 2008b; Choi et al., 2008c; Wei and Choi, 2010; Chiu et al., 2011). For instance, Choi et al. (2008c) study the coordination of a buyback contract under the mean-variance framework. They find that channel coordination is not always achievable under risk constraints, in contrast to results indicating that the conventional buyback contract can always coordinate a supply chain (Pasternack, 1985; Tsay, 2001; Lee and Rhee, 2007). Chiu et al. (2011) investigate the channel coordination problem for a target sales rebate contract in which supply chain parties make decisions based on a mean-variance analysis. Wei and Choi (2010) explore the coordination of both a wholesale price and a profit-sharing contract under the mean-variance model. They analytically characterize the necessary and sufficient conditions under which supply chain coordination is achieved. The present paper contributes to this line of research by providing a mean-variance analysis of option contracts, with a focus on supply chain coordination and equilibrium analysis for a two-echelon supply chain.

Contract arrangements provide a useful risk management mechanism in supply chains under demand uncertainty. For example, option contracts allow a buyer to determine how much to purchase according to the realized market demand, while providing a supplier with upfront payments. Option contracts have seen widespread application in a number of industries, including IT, telecommunications, semiconductors, and electricity (Wu and Kleindorfer, 2005; Anderson et al., 2017). For example, many giant companies, such as IBM, Sun Microsystems and Hewlett-Packard, have taken a portfolio procurement strategy with options (Tsay and Lovejoy, 1999). In addition, option contracts have been used in the agriculture industry (Zhao et al., 2013; Wang and Chen, 2017). For example, to facilitate vegetable sales in Ishikawa, Japan, some local farmers established an agriculture agency as their representative to negotiate with vegetable buyers such as stores and restaurants. The agency has offered the option contracts of vegetables to its buyers since 2008. The buyers first place an option quantity before the growing season and pay 4% of the total value as deposits. The farmers then grow the vegetable based on the buyersô orders. During the selling season, the buyers purchase an amount of the vegetable up to the option quantity from the farmers at a pre-determined exercise price to satisfy the realized market demand. Figure 1 illustrates this transaction process.

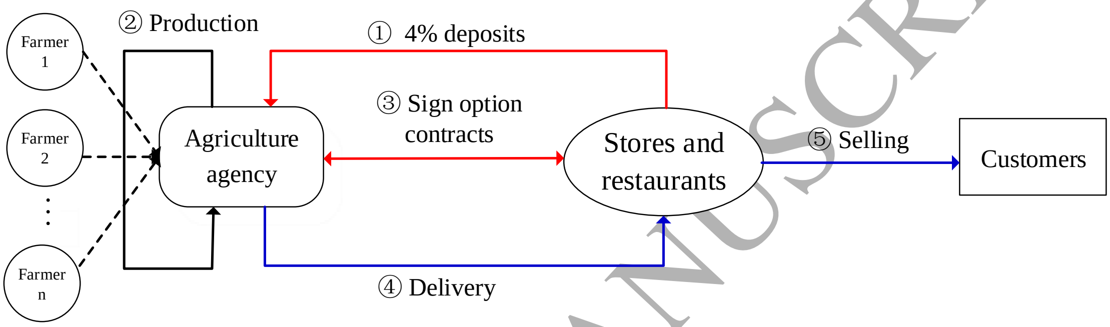

Fig. 1. Transaction process

An increasing number of studies have focused on the application of option contracts to procurement risk management (Wu and Kleindorfer, 2005; Wang et al., 2006; Wang et al., 2012; Zhao et al., 2013; Liu et al., 2014; Nosoohi and Nookabadi, 2016; Paul et al., 2016; Sawik, 2016; Anderson et al., 2017; Zhao et al., 2018). Zhao et al. (2013) examine the feedback effects of the bidirectional option on the retailerôs initial order strategy. Nosoohi and Nookabadi (2016) investigate the manufacturerôs decisions in two stages under call, put and bidirectional options. Wang et al. (2006) analyze a call option contract and show that this contract improves the buyerôs performance. Wang et al. (2012) show that in a two-stage model, the buyer has a higher expected profit in the first stage, whereas the supplier may have worse performance in the second stage compared with the case without option contracts. Those studies compare the optimal decisions relating to option contracts with the conventional newsvendor model within a risky environment. However, little research has examined how risk (as an exogenous factor) affects the supply chain decisions involved in option contracts. Introducing risk constraints into a mean-variance model, we examine supply chain coordination and optimal decisions for option contracts. We find that channel coordination depends on the retailerôs risk attitude and may not always be achieved, in contrast to results indicating that properly designed option contracts can always coordinate a supply chain (Gomez_Padilla and Mishina, 2009; Wang and Liu, 2007; Zhao et al., 2010; Wang et al., 2015).

In this paper, we study the mean-variance model under option contracts in a two-echelon supply chain. We investigate the tradeoff between profit and risk faced by supply chain parties. Our proposed mean-variance model of option contracts is in sharp contrast to that of a buyback contract presented by Choi et al. (2008 c) and that of a profit sharing contract presented by Wei and Choi (2010). Table 1 summarizes the difference of the three contracts with risk constraints.

Table 1. The comparisons of three contracts with risk constraints

Contracts	Control parameter	Degree of control	Coordination
Buyback contract (Choi et al. 2008c)	Returns price ώ̃	Weak	Not always
Profit sharing contract (Wei and Choi 2010)	Wholesale price ύ and profit sharing ratio ‗	Strong	Always
Option contract (our paper)	Option price έ and exercise price ῼ	Strong	Not always

In terms of model setup, the supplier in Choi et al. (2008c) only decides the returns price ώ̃ while the wholesale price is fixed. The manufacturer in Wei and Choi (2010) decides the wholesale price ύ and the profit sharing ratio ‗. In our option contract, the supplier decides the option price έ and exercise price ῼ. These three contracts therefore provide the supplier with different degrees of control in achieving supply chain coordination. As a result, the coordination outcomes are different as well. In Choi et al. (2008c), a higher buyback price offers the retailer higher expected profit and lower risk but imposes on the supplier lower expected profit and higher risk. The results seem inconsistent with classical investment theory, in which a high risk is often accompanied by a great expected profit. Wei and Choi (2010) show the necessary and sufficient conditions that coordinate the supply chain, and they characterize the equilibrium for the Stackelberg game in a decentralized supply chain when the proportion of the profit and risk sharing is predetermined. Our proposed model, however, shows that when the supplier (retailer) bears a lower risk, she (he) obtains a lower expected profit. In addition, in our mean-variance models, the proportion of risk sharing between the supplier and retailer is not predetermined; instead, it is determined by the option price and exercise price. By changing the prices, the allocation of expected profit and risk sharing will be altered. Our results are in line with the observation that with a higher risk tolerance, the supplier always prefers to reduce the exercise price, and the retailer increases the option quantity to enjoy more profit.

We summarize the key results of our paper as follows. We first study the channel coordination of option contracts with risk constraints. We find that supply chain coordination depends on the retailerôs risk tolerance and, more importantly, may not always be achieved. We next study a decentralized supply chain in which the supplier and retailer are maximizing their own profits subject to risk constraints. We consider two cases: (1) the retailerôs risk aversion threshold is public information; and (2) the threshold is private information of the retailer. In the former case, we find that changing the option price and exercise price reallocates expected profit and risk sharing between the retailer and the supplier. We also show that a unique equilibrium exists in the Stackelberg game, and the equilibrium outcomes depend largely on the supplierôs and retailerôs risk tolerance levels. In the latter case, we first show that the retailer benefits from pretending to be less risk averse. To avoid untruthful information reporting on the part of the retailer, we propose a minimum option quantity commitment for the supplier.

The contribution of our paper is twofold. First, our paper contributes to the option contract literature by investigating the implication of risk considerations for option contracts. In doing so, we develop insights into how risk considerations shape the coordination results and equilibrium outcomes. Second, this paper contributes to the literature on contract design with risks by studying supply chain coordination and equilibrium analysis in an option contract setting. In particular, we study both symmetric and asymmetric information settings in which the retailer's risk attitude may be known or unknown to the supplier.

The rest of this paper is organized as follows. Section 2 describes the notation and assumptions. Section 3 studies supply chain coordination with option contracts in the mean-variance model. Section 4 conducts the equilibrium analysis in the decentralized case under both symmetric information and asymmetric information cases. Section 5 concludes and provides some management insights.

2. Model description

We consider a two-echelon supply chain consisting of a supplier and a retailer in which the newsvendor-like retailer orders products from the supplier to satisfy an uncertain demand D. The probability density function (PDF) of D is $f(x)$, the cumulative distribution function (CDF) is $F(x)$, and the complementary CDF is $\bar{F}(x)$. The mean and standard variance of D are μ and σ, respectively. For convenience, we refer to the supplier as "she" and the retailer as "he" in the following analysis.

We are interested in a situation in which option contracts are used to capture the contractual relationship between the supplier and the retailer. As discussed earlier, option contracts have been used in many industries, such as telecommunications, IT and agriculture. The option contract is characterized by an option price o and an exercise price e. By convention, e is the price that the retailer pays to the supplier per unit of the product purchased, and o is the price paid in advance for the reserved options. In practice, the option price o can be thought of as an upfront payment made by the retailer for reserving one unit of the product before the sales season.

The supplier decides the option price o and exercise price e, and the retailer decides how much to reserve from the supplier, which we term the option quantity q. Based on the realized demand x, the retailer purchases $\min(x, q)$ units from the supplier at the exercise price e. The expected sales quantity is given by $S(q) = E[\min(D, q)]$, where the expectation is taken over the random demand D. It is straightforward to show that ῪΎ =ή ˷ ؼ ῀Ὸ ώ Ὼώ϶ To avoid triviality, we assume ἑ ώ̃ ἑ Ὼ ὴ (Zhao et al., 2010; Feng et al., 2014). In fact, assuming Ϊ ώ̃ avoids the unreasonable case in which the supplierȏs production is risk-free. Moreover, assuming Ᾰ ἑ Ὼ and Ϊ Ᾰ ὴ avoids the trivial cases in which the supplier is unwilling to produce and the retailer is unwilling to order. We also consider zero salvage values for the unsold products. Such a setting is appropriate for seasonal products with a long lead time and a short selling horizon. The above setting has been used in many supply chain management papers, such as Kouvelis and Zhao (2012), Kouvelis and Zhao (2016), Feng et al. (2015) and Chen (2015). The sequence of events is illustrated in Fig. 2.

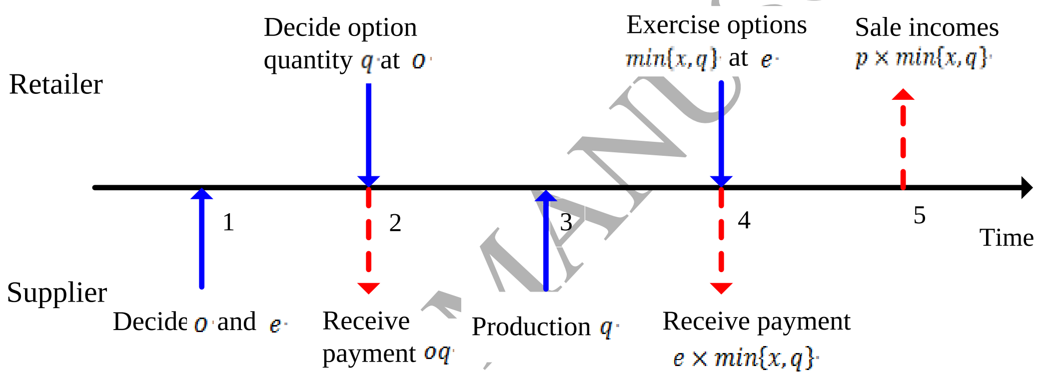

Fig. 2. Sequence of events

Incorporating risk preferences of supply chain members, we construct the mean-variance model to analyze the decisions involved in an option contract. Each supply chain decision maker aims to maximize their expected profits given their risk constraints. For clear interpretation, we list the main notation in Table 2.

Table 2. Summary of notations.

Notation	Definition
ὴ	Selling price
ἑ	Per-unit option price
ώ̃	Procurement cost
Ὼ	Per-unit exercise price
ώ	Market demand level

Table 4. The optimal Ὼᶻ and ή؛ꜧؤب for different ὐؿ and ὐ؛ in the decentralized case.

ὐؿ	ὐ؛	Ὼᶻ	ή؛ꜧؤب	Όὓؿᵚ	Όὓ؛	Όὓ؛	Ὺὓؿᵚ	Ὺὓ؛	Ὺὓؿ	Όὓ/Όὓؿᵚ
500	100	89.00	39.7	3228.9	23.9	3204.9	561.9	61.9	500.0	99.2%
	200	89.00	39.7	3228.9	23.9	3204.9	561.9	61.9	500.0	99.2%
	500	89.00	39.7	3228.9	23.9	3204.9	561.9	61.9	500.0	99.2%
	1000	89.00	39.7	3228.9	23.9	3204.9	561.9	61.9	500.0	99.2%
	1500	89.00	39.7	3228.9	23.9	3204.9	561.9	61.9	500.0	99.2%
750	100	88.36	50.9	4054.8	51.4	4003.4	848.7	98.7	750.0	98.7%
	200	88.36	50.9	4054.8	51.4	4003.4	848.7	98.7	750.0	98.7%
	500	88.36	50.9	4054.8	51.4	4003.4	848.7	98.7	750.0	98.7%
	1000	88.36	50.9	4054.8	51.4	4003.4	848.7	98.7	750.0	98.7%
	1500	88.36	50.9	4054.8	51.4	4003.4	848.7	98.7	750.0	98.7%
1000	100	88.35	51.0	4072.8	52.2	4020.6	850.0	100.0	750.0	98.7%
	200	87.60	60.9	4736.8	92.3	4644.5	1141.7	141.7	1000.0	98.0%
	500	87.60	60.9	4736.8	92.3	4644.5	1141.7	141.7	1000.0	98.0%
	1000	87.60	60.9	4736.8	92.3	4644.5	1141.7	141.7	1000.0	98.0%
	1500	87.60	60.9	4736.8	92.3	4644.5	1141.7	141.7	1000.0	98.0%
1500	100	88.35	51.0	4072.8	52.2	4020.6	850.0	100.0	750.0	98.7%
	200	86.40	71.0	5370.2	164.9	5205.3	1470.6	200.0	1270.6	96.9%
	500	85.30	79.5	5844.9	237.0	5607.9	1762.2	262.2	1500.0	95.9%
	1000	85.30	79.5	5844.9	237.0	5607.9	1762.2	262.2	1500.0	95.9%
	1500	85.30	79.5	5844.9	237.0	5607.9	1762.2	262.2	1500.0	95.9%
2000	100	88.35	51.0	4072.8	52.2	4020.6	850.0	100.0	750.0	98.7%
	200	86.40	71.0	5370.2	164.9	5205.3	1470.6	200.0	1270.6	96.9%
	500	81.20	98.9	6736.3	558.5	6177.8	2464.1	464.1	2000.0	91.7%
	1000	81.20	98.9	6736.3	558.5	6177.8	2464.1	464.1	2000.0	91.7%
	1500	81.20	98.9	6736.3	558.5	6177.8	2464.1	464.1	2000.0	91.7%

To further depict the impacts of risk on Ώ and the ΌŮs, we examine how Ώ and the ΌŮs change with the standard variance „. Fig. 6, 7 and 8 illustrate that in both cases, as „ increases, the supplier increases Ώ and that the ΌŮs of the retailer and supply chain both decrease. When facing the high demand risk indicated by a large „, the retailer reduces the option quantity to lower the potential risk. The supplier correspondingly increases Ώ to compensate the expected profit. Both actions reduce the ΌŮs of the retailer and supply chain.

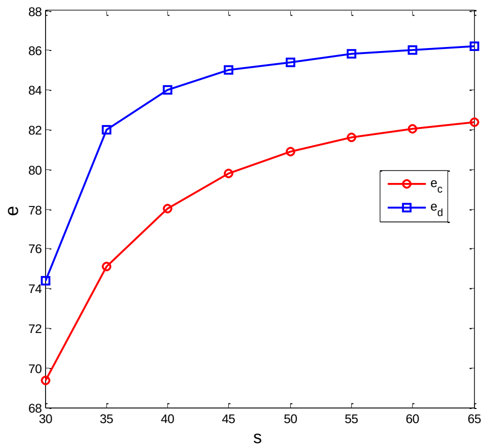

Fig. 6. The changes in Ώ with „ in both cases

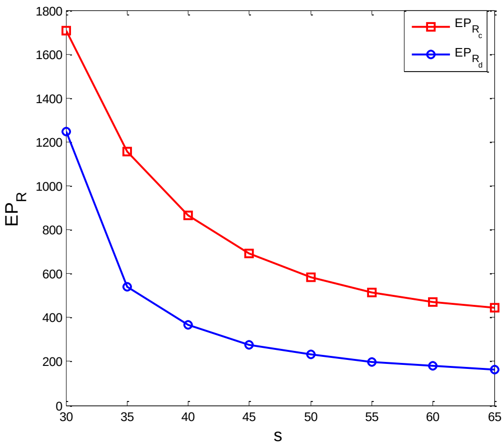

Fig. 7. The changes in ΌŮ; with „ in both cases

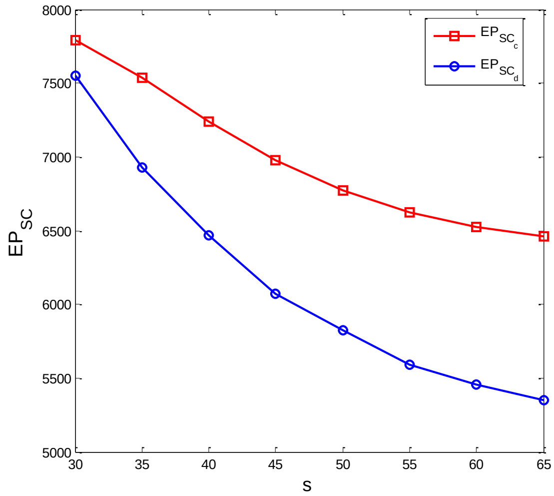

Fig. 8. The changes in ΌŮ with „ in both cases

4.2 Asymmetric information: the retailer¶ risk aversion threshold is private

In the previous section, we focused on the information symmetry case in which the retailerôs risk attitude is known. However, in practice, the supplier may not know the retailerôs risk aversion threshold before offering her prices. It is an interesting question to examine how information asymmetry affects all the decisions in the decentralized case. The sequence of events is as follows: First, the retailer discloses his risk aversion threshold to the supplier, which may not be truthful. Second, the supplier offers an option price and an exercise price to the retailer. Third, the retailer decides the option quantity according to his true risk aversion threshold.

Retailer's problem

Suppose that ὐؿ is the retailerôs risk aversion threshold disclosed to the supplier. Correspondingly, the supplier adjusts the exercise prices Ὠ଴ and Ὠଵ to Ὠ଴ ὐؿ and Ὠଵ ὐؿ based on Propositions 2 and 5. Lemma 2 presents the retailerôs information disclosure decision.

Lemma 2. *If* ὐؿ ὐؿ, *then* ὈὒؿὐؿὈὒؿ ὐؿ.

Lemma 2 shows that the retailer has an incentive to pretend to be less risk averse. By disclosing a smaller risk aversion threshold, the retailer makes the supplier believe that he will likely order more. This incentivizes the supplier to reduce the exercise price. The proof of Lemma 2 indicates that the retailerôs expected profit is decreasing in the exercise price. Therefore, pretending to be less risk averse will lead to a greater profit for the retailer.

Supplier's problem

Lemma 2 shows that the retailer has an incentive to set ὐؿ ὐؿ. This untruthful disclosure benefits the retailer. What action can the supplier take as a Stackelberg leader to prevent this from happening? Motivated by Wei and Choi (2010), we construct a minimum option quantity contract in which both the exercise price and minimum option quantity Ñ are specified. If the retailer chooses a certain contract, then he will order no less than Ñ at a corresponding exercise price. Proposition 6 shows how the minimum option quantity contracts are designed.

Proposition 6. *(i) When* ὺἱ ἁὤὼ ῪὒἹ ήἷἱᾃ ἑἱΏᾃ ἱῪὒἹ ήἷἱᾃ ἑἱΏᾃ *, if* Ώᾃ Ώᾃ ὺἷ *, then* ήᾃ ήἷἱᾃ Ώᾃ ὺἷ ἱὺἷ *and* Ώᶻ ὺἷ Ώᾃ ὺἷ *; if* Ώᾃ ὺἷ Ώᾃ *, then* ήᾃ ήἷἱᾃ ἑἱΏᾃ *and* Ώᶻ ὺἷ Ώᾃ *; (ii) When* ὺἱ ἁὤὼ ῪὒἹ ήἷἱᾃ ἑἱΏᾃ ἱῪὒἹ ήἷἱᾃ ἑἱΏᾃ *, if* Ώᶻ ὺἷ Ώᾃ ὺἷ *, then* ήᾃ ήἹἱᾃ Ώᾃ ὺἷ ἱὺἷ *and* Ώᶻ ὺἷ Ώᾃ ὺἷ *; if* Ώᶻ ὺἷ Ώᾃ*, then* ήᾃ ήἷἱᾃ ἑἱΏᾃ *and* Ώᶻ ὺἷ Ώᾃ.

We explain the result in Proposition 6 as follows. First, in the case of ὺἱ ἁὤὼ ῪὒἹ ήἷἱᾃ ἑἱΏᾃ ἱῪὒἹ ήἷἱᾃ ἑἱΏᾃ , the supplier is more risk tolerant and the risk constraint is inactive. If the risk constraint with ὺἷ is active for the retailer, then the supplier sets the minimum option quantity as ήᾃ ήἷἱᾃ Ώᾃ ὺἷ ἱὺἷ . If the risk constraint with ὺἷ is inactive for the retailer, the supplier sets the minimum option quantity as ήᾃ ήἷἱᾃ ἑἱΏᾃ .

Second, in the case of ὺἱ ἁὤὼ ῪὒἹ ήἷἱᾃ ἑἱΏᾃ ἱῪὒἹ ήἷἱᾃ ἑἱΏᾃ , the supplier is less risk tolerant and the risk constraint is active. If ὺἷ is active for the retailer, then the supplier sets the minimum option quantity as ήᾃ ήἷἱᾃ ἑἱΏᾃ ὺἷ ήἹἱᾃ Ώᾃ ὺἷ . If ὺἷ is inactive for the retailer, then the supplier sets the minimum option quantity as ήᾃ ήἷἱᾃ ἑἱΏᾃ .

For ὺἷ to be active, since ῪὒἹ ήἷἱᾃ ἑἱΏᶻ ὺἷ ήᾃ ὺἷ, the retailer bears the larger risk. The retailer will have to disclose his true risk aversion information. For ὺἷ to be inactive, the retailerȏs untruthful disclosure has no impact on the supplierȏs decision. Thus, the supplier sets ήᾃ ήἷἱᾃ ἑἱΏᶻ ὺἷ only based on her risk constraint. Overall, the contract proposed in Proposition 6 efficiently prevents the retailer from reporting untruthfully.

In Wei and Choi (2010), the retailerȏs largest order quantity that satisfies his risk constraint is independent of the wholesale price. The retailer can therefore control his risk. However, in our model, the retailerȏs largest option quantity that satisfies his risk constraint depends on the exercise price, which is determined by the supplier based on the retailerʼs disclosed risk aversion information and the supplierʼs risk constraint. Therefore, the information that the retailer intentionally discloses can influence the actual option quantity.

To gain further insights into the supplierʼs action, we use Table 5 to illustrate how the supplier sets minimum option quantity contracts. The scenario of ὐɟ ὐɟ represents the case where the retailer provides the true information of the risk aversion threshold. Compared to case (1a), case (1b) presents the case where the retailer pretends to be less risk averse (ὐɟ ρυππ ὐɟ 1000). Then, the supplier sets a smaller exercise price Ὼᶻ ὐɟ 84.50 than Ὼᶻ ὐɟ 86.50 based on the true information. This is consistent with Ὼῐ Ὼȹ ὐɟ Ὼȹ ὐɟ in Proposition 6. The supplierʼs estimated option quantity is 84.35. However, based on Ὼᶻ ὐɟ 84.50 and the true ὐɟ 1000, the retailerʼs actual option quantity is 65.58. This benefits the retailer but hurts the supplier. To prevent this from happening, the supplier sets the minimum option quantity ή ή Ὼȹ ὐɟ ὐɟ 84.35. Compared to case (2a), case (2b) is consistent with Ὼȹ ὐɟ Ὼῐ Ὼȹ ὐɟ in Proposition 6. Then, the supplier sets the minimum option quantity ή ή έὩῐ 107.2. Compared to case (3a), case (3b) is consistent with case Ὼȹ ὐɟ Ὼȹ ὐɟ Ὼῐ. The supplierʼs optimal exercise price Ὼῐ is independent of the retailerʼs risk aversion threshold. The faked information ὐɟ therefore has no impact on the supplierʼs decision. The supplierʼs estimated option quantity equals the retailerʼs actual option quantity, i.e., ή έὩᶻ ὐɟ ή έὩᶻ ὐɟ ή έὩῐ 107.2. Similarly, in cases (4) and (5), the faked information ὐɟ has no impact on the supplierʼs decision.

Table 5. The optimal Ὼ^{z} and ήؤب for different ὐ and ὐ when the retailerôs risk-aversion threshold is private.

	ὐ	ὐ	ὐ	Ὼ ὐ ὐ	Ὼ^{z} ὐ ὐ	ήؤب ὐ ὐ	ή	ΌŨ	ΌŨ	ῪŨ	ῪŨ
(1a)	2500	200	200	86.50(86.50)	86.50(86.50)	71.2(71.2)	71.2	5218.6	158.4	1275.1	200.0
(1b)	2500	200	300	84.50(86.50)	84.50(86.50)	84.35(65.58)	84.35	4759.9	277.5	1090.2	200.0
(2a)	2500	500	500	80.50(80.50)	80.50(80.50)	101.2(101.2)	101.2	6207.3	613.8	2049.7	500.0
(2b)	2500	500	1000	70.00(80.50)	78.50(80.50)	107.2(95.2)	107.2	5815.9	771.3	1827.3	500.0
(3a)	2500	1000	1000	70.00(70.00)	78.50(78.50)	107.2(107.2)	107.2	6239.0	783.8	2165.5	593.4
(3b)	2500	1000	1500	60.00(70.00)	78.50(78.50)	107.2(107.2)	107.2	6239.0	783.8	2165.5	593.4
(4a)	1000	200	200	87.00(87.00)	88.14(88.14.)	60.58(60.58)	60.58	4652.2	61.6	1000.0	134.6
(4b)	1000	200	300	87.00(87.00)	88.14(88.14.)	60.58(60.58)	60.58	4652.2	61.6	1000.0	134.6
(5a)	1000	500	500	87.00(87.00)	88.14(88.14.)	60.58(60.58)	60.58	4652.2	61.6	1000.0	134.6
(5b)	1000	500	500	87.00(87.00)	88.14(88.14.)	60.58(60.58)	60.58	4652.2	61.6	1000.0	134.6

Note: The symbols ñaò and ñbò represent the retailerôs true and faked information disclosure, respectively.

5. Conclusion and management insights

In this paper, we analyze supply chain coordination and option contract design under the mean-variance model. In this model, each party aims to maximize their expected profits subject to constraints on the risk. Our main results are fourfold.

First, the supply chain is not always coordinated under option contracts with risk constraints. By leveraging the exercise price, the supplier achieves the channel coordination only when the retailerôs risk aversion threshold falls within certain intervals. Such a result is distinct from existing research on option contracts without risk constraints, in which the coordination of a supply chain can always be achieved. The option contract with risk constraints may help the supplier balance the tradeoff between the expected profit and risk. In particular, setting the option and exercise prices that maximize the supply chainôs expected profit may benefit the supplier.

Second, the adjustment of the option price and exercise price reallocates the proportion of the expected profit and risk sharing between the supplier and retailer. As the option price increases, the supplierôs expected profit increases, whereas the retailerôs expected profit decreases. As the exercise price increases, the supplierôs expected profit and risk increase, whereas the retailerôs expected profit and risk decrease. This suggests that a supplier with a higher risk tolerance always prefers to reduce the exercise price and that a retailer with a higher risk tolerance prefers to increase option quantity. This finding is consistent with classical investment theories, in which a higher profit always accompanies a higher risk.

Third, there exists a unique equilibrium for the Stackelberg game in a decentralized supply chain. Both the equilibrium exercise price and the option quantity depend on the risk aversion thresholds and the solutions for the risk-neutral case. When the supplier and retailer both have high risk tolerance, which corresponds to large risk thresholds, they will adopt relatively positive operational strategies.

Finally, in the scenario where the retailerôs risk aversion threshold is private, we find that the retailer has an incentive to pretend to be less risk averse. We also find that by constructing a minimum option quantity contract, the supplier is able to prevent the retailer from intentionally disclosing faked information. When the retailerôs risk constraint is active, a minimum option quantity commitment proposed by the supplier places a higher risk on the retailer than his true risk tolerance. The retailer is therefore motivated to disclose his true information. When the retailerôs risk constraint is inactive, the retailerôs faked information has no impact on the supplierôs decision, and thus, the supplier sets a minimum option quantity based solely on her risk constraint.

Our work points to two important managerial insights. First, all decisions involved in option contracts are dependent on the risk tolerance. A supplier with a higher risk tolerance always prefers to reduce the exercise price to induce the retailer to order more. A retailer with a higher risk tolerance is willing to increase option quantity to gain more expected profit. Such actions lead to a higher supply chain risk. Second, the adjustment of the option price and exercise price causes the reallocation of the expected profit and risk sharing between the supplier and retailer. By setting prices, the supplier is able to determine who can enjoy more profit or take less risk in the supply chain under an option contract.

Finally, we discuss several potential extensions arising from this research. First, the current paper considers a deterministic selling price. It is a potentially meaningful research direction to consider the selling price as an endogenous decision variable (Choi and Chiu, 2012). Second, both the supplier and the retailer in our model are endowed with unlimited capital. However, in reality, supply chain parties may be financially constrained. Thus, another possible extension is to consider the playersô financial constraints in the presence of bankruptcy risk. Third, we model risk within the commonly used mean-variance framework. It would be interesting to explore other modeling frameworks. A notable example is the CVaR framework, which focuses on the decision makerôs expected profit from the lower quantile (Lotfi and Zenios, 2018). By considering different risk modeling frameworks, one may draw comparisons with our mean-variance framework. We leave these extensions as future research.

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Appendixes

Appendix A (Proof of Proposition 1)

(i) Taking the first-order condition of ῪῦῚ with respect to ή yields ῀ ΰ Ὸ ή ῀ Ὸ ὼ Ὼὼ. Obviously, π. Furthermore, we have that ῪῦῚ is increasing in ή.

(ii) Taking the first-order condition of ῸῦῚ with respect to ή yields ὴ ὢ ὴ Ὸ ή. Since ὴ Ὼ ή π, ῸῦῚ is concave. Let π. We have ή Ὸ . Since ς ρ Ὸ ή Ὸ ὼ Ὼὼ π, , ή is increasing in ή. Let ή ὢὶ Ὼ άὤὼ ῪῦῚ ή ὺ. When ῪῦῚ ή ὺ, then ή ή. Since ῸῦῚ is increasing in ή in the interval πἫή, the optimal option quantity that satisfies (P1) ή ή ή. When ῪῦῚ ή ὺ, then ή ή. The optimal option quantity that satisfies (P1) ή ή ή. Therefore, ή ά Ὶὲ ή ἫήῚ. Since ή ὢὶ Ὼ ά ὤὼ ῪῦῚ ή ὺ is increasing in ὺ and ή is independent of ὺ, we have that ή is non-decreasing in ὺ.

Appendix B (Proof of Proposition 2)

Taking the first-order condition of Ὸῦ with respect to ή yields ὴ Ὼ έ ὴ Ὼ Ὸ ή. Since ὴ Ὼ Ὼ ή π, Ὸῦ is concave.

Let ۾ ̊ ۋ / ݉ݎ π. We have ή፡ቤ̊ ێǡ ݍ ሺͲሻ ൌ ݀ଵ݄ଶ / ݀ଵ݄ . Taking the first-order condition of ή፡ቤ̊ ێǡ ݍ with respect to ݍ yields ۾ݎ ቤ ݄ଶ / ݀ݍ ൌ ݄ / ݀ଵ݄ ݂ ݎ ቤ ݄ଶ π . Therefore, ή፡ቤ̊ ێǡ ݍ is decreasing in ݍ.

Since ή፡ቤ፡ ݍ ൌ ݉݅݊ݔ ݓ ሾܷሺή ሻ ൒ ߟሿ and ݀ή / ݀ݔ , ή is increasing in ή, we have ή ሺݍሻ ൌ ሼߟ, ή፡ቤ፡ ሺݍሻሽ ൒ ߟ given any risk-aversion threshold ߟ .

Furthermore, ۾ݎ ቤ ݅ / ݀ݍ ൌ ݂ ݎ ቤ ݅ / ή ݍ ̰ ݎ ቤ ݅ ... π . Therefore, ή፡ቤ፡ ሺݍሻ is increasing in ݍ.

Let ݍ଴ ൌ ή ݄ / ̰ ݎ ቤ ݄ଶ be a unique root of ή፡ቤ̊ ێǡ ݍ ൌ ή፡ቤ፡ ݍ . When ݍ ൑ ݍ଴ , then ή፡ቤ፡ ݍ ൒ ή፡ቤ̊ ێǡ ݍ and ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ ൒ ߟ . The optimal option quantity that satisfies (P1) ή፡ቤ ێǡ ݍ ൌ ή፡ቤ፡ ݍ ൒ ή፡ቤ̊ ێǡ ݍ . Hence, ή፡ቤ ێǡ ݍ is increasing in ݍ. When ݍ ൐ ݍ଴, then ή፡ቤ፡ ݍ ൏ ή፡ቤ̊ ێǡ ݍ and ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ ൒ ߟ . The optimal option quantity that satisfies (P1) ή፡ቤ ێǡ ݍ ൌ ή፡ቤ̊ ێǡ ݍ ൐ ή፡ቤ፡ ݍ . Furthermore, ή፡ቤ ێǡ ݍ is decreasing in ݍ. Therefore, we have ή፡ቤ ێǡ ݍ ൌ ݉݅݊ሼή፡ቤ̊ ێǡ ݍ ǡ ή፡ቤ፡ ݍ ሽ .

Appendix C (Proof of Proposition 3)

Taking ێ and ݍ as variables and solving the equation ή፡ቤ̊ ێǡ ݍ ൌ ή፡ቤ, we obtain the following option contract set, denoted as ߗ, where ߗ ൌ ሼሺێǡ ݍሻ ȁ ێ ൌ ή ݍ ሺͲሻ ή፡ቤ ሽ . If ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ ൒ ߟ , then ή፡ቤ ێǡ ݍ ൌ ή፡ቤ̊ ێǡ ݍ ൌ ή፡ቤ. The supply chain is coordinated under any option contract ሺێǡ ݍሻ in the set ߗǤ Let ή፡ቤ፡ ݍ ൌ ή፡ቤ. We have ݍ ൌ ή ݅ / ݂ ݎ ቤ . Taking ێ and ݍ as variables and solving the equation ή፡ቤ፡ ݍ ൌ ή፡ቤ, we obtain the following option contract set, denoted as ߖ, where ߖ ൌ ሼሺێǡ ݍሻ ȁ ݍ ൌ ή ݅ / ݂ ݎ ቤ ሽ .

If ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ ൏ ߟ , then ή፡ቤ ێǡ ݍ ൌ ή፡ቤ፡ ێǡ ݍ ൌ ή፡ቤ. The supply chain is coordinated under any option contract ሺێǡ ݍሻ in the set ߖǤ If ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ ൏ ߟ ൑ ሾܷሺή፡ቤ̊ ێǡ ݍ ሻሿ , then ή፡ቤ̊ ێǡ ݍ ൌ ή፡ቤ and ή፡ቤ፡ ێǡ ݍ ൌ ή፡ቤ . Since ή፡ቤ፡ ێǡ ݍ ൌ ή፡ቤ̊ ێǡ ݍ and [illegible] , we have [illegible] and [illegible]. Therefore, the supply chain cannot be coordinated.

Appendix D (Proof of Proposition 4)

From the expressions of the [illegible]s and [illegible]s of the supplier and retailer, Proposition 4 can be easily obtained. The details are therefore omitted.

Appendix E (Proof of Lemma 1)

From Proposition 2(i), the retailer's optimal order quantity is [illegible]. For any given [illegible], [illegible]. Thus, [illegible]. The supplier's problem of choosing [illegible] is therefore equivalent to choosing [illegible]. Taking the first-order condition of [illegible] with respect to [illegible] yields [illegible]. Taking the second-order derivative of [illegible] with respect to [illegible] yields [illegible]. Let [illegible]. Then, taking the first-derivative of [illegible] with respect to [illegible] yields [illegible]. Since [illegible] is increasing in [illegible], [illegible]. Furthermore, [illegible]. Thus, [illegible]. Therefore, [illegible] and [illegible] is concave. Based on [illegible], we have [illegible].

Appendix F (Proof of Proposition 5)

We first prove that the supplier's expected profit is concave in [illegible] when both the supplier and the retailer are risk-neutral. Then, we prove Proposition 5.

Taking the first-order condition of ΈΟΰ with respect to Ώ yields ῥ ὤ ΏΌ ή ἐ Ώ ... "Ό ὼ Ώὼ ὴ"Ό ή ἐ Ώ ῷ ... "Ό ὼ Ώὼ. Since "Ό ή ἐ Ώ ..., we have ... . Substituting ... into ... yields ... ὴ"Ό "Ό ή ἐ Ώ ῷ ... "Ό ὼ Ώὼ . From the proof of Lemma 1, ΈΟΰ ή ἐ Ώ is increasing in the interval π ή and decreasing in the interval ή Њ . Hence, if ή ἐ Ώ ή , then ὴ"Ό ή ἐ Ώ ῷ ... "Ό ὼ Ώὼ π . If ή ἐ Ώ ή , then ὴ"Ό ή ἐ Ώ ῷ ... "Ό ὼ Ώὼ π. Since ... π, ... π if Ώ Ώ and ... π if Ώ Ώ. Therefore, the supplier's expected profit without risk constraints is concave in Ώ.

(i) If ὺ ά ὥὼ "ΎΰΈ ή ἐ Ώ , the supplier's risk constraint is inactive. If Ώ Ώ, then ή ἐ Ώ ή Ώ ή ἐ Ώ based on Proposition 2(i). Hence, ... "Ό ὼ Ώὼ ἐ ῷ Ώ"Ό ή Ώ ... . Since ή Ώ ὥὶ"Ώά ὥὼ "ΎΰΈ ή Ώ ὺ and "ΎΰΈ ή Ώ is increasing in ή Ώ , we have

ὴ Ώ "Ό ή Ώ ... "Ό ὼ Ώὼ ... , ή Ώ ςή Ώ

... "Ό ὼ Ώὼ ς ... ὼ"Ό ὼ Ώὼ ... "Ό ὼ Ώὼ ή Ώ

... "Ό ὼ Ώὼ ... ή Ώ ςὼ "Ό ὼ Ώὼ ... ή Ώ

ςὼ "Ό ὼ Ώὼ ... "Ό ὼ Ώὼ ή Ώ ... "Ό ὼ Ώὼ "Ό ... .

... ή Ώ ςὼ Ώὼ ... ή Ώ ςὼ Ώὼ

... "Ό ὼ Ώὼ ή Ώ ... "Ό ὼ Ώὼ ... "Ό ὼ Ώὼ .

Furthermore, ὴ Ώ "Ό ή ... "Ό ὼ Ώὼ. Hence, we have ή"Ο ή Ώ έ ώ . Let Ώ satisfy the equation ή Ώ "Ο . If Ώ Ώ, then ή Ώ ή Ώ ή Ώ .

Furthermore, "Ο ή Ώ έ ώ ή"Ο ή Ώ έ ώ Ùπ . Therefore, π. If Ώ Ώ, then "Ο ή "Ο ή Ώ based on Lemma 1. Furthermore, ή ή Ώ ή Ώ ή έ Ώ . Therefore, Ώ Ώ Ώ. Since ή Ώ is increasing in Ώ, Ό is increasing in Ώ. Furthermore, Ό is increases with Ώ in the interval ώ έ Ώ . Therefore, we have Ώ Ώ. If Ώ Ώ, then ή έ Ώ ή έ Ώ based on Proposition 2(ii). In this case, the retailerôs risk constraint is inactive. Therefore, if Ώ Å, then Ώ Ώ. If Ώ Å, then Ό is decreasing in Ώ in the interval Ώή έ , and we have Ώ Ώ . Furthermore, Ώ άώώ Ώ Ώ .

If ύ άώώ "Ύ ή έ Ώ , then there exists ή Ώ to satisfy ή Ώ ή έ Ώ . Since ή Ώ ώ Ώ άώώ "Ύ ή Ώ ύ and , ή is increasing in ή, we have Ώ , ή Ώ ύ given any risk-aversion threshold ύ. Furthermore, π. Therefore, ή Ώ is decreasing in Ώ . Furthermore, the equation ή έ Ώ ή Ώ has two solutions. Define by Ώ the corresponding exercise price such that ή έ Ώ ή Ώ , where ό ό.

If άώώ "Ύ ή έ Ώ "Ύ ή έ Ώ ύ άώώ "Ύ ή έ Ώ , then άώώ Ώ Ώ Ώ or άώώ Ώ Ώ Ώ . The supplier maximizes the expected profit at point Ώ Ώ or Ώ Ώ. Therefore, if Ώ Ώ, then Ώ Ώ. If Ώ Ώ, then Ό is increasing in Ώ in the interval ώ έ Ώ and is decreasing in Ώ in the interval Ώή έ . Hence, Ώ Ώ. Furthermore, we have Ώ άώώ Ώ Ώ .

(ii) If ύ άώώ "Ύ ή έ Ώ "Ύ ή έ Ώ , then Ώ άώώ Ώ Ώ Ώ. When Ώ Ώ Ώ, then ή Ώ ή έ Ώ . Therefore, the supplier chooses Ώ ᴺ ώ έ Ώ "Ύ Ώ ή έ . From the proof of (i), Ό ή έ Ώ is increasing in Ὠ in the interval ὤἷὨ ̧ and decreasing in Ὠ in the interval Ὠ ̧ ἷ ἠ ἕ . Therefore, we have Ὠᶻ ὤὶ Ὠ ά ὤὼ Ὀὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ ἷ Ὀὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ ̧

Appendix G (Proof of Lemma 2)

If ὐ ̧ ὐ ̧ , then ή ̧ἷ ̧ Ὠ ἷ ὐ ̧ ή ̧ἷ ̧ Ὠ ἷ ὐ ̧ . Furthermore, Ὠ ὐ ̧ Ὠ ὐ ̧ .

(i) If ὐḙ ά ὤὼ Ὕὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ ἷ Ὕὕḙ ή ̧ἷ ̧ ἕἷὨ , then Ὠᶻ ά ὤὼ Ὠ ̧ ἷ Ὠ and the supplierꞌs risk constraint is inactive. There exist the following three subcases.

Subcase 1: if Ὠ ̧ Ὠ ὐ ̧ Ὠ ὐ ̧ , then the estimated exercise price is Ὠᶻ ὐ ̧ Ὠ ὐ ̧ , while the optimal exercise price based on the true information is Ὠᶻ ὐ ̧ Ὠ ὐ ̧ . Thus, Ὠᶻ ὐ ̧ Ὠᶻ ὐ ̧ .

Subcase 2: if Ὠ ὐ ̧ Ὠ ̧ Ὠ ὐ ̧ , then the estimated exercise price is Ὠᶻ ὐ ̧ Ὠ ̧, while the optimal exercise price based on the true information is Ὠᶻ ὐ ̧ Ὠ ὐ ̧ . Thus, Ὠᶻ ὐ ̧ Ὠᶻ ὐ ̧ .

Subcase 3: if Ὠ ὐ ̧ Ὠ ὐ ̧ Ὠ ̧, then the estimated exercise price is equal to the optimal exercise price based on the true information, i.e., Ὠᶻ ὐ ̧ Ὠᶻ ὐ ̧ Ὠ ̧.

(ii) If ὐḙ ά ὤὼ Ὕὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ ἷ Ὕὕḙ ή ̧ἷ ̧ ἕἷὨ , then Ὠᶻ ὤὶ Ὠ ά ὤὼ Ὀὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ ἷ Ὀὕḙ ή ̧ἷ ̧ ἕἷὨ ̧ . Since ὐ ̧ ὐ ̧ , ή ̧ἷ ̧ Ὠἷ ὐ ̧ ή ̧ἷ ̧ Ὠἷ ὐ ̧ . Furthermore, ή ̧ἷ ̧ Ὠἷ ὐ ̧ ή ̧ἷ ̧ Ὠἷ ὐ ̧ . From Proposition 5(i), we know that ή ̧ἷ ̧ Ὠ is decreasing in Ὠ . Since ή ̧ἷ ̧ Ὠἷ ὐ ̧ ή ̧ἷ ̧ Ὠἷ ὐ ̧ , Ὠ ̧ ὐ ̧ Ὠ ̧ ὐ ̧ , where ὸ ὤἷ ό. From Proposition 2, ή ̧ἷ ̧ Ὠ is increasing in Ὠ while ή ̧ἷ ̧ ἕἷὨ is decreasing in Ὠ. Therefore, the equation ή ̧ἷ ̧ Ὠ ή ̧ἷ ̧ Ὠ has at most one solution, Ὠ Ὠ ̧. The equation ή ̧ἷ ̧ ἕἷὨ ή ̧ἷ ̧ Ὠ has at least one solution, Ὠ Ὠ ̧. There exist the following two subcases.

Subcase 1: if Ὠᶻ Ὠ ̧, then the estimated exercise price is Ὠᶻ ὐ ̧ Ὠ ̧ ὐ ̧ , while the optimal exercise price based on the true information is Ώᶻ ὑ ̧ Ώ̦ ὑ ̧ . Therefore, Ώᶻ ὑ ̧ Ώᶻ ὑ ̧ .

Subcase 2: if Ώᶻ Ώ, then the estimated exercise price is equal to the optimal exercise price based on the true information, i.e., Ώᶻ ὑ ̧ Ώᶻ ὑ ̧ Ώ.

To summarize the proofs of (i) and (ii), we have Ώᶻ ὑ ̧ Ώᶻ ὑ ̧ .

Taking the first derivative of ὈὓῚ with respect to Ώ yields ὴ Ώ Ὀ ή έΏ έ Ὀ ώ Ώώ . When ή έΏ ή Ώ , then ὴ Ώ Ὀ ή Ώ Ὀ ώ Ώώ based on the proof of Proposition 5(i). Furthermore, π. When ή έΏ ή έΏ , then Ὀ ή έΏ . Furthermore, Ὀ ώ Ώώ π. Therefore, ὈὓῚ is decreasing in Ώ. Since Ώᶻ ὑ ̧ Ώᶻ ὑ ̧ , ὈὓῚ ὑ ̧ ὈὓῚ ὑ ̧ . The retailer has an incentive to pretend to be less risk averse.

Appendix H (Proof of Proposition 6)

(i) When ὑ ά ώ ή έΏ ή έΏ , then Ώᶻ ά ώ Ώ Ώ and the supplierôs risk constraint is inactive. If ὑ ̧ ὑ ̧ , then ή Ώ ὑ ̧ ή Ώ ὑ ̧ . Furthermore, Ώ ὑ ̧ Ώ ὑ ̧ . There exist the following three subcases.

Subcase 1: if Ώ Ώ ὑ ̧ Ώ ὑ ̧ , then Ώᶻ ὑ ̧ Ώ ὑ ̧ Ώᶻ ὑ ̧ Ώ ὑ ̧ . Therefore, the supplierôs estimated option quantity is ή έΏᶻ ὑ ̧ ή Ώ ὑ ̧ ὑ ̧ . Based on Ώᶻ ὑ ̧ and the true ὑ ̧, the retailer orders the option quantity of ή Ώ ὑ ̧ ὑ ̧ . Since ὑ ̧ ὑ ̧ , ή Ώ ὑ ̧ ὑ ̧ ή Ώ ὑ ̧ ὑ ̧ . Hence, ή ή Ώ ὑ ̧ ὑ ̧ .

Subcase 2: if Ώ ὑ ̧ Ώ Ώ ὑ ̧ , then Ώᶻ ὑ ̧ Ώ Ώᶻ ὑ ̧ Ώ ὑ ̧ . Therefore, the supplierôs estimated option quantity is ή έΏᶻ ὑ ̧ ή έΏ . Based on Ώᶻ ὑ ̧ and the true ὑ ̧, the retailer orders the actual option quantity of ή Ώ ὑ ̧ . From the proof of Proposition 2, ή Ώ is increasing in Ώ, while ή έΏ is decreasing in Ώ. Furthermore, ή Ώ ὑ ̧ ή꜀ⱨ꜀ꜝ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ ὐ꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ . Hence, ή꜀꜀꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ .

Subcase 3: if ΅Ω꜀ ὐ꜀ ΅Ω꜀ ὐ꜀ ΅Ω꜀, then ΅Ωᶻ ὐ꜀ ΅Ω ὐ꜀ ΅Ω꜀. Therefore, the supplierôs estimated option quantity equals the retailerôs actual option quantity, i.e., ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ . Furthermore, the supplierôs optimal exercise price ΅Ω꜀ is independent of the retailerôs risk aversion threshold. The faked information ὐ꜀ has no impact on the supplierôs decision. Hence, ή꜀꜀꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ .

(ii) When ὐ꜀ ά῍ὼ῎ΫὓῘ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ω꜀ ⱨ῎ΫὓῘ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ω꜀ , then ΅Ωᶻ ῍ὶ῎Ωά῍ὼ ΌὓῘ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ω꜀ ⱨΌὓῘ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ω꜀ . If ὐ꜀ ὐ꜀ , then ΅Ω꜀ ὐ꜀ ΅Ω꜀ ὐ꜀ and ΅Ω꜀ ὐ꜀ ΅Ω꜀ ὐ꜀ ΅Ω꜀ based on the proof of Lemma 2(ii). There exist the following two subcases.

Subcase 1: if ΅Ωᶻ ΅Ω꜀, then ΅Ωᶻ ὐ꜀ ΅Ω꜀ ὐ꜀ ΅Ωᶻ ὐ꜀ ΅Ω꜀ ὐ꜀ . Therefore, the supplierôs estimated option quantity is ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ꜀꜀ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ . Based on ΅Ωᶻ ὐ꜀ and the true ὐ꜀, the retailer orders the actual option quantity of ή꜀ⱨ꜀꜀ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ . Obviously, ή꜀ⱨ꜀꜀ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ ή꜀ⱨ꜀꜀ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ . Hence, ή꜀꜀꜀ ή꜀ⱨ꜀꜀ ΅Ω꜀ ὐ꜀ ⱨὐ꜀ .

Subcase 2: if ΅Ωᶻ ΅Ω꜀, then ΅Ωᶻ ὐ꜀ ΅Ωᶻ ὐ꜀ ΅Ω꜀. Therefore, the supplierôs estimated option quantity equals the retailerôs actual option quantity, i.e., ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ꜀꜀ έⱨ΅Ωᶻ ὐ꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ . Therefore, the supplierôs optimal exercise price ΅Ω꜀ is independent of the retailerôs risk aversion threshold. The faked information ὐ꜀ has no impact on the supplierôs decision. Hence, ή꜀꜀꜀ ή꜀ⱨ°꜀ έⱨ΅Ω꜀ .

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