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Make-to-order supply chain coordination through option contract with random yields and overconfidence

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Abstract

This paper investigates a two-echelon supply chain with a supplier and a manufacturer with yield uncertainty. We assume that the manufacturer is overconfident about its yield and examine how this could impact on the performance for each company and the supply chain. We propose option contracts to be used to coordinate the ordering and production across the supply chain. A wholesale price contract without overconfidence (i.e., with complete rationality) about the manufacturer's yield is first developed as a benchmark. Based on that, we analyze the impact of overconfidence on the decisions and the expected profits for each player in the supply chain

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under the wholesale price contract. This setting is then applied to the case of option contracts. We derive analytical results on the decisions and the expected profits, and propose conditions for the option price and the option execution price to achieve supply chain coordination. Overall we find that overconfidence has an adverse impact on the performance of both companies. Their expected profits will decline as the level of overconfidence goes up. Option contracts can improve the performance for both companies but cannot completely eliminate the impact of overconfidence. This paper therefore could be used to guide the coordination and cooperation of companies along a supply chain when there exists yield uncertainty and overconfidence. Our propositions are validated through numerical experiments on a hypothetical case and supported by extensive parameter sensitivity analyses.
Keywords: make-to-order, random yields, overconfidence, wholesale price contract, option contract, supply chain coordination

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1. Introduction

With the development of the Internet, many manufacturing companies are starting to use make-to-order (MTO) in response to consumers' personalization and customization requirements. These MTO companies produce and deliver as per consumers' delivery, quality and quantity needs. MTO is commonly used by industries such as apparel, toys, electronic products, and fresh food processing. Many commodities in these industries are, at least in a sense, perishable and consequently, the value of such commodities will reduce if timely sales could not be achieved for them (Chen et al., 2014). The decisions around procurement and production of perishable products belong to the class of newsvendor problems, and the optimal solution to which had been proposed by Arrow et al. (1951). Since then, many extensions to and applications of the newsvendor problem have been studied in the literature.

The yield of many manufacturing companies can be uncertain under the influence of different factors, such as employees, equipment, and materials (Xu, 2010; Güler and Keskin, 2013). Due to these uncertain factors, MTO companies will be exposed to losses if their actual non-defective production outputs deviate from the orders for perishable products. In order to cope with these risks and improve the response (thus on-time delivery) to customer demand, companies along the supply chain can sign wholesale price contracts or option contracts. Compared with wholesale price contracts, option contracts can on one hand help the downstream supply chain partners transfer the risk of supply and demand mismatch through flexible purchasing strategies, and on the other hand increase the total return for the upstream supply chain partners (Zhao et al., 2013).

When demand or yield is random, research based on option contracts in the literature studied retailers' or manufacturers' ordering and production decisions, and supply chain coordination among supply chain partners. For example, in a two-echelon supply chain which consists of a manufacturer and a retailer, Wang and Liu (2007) and Hu et al. (2014) derived the retailer's optimal ordering and the manufacturer's production decisions based on option contracts, and proposed conditions to achieve supply chain coordination. Zhao et al. (2010) compared the impact of option contracts and wholesale price contracts on the supply chain based on cooperative game methods. Vafa Arani et al. (2016) applied game theory to the coordination mechanism of call options, and proposed revenue sharing, instant purchase and stock-out penalty mechanisms. Wang et al. (2017) studied the impact of customer returns on company pricing and ordering decisions, and obtained single-period and multi-period decisions under option contracts. Hu et al. (2018) demonstrated that option joint pricing mechanism can coordinate and benefit supply chain partners.

With the above in mind, this paper considers a two-echelon supply chain where both the demand and the yield are random. The supply chain consists of a manufacturer, and a supplier who provides key components to the manufacturer. This problem is based on the observation of an electronics manufacturer in Zhongshan, Guangdong China. One MTO product that the manufacturer produces is the customized plugs for different electronic products, which need copper and aluminum as raw materials. With overconfidence in yield rate, the planning for raw materials could be too low to meet the shipment deadline. At the same time, the prices of copper and aluminium fluctuate quite rapidly over time. The manufacturer in this case signs an option contract with the supplier. Specifically, the manufacturer orders majority of the raw materials based on customer order quantity and the yield rate estimation, and places option reserved quantity. The manufacturer then starts production and based on the actual yield quantity to determine the quantity of options. In this way, the manufacturer can control its manufacturing cost and lower its procurement risk.

In the two-echelon supply chain considered in this paper, the manufacturer purchases the key components from the supplier for its manufacturing, and at the same time sells the finished products directly to customers. In response to this supply chain, Xu (2010) analyzed the impacts of two ordering methods of the manufacturer – option orders and instant orders – on corporate decisions and profits. Luo and Chen (2017) considered the spot market price and the randomness of each enterprise's output, constructed a supply chain cooperative game model, and a Stackelberg game model based on option contracts under decentralized decision-making. They further provided the conditions on which Pareto-improvement could be achieved. Nosoohi and Nookabadi (2016) studied the impacts of randomness of demand and processing cost on the manufacturer's optimal initial order quantity and option order quantity under the option contract model. In the context of disaster and humanitarian operations management, in view of the high price and supply scarcity of immediate procurement of relief materials after the strike of disasters, Wang et al. (2015) constructed a relief supply chain. The relief supply chain consists of governments or non-profit organizations as buyers and relief material providers as suppliers. The chain proposes a pre-purchasing strategy based on option contract and buyback contract and an instant purchase strategy with a return policy. In practice, option contracts are found to be used by many companies such as Hewlett Packard for its procurement of memory chips (Fu et al., 2010) and Suning Appliance (a home appliance retailer in China).

A common assumption in the research on option contracts is that the forecasts of the random demand and random yield match with the reality, which consequently leads to the match between decisions and theoretical derivations. However, empirical studies have shown that there are systematic deviations between the actual individual ordering decisions and the optimal solutions obtained from the newsvendor model (Schweitzer and Cachon, 2000; Katok and Wu, 2009). Moore and Healy (2008) used overconfidence to explain this phenomenon: individuals have overconfidence in their forecasts which usually leads to narrower range of forecasts than the actual demands, i.e., overprecision. In total, Moore and Healy (2008) summarized three types of overconfidence: overprecision, overestimation and overplacement. In the newsvendor problem, Ren and Croson (2013) demonstrated experimentally that there is an ordering deviation attributed by overconfidence in forecasting which means that the forecast demand variance is smaller than the actual demand variance. Ren et al. (2017) further pointed out that the retailer's order deviation is linearly correlated to its level of overconfidence, and increases as the variance of demand distribution increases. Li et al. (2016) considered the overconfidence behavior of two competing retailers for demand forecasting and studied the impact of the level of overconfidence on the expected profit of each company. The results showed that overconfidence has a positive effect on corporate profits under the competitive newsvendor model.

However, there is a paucity of research which combines option contracts with corporate overconfidence. For the two-echelon supply chain considered in this paper, Wang et al. (2018) dealt with the manufacturers' overconfidence in demand forecasting and coordinated the supply chain through option contracts to tackle the risk associated with ordering and to increase the profitability for both companies. However, the study by Wang et al. (2018) did not consider the overconfidence of yield. Pu et al. (2017) considered the case when the manufacturer is overconfident about its yield under the Cournot competition model. Their research showed that under the Cournot competition, the overconfidence of one party has adverse effects on the other party which is completely rational. Pu and Zhuge (2014) studied the influence of suppliers' overconfidence and fairness concerns on supply chain bilateral efforts and profits, however, they did not incorporate the application of option contracts.

Based on the above review, this study focuses on a two-echelon supply chain composed of a manufacturer and a supplier and considers their yield randomness. The overconfidence of the manufacturer on its yield is combined with option contracts. Using wholesale price contracts with complete rationality as the benchmark, we analyze the ordering and production decisions under wholesale price contract/option contract with complete rationality/overconfidence and provide analytical results for them. From there, we demonstrate the relationships between the level of overconfidence of the manufacturer, the option and option execution prices and the manufacturer's and the supplier's ordering and production decisions and their expected profits.

This paper is innovative in two ways. First, we combine yield randomness, overconfidence, wholesale price and option contracts into a single study. Our findings suggest that if the manufacturer is overconfident in its yield, it can reduce its risk by signing an option contract with the supplier. Secondly, we simultaneously consider yield randomness across the two-echelon supply chain, and investigate the decisions on the initial ordering quantity and the option order quantity under option contracts. There exist optimal values for the option and the option execution prices when taking a supply chain perspective. Consequently, this research calls for supply chain coordination, cooperation, and negotiation among supply chain partners to drive supply chain performance excellence.

From a theoretical perspective, this paper analytically demonstrates that when the manufacturer is overconfident about its yield, the option contract can offset the risk associated with too much or too little initial ordering quantity; while for the supplier, there exists the possibility of extra ordering benefits. Therefore the two parties across the two-echelon supply chain will both benefit from the option contract when compared with the wholesale price contract. The results further reveal that the manufacturer's overconfidence not only hurts its own profit, but also has ramifications across the supply chain. This reinforces the above call for supply chain coordination, cooperation, and negotiation.

From a practical perspective, this research provides guidance for the manufacturer regarding its decision-making on demand and yield forecasts and material procurement, hence reduces its procurement and production risks. From a supply chain perspective, this paper proposes the mechanisms for option contracts between the upstream and downstream supply chain partners, and suggests ways to set reasonable prices on the option and the option execution prices to optimize across the supply chain and offers coordination mechanisms such as revenue sharing and cost sharing to promote coordination and cooperation to achieve a win-win situation across the supply chain.

The remainder of this paper is organized as follows. Section 2 lists the assumptions and the parameters for our problem. Section 3 analyzes the optimal decisions for both companies when they are completely rational and overconfident about their yields under the wholesale price contracts. Section 4 mirrors the analysis of Section 3 for the cases with the option contracts. In Section 5, we present the numerical results for a hypothetical case to demonstrate the impacts of different parameters on the performance of both companies and the supply chain as a whole. We conclude this paper in Section 6. All proofs to the propositions and corollaries in the paper can be found in Appendix A.

2. Assumptions and Parameters

2.1. Model assumptions

We make the following assumptions in this paper. First, in the two-echelon MTO supply chain consisting of a manufacturer and a supplier, the manufacturer receives customer orders online, compiles production plans according to customer delivery requirements, and issues purchase orders for the key components to the supplier according to its planned production quantities. The supplier determines the quantity to be produced according to the manufacturer's requirements and delivers the key components according to the delivery time requirements. Without loss of generality, we assume the material requirements for both parties maintain a $1:1$ relationship.

Secondly, the products are perishable. Due to various random factors in the production processes, the yields of the manufacturer and the supplier are uncertain. Pu et al. (2017) investigated two types of expectations for yield estimation, namely complete rationality and overconfidence. When the estimation is completely rational, the distribution of the yield is consistent with the actual yield. When overconfidence is presented, the estimated yield is assumed to have the same mean with the actual yield, however with a smaller variance.

Thirdly, due to yield uncertainty, the costs of mismatch between supply and demand are as follows. With wholesale price contracts, if the initial yield quantity of the manufacturer cannot meet the customer demand, the order delivery will need to be postponed. At the same time, the unmet demand will be expedited through spot market procurement and production, and compensation such as price discounts could be offered to the customer for the delayed delivery. Similarly, if the supplier's initial yield quantity does not meet the manufacturer's requirements, the supplier will expedite its production and procurement through the spot market. With the option contract model, the manufacturer has two ordering opportunities: initial ordering and option ordering. If the manufacturer still has unmet demand after the initial order and executing the option, it will incur a penalty cost. The supplier has two production opportunities: it can determine an initial production quantity and deliver them once completed; if the manufacturer executes the option, it will expedite production and deliver again. During the expedited production processes, the amount to be produced is usually small and extra care could be taken during the production. As a result, all products are considered to be meeting the quality requirements. Due to the perishability of the product, excessive finished or work-in-progress products will need to be sold at discounted prices. The manufacturer cannot return its excessive order quantity to the supplier. We do not consider the residual value of the nonconforming products during the manufacturing processes.

In this paper, the optimal ordering and production decisions, and the expected profits are examined for four scenarios: wholesale price contract with complete rationality, wholesale price contract with overconfidence, option contract with complete rationality, and option contract with overconfidence. Using the wholesale price contract and assume complete rationality for both parties as the benchmark for this study, we analyze the impacts of the level of overconfidence, option prices, option execution prices and wholesale prices on the decision making and the expected profits in the supply chain, and propose contract coordination mechanisms for this supply chain.

2.2. Parameters

In this section, we introduce the relevant parameters used in this paper.

We use D and p to represent the demand and the price for the finished MTO product during the planning period.

For the manufacturer m, decision variable Q indicates its order quantity of the key components in the wholesale price contract; decision variables Q_0 and Q_1 are the initial order quantity and the option order quantity in the option contract. The manufacturer's yield rate in the case of overconfidence, as per Pu et al. (2017), is expressed as:

$$\lambda'_m = \alpha_m \bar{\lambda}_m + (1 - \alpha_m)\lambda_m, \tag{1}$$

where λ_m is the actual yield rate when the manufacturer is completely rational, which follows a random distribution, i.e., $0 \leqslant \lambda_m \leqslant 1$. $\bar{\lambda}_m$ is the expected yield rate. The overconfidence factor α_m measures the degree of overconfidence of the manufacturer. When $\alpha_m = 0$, it indicates that the manufacturer is completely rational; while $\alpha_m = 1$ indicates that the manufacturer is extremely overconfident, at which time $\lambda'_m = \bar{\lambda}_m$. Let δ'_m (or δ_m) represent the standard deviation of λ'_m (or λ_m), according to Equation (1), we have:

$$\alpha_m\bar{\lambda}_m \leqslant \lambda'_m \leqslant \alpha_m\bar{\lambda}_m + 1 - \alpha_m,\ \bar{\lambda}'_m = \bar{\lambda}_m,\ \delta'_m = (1-\alpha_m)\delta_m.$$

Other parameters related to the manufacturer m are: c_m^0 represents the unit production cost of the initial production; c_m^1 represents the unit production cost for the expedited production; r_m is the unit spot buying price of the key component; φ is the discount rate for finished products in the case of delayed delivery; b_m is the unit penalty cost for the portion not meeting the customer's required demand; v_m represents the unit residual value of overproduced finished products.

We use $f(x)$ and $F(x)$ to represent the probability density function and the cumulative distribution function of λ_m; π_m^d, π_m^o and $E(\pi_m^d)$, $E(\pi_m^o)$ to represent the profit functions and the expected profit functions of the manufacturer under the wholesale price contract and the option contract, respectively.

For the supplier s, decision variable I specifies its planned material requirement for production. Parameters related to the supplier s consist of: w_s is the wholesale price of the key component; λ_s is the yield rate which subjects to a random distribution with $\bar{\lambda}_s$ as the expected value and σ_s as the standard deviation; o refers to the option price per unit which is paid in advance by the manufacturer to secure the right for option execution; e refers to the option execution price per unit which is paid to the supplier when the manufacturer executes the option; v_s is the unit residual value of excessive qualified products.

We denote c_s^0 the sum of production and procurement costs per unit for the initial production; c_s^1 the sum of spot buying price per unit when the supplier's initial output does not meet the manufacturer's order requirements; c_s^2 the sum of expedited production and purchase costs per unit for the units produced as a result of option execution.

We use $g(y)$ and $G(y)$ to represent the probability density function and the cumulative distribution function of λ_s; π_s^d, π_s^o and $E(\pi_s^d)$, $E(\pi_s^o)$ to represent the profit functions and the expected profit functions of the supplier under the wholesale price contract and the option contract, respectively.

For simplicity, we define $E(\pi_{ms}^d)$ and $E(\pi_{ms}^o)$ as the sums of the expected profits of both companies under the wholesale price contract and the option contract, respectively; $[N]^+ = \max(N, 0)$. Without loss of generality, let λ_j $(j = m, s)$ obey uniform distribution, i.e., $\lambda_j \sim U(\lambda_j^1, \lambda_j^2)$.

We observe the relationships among different parameters as follows. Among all the price or cost parameters, p is the highest, attributed by the fact that the profits obtained by both companies should eventually come from the end customers. Compared with the initial production, the expedited production might need more resources and overtime, and therefore we have $c_m^1 > c_m^0$. Any delay in delivery for the manufacturer or the supplier will impact their costs, and therefore we have: $c_m^1 + r_m - \varphi p > c_m^0$, $e + c_m^1 - \varphi p > v_m$, $c_s^0 < w_s < c_s^1$. We let $b_m = c_m^1 + r_m - \varphi p$ to facilitate the comparison between the wholesale price contract and the option contract.

We let $p\bar{\lambda}_m > c_m^0 + w_s$, $w_s\bar{\lambda}_s > c_s^0 > v_s\bar{\lambda}_s$ so that the unit profit for qualified products is positive and overproduction will be controlled. The spot market procurement of the key components belongs to urgent purchases and therefore $r_m = c_s^1 > w_s$. If the manufacturer executes the option, the supplier will likely need to urgently purchase and produce; therefore $c_s^0 < c_s^2$.

The residual value of the manufacturer's finished products is higher than the residual value of its key components, i.e., $v_m > v_s$. Overall the decision variables maintain $I \geqslant Q > 0$, $Q_0 > 0$, $Q_1 > 0$. All parameters and decision variables take positive values.

3. The Wholesale Price Contract Models

Under the wholesale price contract model, the supplier delivers the key components to the manufacturer at the wholesale price. If the manufacturer is completely rational about its yield rate, the manufacturer's profit function is as follows:

$$\begin{aligned}\pi_m^d(Q) = p\min(\lambda_m Q, D) + v_m[\lambda_m Q - D]^+ - \\ (c_m^1 + r_m - \varphi p)[D - \lambda_m Q]^+ - (w_s + c_m^0)Q.\end{aligned} \tag{2}$$

Equation (2) calculates the sales revenue of the finished products, the residual value of the excessive qualified products, the penalty cost for delayed delivery, and the sum of the purchase and production costs.

The supplier's profit function is expressed as follows:

$$\begin{aligned}\pi_s^d(I) = w_s \min(\lambda_s I, Q) + v_s[\lambda_s I - Q]^+ - \\ (c_s^1 - w_s)[Q - \lambda_s I]^+ - c_s^0 I.\end{aligned} \tag{3}$$

Equation (3) calculates the sales revenue, the residual value of excessive qualified products, the penalty cost, and the production and procurement costs.

Let $V_1(Q) = E\left(\min(\lambda_m Q, D)\right)$, $V_2(I) = E\left(\min(\lambda_s I, Q)\right)$, the expected profit functions for the manufacturer and the supplier can be written as follows:

$$E\left(\pi_m^d(Q)\right) = (p + c_m^1 + r_m - \varphi p - v_m)V_1(Q) - \\ (w_s + c_m^0 - v_m\bar{\lambda}_m)Q - (c_m^1 + r_m - \varphi p)D. \tag{4}$$

$$E\left(\pi_s^d(I)\right) = (c_s^1 - v_s)V_2(I) - (c_s^1 - w_s)Q_0 - (c_s^0 - v_s\bar{\lambda}_s)I. \tag{5}$$

Proposition 1 expresses the optimal ordering quantities for both companies with full rationality under the wholesale price contract.

Proposition 1. *Under the wholesale price contract, when the manufacturer is completely rational with its yield rate,* $E\left(\pi_m^d(Q)\right)$ *is a concave function of* Q. $E\left(\pi_m^d(Q)\right)$ *reaches its maximum if and only if* $Q = Q_d^r$. Q_d^r *satisfies:*

$$\int_0^{\frac{D}{Q_d^r}} x f(x)\,\mathrm{d}x = \frac{w_s + c_m^0 - v_m\bar{\lambda}_m}{p + c_m^1 + r_m - \varphi p - v_m}. \tag{6}$$

$E\left(\pi_s^d(I)\right)$ *is a concave function of* I*, and reaches its maximum if and only if* $I = I_d^r$. I_d^r *satisfies:*

$$\int_0^{\frac{Q_d^r}{I_d^r}} y g(y)\,\mathrm{d}y = \frac{c_s^0 - v_s\bar{\lambda}_s}{c_s^1 - v_s}. \tag{7}$$

We assign a_1 and a_2, which are called key quantiles in Li et al. (2016), as follows:

$$a_1 = \frac{w_s + c_m^0 - v_m\bar{\lambda}_m}{p + c_m^1 + r_m - \varphi p - v_m},$$

$$a_2 = \frac{c_s^0 - v_s\bar{\lambda}_s}{c_s^1 - v_s}.$$

If $\lambda_j \sim U(\lambda_j^1, \lambda_j^2)$ $(j = m, s)$, according to Proposition 1, we have:

$$\frac{D}{Q_d^r} = \sqrt{(\lambda_m^1)^2 + 2a_1(\lambda_m^2 - \lambda_m^1)}, \tag{8}$$

$$\frac{Q_d^r}{I_d^r} = \sqrt{(\lambda_s^1)^2 + 2a_2(\lambda_s^2 - \lambda_s^1)}. \tag{9}$$

Based on Equations (2), (8) and (9), the expected profits of the manufacturer and the supplier with complete rationality under the wholesale price contract are:

$$E\left(\pi_m^{dr}(Q_d^r)\right) = \Bigg[(p + c_m^1 + r_m - \varphi p - v_m)\left(1 - F\left(\frac{D}{Q_d^r}\right)\right) \\ - (c_m^1 + r_m - \varphi p)\Bigg] D, \tag{10}$$

$$E\left(\pi_s^{dr}(I_d^r)\right) = \left[(c_s^1 - v_s)\left(1 - G\left(\frac{Q_d^r}{I_d^r}\right)\right) - (c_s^1 - w_s)\right] Q_d^r. \tag{11}$$

From Equation (2), we can see that when the order quantity of the manufacturer is small, the sales revenue depends on the order quantity, the profit is small and the penalty cost for delayed delivery is large. As the order quantity gradually increases, the profit increases, the penalty cost for delayed delivery decreases, and the expected total revenue exceeds the total cost and the difference between the two gets larger and larger until the order quantity reaches a certain level, at which the difference between the two is the largest, that is, the expected profit is maximized. In the same vein, we can see a similar trend for the supplier's profit from Equation (3).

Proposition 1 indicates that under the wholesale price contract model, when the manufacturer is completely rational about its yield rate, both companies have optimal order and production decisions.

In the case where the manufacturer is overconfident about its yield rate, we offer Proposition 2.

Proposition 2. *Under the wholesale price contract, when the manufacturer is overconfident about its yield rate, $E\left(\pi_m^d(Q)\right)$ is a concave function of Q. $E\left(\pi_m^d(Q)\right)$ reaches its maximum if and only if when $Q = Q_d^c$. Here, Q_d^c satisfies:*

$$\int_{\alpha_m\bar{\lambda}_m}^{\frac{D}{Q_d^c}} \frac{x}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x = \frac{w_s + c_m^0 - v_m\bar{\lambda}_m}{p + c_m^1 + r_m - \varphi p - v_m}. \tag{12}$$

$E\left(\pi_s^d(I)\right)$ is a concave function of I, and reaches its maximum if and only if $I = I_d^c$. I_d^c satisfies:

$$\int_0^{\frac{Q_d^c}{I_d^c}} yg(y)\,\mathrm{d}y = \frac{c_s^0 - v_s\bar{\lambda}_s}{c_s^1 - v_s}. \tag{13}$$

Based on Equation (12), we have:

$$\frac{D}{Q_d^c} = \sqrt{\left[\alpha_m\bar{\lambda}_m + (1-\alpha_m)\lambda_m^1\right]^2 + 2a_1(\lambda_m^2 - \lambda_m^1)(1-\alpha_m)}. \tag{14}$$

From Equations (2), (9) and (14), the expected profits for the manufacturer and the supplier with manufacturer overconfidence under the wholesale price contract are as follows:

$$\begin{aligned} E\left(\pi_m^{dc}(\alpha_m)\right) = &(p + c_m^1 + r_m - \varphi p - v_m)V_1(Q_d^c) - \\ &(w_s + c_m^0 - v_m\bar{\lambda}_m)Q_d^c - (c_m^1 + r_m - \varphi p)D, \end{aligned} \tag{15}$$

$$E(\pi_s^{dc}) = (c_s^1 - v_s)V_2(I_d^c) - (c_s^1 - w_s)Q_d^c - (c_s^0 - v_s\bar{\lambda}_s)I_d^c. \tag{16}$$

Proposition 2 can be interpreted in a similar way to Proposition 1. From Equation (2), we know that if the manufacturer is overconfident, the order quantity or the production quantity is optimal when the difference between the total expected profit and the total cost is the largest. Propositions 1 and 2 demonstrate the existence and uniqueness of the optimal decisions for both companies under the wholesale price contract when the manufacturer is completely rational or overconfident in its yield rate forecast. Corollary 1 compares the relationship among both companies' relevant decisions when the manufacturer is completely rational or overconfident under the wholesale price contract.

Corollary 1. *Under the wholesale price contract, if the manufacturer is overconfident about its yield rate and $\lambda_m \sim U(\lambda_m^1, \lambda_m^2)$, when $a_1 \leqslant \lambda_m^1/2$, the following rules apply: 1) As α_m increases, $\frac{D}{Q_d^c}$ increases, i.e., Q_d^c and I_d^c decrease; 2) $Q_d^c < Q_d^r$, $I_d^c < I_d^r$, $E(\pi_m^{dc}) < E(\pi_m^{dr})$; 3) As α_m increases, $E\left(\pi_m^{dc}(\alpha_m)\right)$ decreases.*

Based on practical production observations, we further assume the following: the gap between the finished product price and the wholesale price is large enough, so that $p > 2w_s$; the residual value of the excessive finished products satisfies $c_m^0 \leqslant v_m\bar{\lambda}_m \leqslant c_m^0 + w_s$; the loss of delayed delivery is large enough so that $c_m^1 + r_m - \varphi p \geqslant v_m + w_s$. If the above assumptions hold, we have $0 < a_1 < 1/3$. If the manufacturer's yield rate $\lambda_m^1 \geqslant 2/3$, then $\lambda_m^1 > 2a_1$. This satisfies the assumptions made for Corollary 1. Corollary 1 shows that under the wholesale price contract, the more overconfident the manufacturer is (i.e., the manufacturer believes it has smaller standard deviation of its yield rate hence smaller production volatility), the smaller its order quantity will be. This leads to a bigger gap to the optimal order quantity, and consequently reduces its expected profit.

The practical significance of Corollary 1 is that when the yield rate of MTO productions is random, it can only be accurately determined once the production is complete. Manufacturers can make varied production plans based on their confidence in their yield rates and operational circumstances. The overconfidence model offers the possibility to differentiate the decisions of different companies for different products and for different customer orders. If a manufacturer has sufficient resources, proper management processes, stable production quality, or the value of the orders is small, or the customer has a lower priority, the manufacturer may take a higher level of confidence, thus reducing its planned production. Otherwise, the manufacturer should reduce its confidence in yield rate, and increase its planned production accordingly.

4. The Option Contract Models

Under the wholesale price contract, the manufacturer only gets one ordering opportunity from the supplier for customer orders during the planning period. Due to the random yield rate, it may lead to delayed delivery or overproduction, thus incurring additional costs. If the manufacturer can sign option contracts with the supplier, the manufacturer will have two ordering opportunities. In addition to the initial order quantity at the beginning of the planning period, an option order quantity can be determined. The option can be executed when there is insufficient output, and therefore transferring part of the risk to the supplier. The supplier could receive more revenue based on the manufacturer's two orders.

Under the option contract, the manufacturer's profit function can be expressed as below when the manufacturer is complete rational about its yield rate:

$$\begin{aligned}
\pi_m^o(Q_0, Q_1) = & \, p\min(\lambda Q_0 + Q_1, D) + v_m(\lambda Q_0 - D)^+ - \\
& (c_m^1 + e - \eta p)\min(Q_1, (D - \lambda Q_0)^+) - \\
& b_m\left[D - (\lambda Q_0 + Q_1)\right]^+ - (w_s + c_m^0)Q_0 - oQ_1.
\end{aligned} \tag{17}$$

Equation (17) calculates the sales revenue of finished products, the residual value of excessive finished products, the total cost of re-production, the penalty cost, the sum of material and production costs, and the option purchase cost.

When a supplier is completely rational about its yield rate, its profit function is expressed as follows:

$$\begin{aligned}
\pi_s^o(I) = & \, w_s \min(\lambda_s I, Q_0) + oQ_1 + e\min(Q_1, [D - \lambda_m Q_0]^+) + \\
& v_s[\lambda_s I - Q_0]^+ - (c_s^1 - w_s)[Q_0 - \lambda_s I]^+ - \\
& c_s^2 \min(Q_1, [D - \lambda_m Q_0]^+) - c_s^0 I.
\end{aligned} \tag{18}$$

Equation (18) considers the supplier's sales revenue, the option sales proceeds, the option execution income, the residual value of excess products, the penalty cost of insufficient initial supply, the supply of expedited production and purchase cost once the manufacturer executes the option, and the sum of production and procurement costs.

Let $V_3(Q_0, Q_1) = E\left(\min(\lambda_m Q_0 + Q_1, D)\right)$, the expected profit functions of both companies are expressed as follows:

$$\begin{aligned}
E\left(\pi_m^o(Q_0, Q_1)\right) = & \, (p + b_m - e - c_m^1 + \varphi p)V_3 + \\
& (e + c_m^1 - \varphi p - v_m)V_1 - \\
& (w_s + c_m^0 - v_m\bar{\lambda}_m)Q_0 - oQ_1 - b_m D,
\end{aligned} \tag{19}$$

$$E(\pi_s^o(I)) = (c_s^1 - v_s)V_2 + oQ_1 - (c_s^2 - e)(V_3 - V_1) - \\ (c_s^1 - w_s)Q_0 - (c_s^0 - v_s\bar{\lambda}_s)I. \tag{20}$$

Based on Equations (19) and (20), we have:

Proposition 3. *Under the option contract, when the manufacturer is completely rational about its yield rate, $E\left(\pi_m^o(Q_0, Q_1)\right)$ is a concave function of Q_0 and Q_1. $E\left(\pi_m^o(Q_0, Q_1)\right)$ reaches its maximum if and only if $Q_0 = Q_0^{or}$ and $Q_1 = Q_1^{or}$. Q_0^{or} and Q_1^{or} satisfy Equation (21). $E(\pi_s^o(I))$ is a concave function of I. $E(\pi_s^o(I))$ reaches its maximum if and only if $I = I_o^r$. I_o^r satisfies Equation (22).*

$$\begin{cases} (p + b_m - e - c_m^1 + \varphi p)\int_0^{\frac{D-Q_1^{or}}{Q_0^{or}}} xf(x)\,\mathrm{d}x + \\ \qquad (e + c_m^1 - \varphi p - v_m)\int_0^{\frac{D}{Q_0^{or}}} xf(x)\,\mathrm{d}x = w_s + c_m^0 - v_m\bar{\lambda}_m \\ (p + b_m - e - c_m^1 + \varphi p)\int_0^{\frac{D-Q_1^{or}}{Q_0^{or}}} f(x)\,\mathrm{d}x = o \end{cases}, \tag{21}$$

$$\int_0^{\frac{Q_0^{or}}{I_o^r}} yg(y)\,\mathrm{d}y = \frac{c_s^0 - v_s\bar{\lambda}_s}{c_s^1 - v_s}. \tag{22}$$

Regarding the optimal decisions of I_d^r and I_o^r for the supplier, although both share the same optimal solution expression, the meanings of the two are different. I_d^r refers to the total production plan under the wholesale price contract, but I_o^r refers to the initial production plan under the option contract. The supplier needs to invest for re-production when the manufacturer executes the option under the option contract.

By analyzing Equation (19) and V_3, we can see that if Q_0 remains constant, as Q_1 increases, the manufacturer's expected profit increases (as revenue increases) even though the option purchase cost increases. After Q_1 reaches a certain level, the sales revenue remains unchanged at constant D, V_3 remains unchanged, but the option purchase cost and production cost will increase. This means the manufacturer reaches its maximum profit when $Q_1 = Q_1^{oc}$. By analyzing V_1, we know that when Q_1 is fixed, as Q_0 increases, V_1 increases accordingly, and the expected profit increases as well. Similarly, when Q_0 reaches a certain level, the sales revenue will depend on the constant D, and the expected increase in the company's revenue is less than the increase of various costs, i.e., the expected profit is maximized at this time.

Based on Proposition 3, we can derive the analytic expressions of Q_0^{or}, Q_1^{or} and I_o^r. Let: $b_1 = p + b_m - e - c_m^1 + \varphi p$, $b_2 = e + c_m^1 - \varphi p - v_m$, $b_3 = w_s + c_m^0 - v_m\bar{\lambda}_m$.

If $\lambda_m \sim U(\lambda_m^1, \lambda_m^2)$, from Equation (21), we have:

$$\frac{D - Q_1^{or}}{Q_0^{or}} = \lambda_m^1 + \frac{o(\lambda_m^2 - \lambda_m^1)}{b_1}.$$

Therefore:

$$\int_{\lambda_m^1}^{\frac{D-Q_1^{or}}{Q_0^{or}}} xf(x)\,\mathrm{d}x = \frac{2\lambda_m^1 o b_1 + (\lambda_m^2 - \lambda_m^1)o^2}{2(b_1)^2},$$

$$\int_{\lambda_m^1}^{\frac{D}{Q_0^{or}}} xf(x)\,\mathrm{d}x = \frac{2(b_3 - \lambda_m^1 o)b_1 - (\lambda_m^2 - \lambda_m^1)o^2}{2b_1 b_2}. \tag{23}$$

Let the right hand side of Equation (23) equal to a_3. If $0 < a_3 \leqslant \bar{\lambda}_m$, we have:

$$\frac{D}{Q_0^{or}} = \sqrt{(\lambda_m^1)^2 + 2a_3(\lambda_m^2 - \lambda_m^1)}.$$

Equation (22) is the same as Equation (7) in Proposition 1, i.e.,

$$\frac{Q_0^{or}}{I_o^r} = \frac{Q_d^r}{I_d^r}.$$

Based on Equations (19) to (22), the expected profits for the supplier and the manufacturer under option contract when the manufacturer is completely rational are:

$$E\left(\pi_m^{or}(Q_0^{or}, Q_1^{or})\right) = \left[b_1\left(1 - F\left(\frac{D - Q_1^{or}}{Q_0^{or}}\right)\right) + b_2\left(1 - F\left(\frac{D}{Q_0^{or}}\right)\right) - b_m\right]D, \quad (24)$$

$$E(\pi_s^{or}(I_o^r)) = \left[(c_s^1 - v_s)\left(1 - G\left(\frac{Q_0^{or}}{I_o^r}\right)\right) - (c_s^1 - w_s)\right]Q_0^{or} + oQ_1^{or} - (c_s^2 - e)(V_3 - V_1). \quad (25)$$

From Equation (19), we know that the overconfidence factor only affects the variance of the yield rate, and does not affect the manufacturer's expected profit and its production quantity decision. Therefore, we can derive the optimal decision based on Proposition 3 for both companies under the option contract with overconfidence, i.e., Proposition 4.

Proposition 4. *Under the option contract, when the manufacturer is overconfident about its yield rate, $E\left(\pi_m^o(Q_0, Q_1)\right)$ is a concave function of Q_0 and Q_1. $E\left(\pi_m^o(Q_0, Q_1)\right)$ reaches the maximum if and only if $Q_0 = Q_0^{oc}$, $Q_1 = Q_1^{oc}$. Q_0^{oc} and Q_1^{oc} satisfy Equation (26). $E\left(\pi_s^o(I)\right)$ is a concave function of I. If only if $I = I_o^c$, $E\left(\pi_s^o(I)\right)$ reaches the maximum. I_o^c satisfies Equation (22).*

$$\begin{cases} (p + b_m - e - c_m^1 + \varphi p)\int_{\alpha_m\bar{\lambda}_m}^{\frac{D-Q_1^{oc}}{Q_0^{oc}}} \frac{x}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x + \\ \quad (e + c_m^1 - \varphi p - v_m)\int_{\alpha_m\bar{\lambda}_m}^{\frac{D}{Q_0^{oc}}} \frac{x}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x \\ \quad = w_s + c_m^0 - v_m\bar{\lambda}_m \\ (p + b_m - e - c_m^1 + \varphi p)\int_{\alpha_m\bar{\lambda}_m}^{\frac{D-Q_1^{oc}}{Q_0^{oc}}} \frac{1}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x = o \end{cases}. \quad (26)$$

Let $k_m = \alpha_m \bar{\lambda}_m + (1-\alpha_m)\lambda_m^1$, $l_m = (1-\alpha_m)(\lambda_m^2 - \lambda_m^1)$, based on Equation (26), we have:

$$\frac{D - Q_1^{oc}}{Q_0^{oc}} = k_m + \frac{o l_m}{b_1}, \tag{27}$$

and:

$$\int_{k_m}^{\frac{D-Q_1^{oc}}{Q_0^{oc}}} \frac{x}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x = \frac{2k_m o b_1 + o^2 l_m}{2(b_1)^2}. \tag{28}$$

Therefore:

$$\int_{k_m}^{\frac{D}{Q_0^{oc}}} \frac{x}{1-\alpha_m} f\left(\frac{x-\alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) \mathrm{d}x = \frac{2(b_3 - k_m o)b_1 - o^2 l_m}{2b_1 b_2}. \tag{29}$$

Let the right hand side of Equation (29) equal to a_4. If $k_m < a_4 \leqslant \alpha_m\bar{\lambda}_m + (1-\alpha_m)\lambda_m^2$, we have:

$$\frac{D}{Q_0^{oc}} = \sqrt{(k_m)^2 + 2a_4 l_m}. \tag{30}$$

From Equation (19), we know $\frac{Q_0^{oc}}{I_o^c} = \frac{Q_d^c}{I_d^c}$. Based on Equations (19) and (20), the expected profits for both companies under option contract with overconfidence are:

$$\begin{aligned} E\left(\pi_m^{oc}(\alpha_m)\right) = {} & (p + b_m - e - c_m^1 + \varphi p)V_3(Q_0^{oc}, Q_1^{oc}) + \\ & (e + c_m^1 - \varphi p - v_m)V_1(Q_0^{oc}) - \\ & (w_s + c_m^0 - v_m\bar{\lambda}_m)Q_0^{oc} - oQ_1^{oc} - b_m D, \end{aligned} \tag{31}$$

$$\begin{aligned} E(\pi_s^{oc}) = {} & (c_s^1 - v_s)V_2(I_o^c) + oQ_1^{oc} - (c_s^2 - e)(V_3 - V_1) - \\ & (c_s^1 - w_s)Q_0^{oc} - (c_s^0 - v_s\bar{\lambda}_s)I_o^c. \end{aligned}$$

Proposition 4 shows that, under the option contract, each company has its optimal ordering quantity and optimal expected profit in accordance to the manufacturer's overconfidence factor. Propositions 3 and 4 show that regardless of the overconfidence level, companies should consider the magnitude of different costs and prices, and decide the optimal ordering or production quantity, once the customer demand is confirmed.

We propose Corollary 2 to compare the optimal order quantities and the production quantities of each company when the manufacturer is either overconfident or completely rational under different contracts.

Corollary 2. *The relationships between the optimal decisions of the manufacturer under the option contract and under the wholesale price contract are as follows:*

$$\frac{D - Q_1^{or}}{Q_0^{or}} < \frac{D}{Q_d^r} < \frac{D}{Q_0^{or}},$$
$$\frac{D - Q_1^{oc}}{Q_0^{oc}} < \frac{D}{Q_d^c} < \frac{D}{Q_0^{oc}}.$$

Corollary 2 shows that, the initial order quantity under the option contract will be less than the initial order quantity under the wholesale price contract. For the manufacturer, although the costs of option purchase and option execution increase, the increase in sales revenue and the reduction of procurement and production costs will lead to an increase of the total expected profit. For the supplier, the signing of the option contract means the initial sales revenue will decrease. However, the gain from options (including the proceedings from the sale and the execution of the options) increases accordingly. In total, the increased revenue exceeds the increased cost and therefore its expected profit increases.

Corollary 2 is of great significance to upstream and downstream companies in a supply chain with random yield and online business customization.

Signing an option contract on top of a wholesale price contract will benefit both the manufacturer and the supplier if the price of the option is reasonable.

Corollary 3 is proposed for the relationship between the manufacturer's optimal ordering decision and the expected profit and its overconfidence factor under the option contract model.

Corollary 3. *When the manufacturer is overconfident about its yield rate, and $\lambda_m \sim U(\lambda_m^1, \lambda_m^2)$, under the option model, the manufacturer's optimal initial order quantity and option order quantity have the following relationship with the overconfidence factor:*

When $\bar{\lambda}_m \leqslant \frac{2b_3}{b_2+2p_0}$, and $b_1 > 2o$, as α_m increases, Q_0^{oc} increases, Q_1^{oc} decrease, and $E\left(\pi_m^{oc}(\alpha_m)\right)$ decreases.

According to the definitions of b_1, b_2, b_3 and o, we can see that $(b_2 + 2o)\bar{\lambda}_m - 2b_3 \leqslant 0$ and $b_1 > 2o$ generally hold. Therefore, Corollary 3 has a wider scope of application. The greater the degree of overconfidence the manufacturer is, the closer the company thinks that its initial production will be able to meet the customer demand. As a result, the manufacturer will decrease its option purchase Q_1^{oc} to reduce option purchase cost. At the same time, as Q_1^{oc} decreases, Q_0^{oc} will increase in order to boost the expected sales revenue. We see from Corollary 3 that as the overconfidence factor increases, the gap between the optimal order quantity with overconfidence and the optimal order quantity with complete rationality widens, and the actual expected profit of the company decreases. The proof of Corollary 3 shows that under the option contract, if α_m moves towards 0, Q_0^{oc} moves towards the minimum value Q_o^{or}, and Q_1^{oc} moves towards the maximum value

Q_1^{or}, thus we propose Corollary 4.

Corollary 4. *Under the option contract, there exist the following relationships regarding the manufacturer's ordering decisions between with overconfidence and with complete rationality:* $Q_0^{or} < Q_0^{oc}$, $Q_1^{or} > Q_1^{oc}$.

Propositions 1, 2, 3 and 4 demonstrate the existence and uniqueness of the optimal decisions under different contracts for both companies under different overconfidence levels. According to the above propositions and corollaries, when all the parameters are within reasonable ranges, the order quantities or the production decisions of each company obey $Q_0^{or} < Q_0^{oc} < Q_d^c < Q_d^r$, $Q_1^{or} > Q_1^{oc}$, $I_o^r < I_o^c < I_d^c < I_d^r$.

Based on the relationship among parameters, we have $e > \max(0, \varphi p + v_m - c_m^1)$, $\dfrac{c_m^0 + w_s}{\bar{\lambda}_m} - c_m^1 + \varphi p < o + e \leqslant r_m$.

Let $A = (c_s^1 - v_s)\left(1 - G\left(\dfrac{Q_d^r}{I_d^r}\right)\right) - (c_s^1 - w_s)$, when the manufacturer is completely rational, we have Proposition 5.

Proposition 5. *When the manufacturer is completely rational, if* (o, e) *satisfy the conditions in Equations* (32) *and* (33)*, the option contract can achieve profit Pareto improvement for both companies.*

$$\max(0, v_m + \varphi p - c_m^1) < e < \frac{(p + b_m)\left[F\left(\frac{D}{Q_d^r}\right) - F\left(\frac{D - Q_1^{or}}{Q_0^{or}}\right)\right] + v_m\left[F\left(\frac{D}{Q_0^{or}}\right) - F\left(\frac{D}{Q_d^r}\right)\right]}{F\left(\frac{D}{Q_0^{or}}\right) - F\left(\frac{D - Q_1^{or}}{Q_0^{or}}\right)} - c_m^1 + \varphi p, \quad (32)$$

$$\max\left(0, \frac{A(Q_d^r - Q_0^{or}) + (c_s^2 - e)(V_3(Q_0^{or}, Q_1^{or}) - V_1(Q_0^{or}))}{Q_1^o}\right) < o < w_s. \quad (33)$$

Compare Equations (10) and (24), let $E\left(\pi_m^{dc}(\alpha_m)\right) > E\left(\pi_m^{dr}(D_d^r)\right)$, we can get Equation (32). Compare Equations (11) and (25), let $E(\pi_s^{dc}) > E(\pi_s^{dr}(I_d^r))$, we can get Equation (33).

Let $V_1^d = v_1(Q_d^c)$, $V_1^c = V_1(Q_0^{oc})$, $V_2^d = V_2(I_d^c)$, $V_2^c = V_2(I_o^c)$, $V_3^c = V_3(Q_0^{oc}, Q_1^{oc})$, when the manufacturer is overconfident, we propose Proposition 6.

Proposition 6. *When the manufacturer is overconfident, if (o, e) satisfy the conditions in Equations (34) and (35), the option contract can achieve profit Pareto improvement for both companies.*

$$\begin{aligned}&\max(0, v_m + \varphi p - c_m^1) < e < \\ &\quad \min\Big(w_s, \tfrac{(p+b_m)(V_3^c - V_1^d) + v_m(V_1^d - V_1^c) + (w_s + c_m^0 - v_m\bar{\lambda}_m)(Q_d^c - Q_0^{oc}) - oQ_1^{oc}}{V_3^c - V_1^c} \\ &\qquad - c_m^1 + \varphi p\Big),\end{aligned} \tag{34}$$

$$\begin{aligned}&\max\Big(0, \tfrac{(c_s^1 - v_s)(V_2^d - V_2^c) + (c_s^2 - e)(V_3^c - V_1^c) + (c_s^1 - w_s)(Q_0^{oc} - Q_d^c) + (c_s^0 - v_s\bar{\lambda}_s)(I_o^c - I_d^c)}{Q_1^o}\Big). \\ &\quad < o < w_s\end{aligned} \tag{35}$$

By comparing Equations (15) with (31), Equation (34) can be obtained. Similarly Equation (35) can be obtained by comparing Equations (16) and (A.4).

Propositions 5 and 6 show that: 1) when the option price and the option execution price are within certain ranges, the manufacturer and the supplier can realize supply chain coordination by signing the option contract; 2) the determination of the option price and the execution price of the option depends on the levels of rationality between the two parties; and the two prices contributes to how reasonable the option contract is and how stable the cooperation between the two parties can be.

5. Numerical Experiments and Sensitivity Analyses

In this section, we construct a case based on an electronics manufacturer in Guangdong, China. The manufacturer provides MTO for online customized products and maintains a stable business relationship with a metal materials supplier. Based on practical observations, we set $\alpha_m = 0.3$, $D = 5,000$, $p = 400$, $c_m^0 = 120$, $v_m = 150$, $c_m^1 = 200$, $r_m = 180$, $\varphi = 0.2$, $b_m = c_m^1 + r_m - \varphi p = 300$, $w_s = 120$, $o = 50$, $e = 100$, $c_s^0 = 80$, $c_s^1 = 180$, $c_s^2 = 120$, $v_s = 50$, $\lambda_m \sim U(0.92, 0.96)$, $\lambda_s \sim U(0.93, 0.97)$ to observe the relevant ordering and production decisions and the expected profits for both companies when the manufacturer is overconfident or completely rational under the wholesale price and the option contracts. We then present sensitivity analyses for key parameters in this case.

5.1. Numerical results

Table 1 lists the optimal decisions and the expected profits for the manufacturer and the supplier under the two types of contracts with difference levels of overconfidence based on Propositions 1 to 4. It can be observed from Table 1 that for the two-echelon supply chain consisting of a manufacturer and a supplier, the expected profits for both companies under the option contract are higher than those under the wholesale contract.

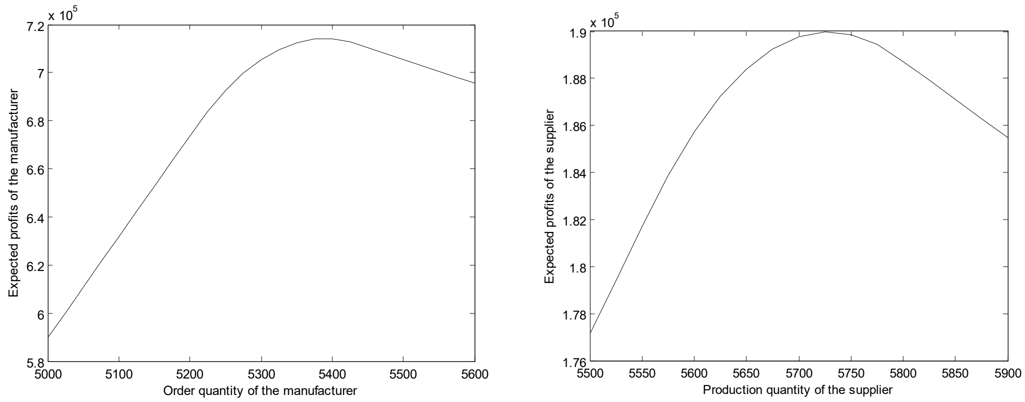
From a decision-making perspective, the manufacturer's initial order quantity under the option contract is lower, but the total order quantity is higher than those under the wholesale price contract. The manufacturer orders less

Contract	α_m	Q_0	Q_1	Q_0+Q_1	I	$E(\pi_m)$	$E(\pi_s)$	$E(\pi_{ms})$
Wholesale	0.0	5,389	0	5,389	5,729	714,226	189,981	904,207
Wholesale	0.3	5,368	0	5,368	5,706	713,723	189,241	902,964
Option	0.0	5,251	148	5,399	5,582	717,480	191,176	908,656
Option	0.3	5,272	103	5,375	5,604	716,711	190,047	906,758

Table 1: The optimal order quantities and the expected profits for the manufacturer and the supplier.

when the yield is uncertain, and executes the option once the initial yield is known. For the supplier, its production decision changes in accordance with the manufacturer's order quantities. As can be seen from Table 1, under the same contract type, the manufacturer and the supplier have lower expected profits when they are overconfident (in this case $\alpha_m = 0.3$). When the manufacturer is overconfident, it has a lower order quantity under the wholesale price contract; while under the option contract, the manufacturer's initial order quantity is higher but the total order quantity is lower. These results verify Propositions 1 to 6 and the related corollaries introduced in this paper.

When the manufacturer is completely rational, according to Equations (4), (5) and (22), we can obtain Figure 1 which depicts the relationship between the manufacturer's order quantity and its expected profit, and the relationship between the supplier's production plan and its expected profit under the wholesale price contract. Under the option contract, when the manufacturer is completely rational, Figure 2 plots the relationship between the manufacturer's expected profits and initial/option order quantities (Q_0/Q_1). Specifically, Figure 3(a) shows the relationship between the man-



(a) The manufacturer

(b) The supplier

Figure 1: Relationships between expected profits and order or production quantity when the manufacturer is completely rational under wholesale price contract

ufacturer's expected profit and the initial order quantity when Q_1 is fixed at 148; Figure 3(b) shows the relationship between the manufacturer's expected profit and the option quantity when Q_0 is fixed at $5,251$.

It can be seen from Figures 1 and 3 that the expected profit functions under different contracts are concave. Based on Propositions 2 and 4, the manufacturer's overconfidence only affects the values of its ordering quantities, and does not affect the trends of its expected profit and its optimal decision. We therefore omit the figures for the case when the manufacturer is overconfident as they are similar to Figures 1 and 3.

5.2. Sensitivity analyses

We know from Sections 3 and 4 that the expectation of, and different cost or price factors related to the manufacturer not only affect its decisions and expected profit, but also those of the supplier's. On the contrary, the cost or price factors that are related to the supplier do not affect the manufacturer.

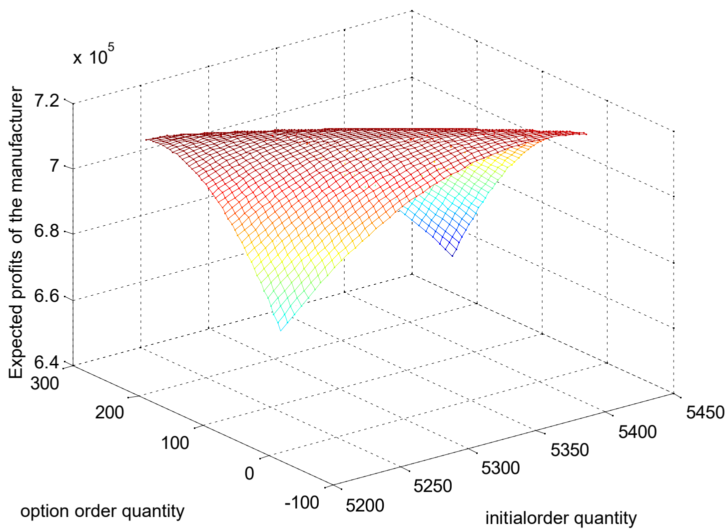
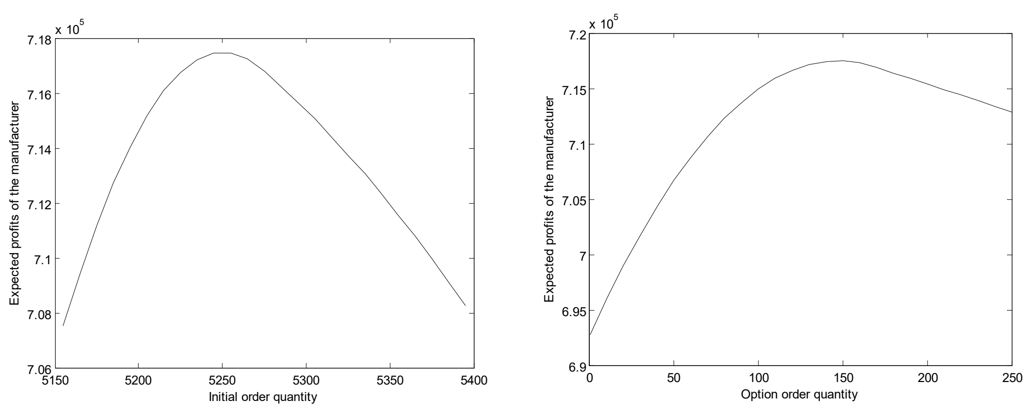


Figure 2: Relationship between expected profit and order quantity when the manufacturer is completely rational under option contract



(a) Option order quantity $Q_1 = 148$ (b) Initial order quantity $Q_0 = 5,251$

Figure 3: Relationships between expected profits and initial order or option quantity when the manufacturer is completely rational under option contract

Therefore in this section, we focus on the following parameters: the manufacturer's overconfidence factor α_m, option price o, option execute price e, wholesale price w_s, the expected yield rate $\bar{\lambda}_m$, and the expedited production cost c_m^1 and conduct sensitivity analyses on them to verify the propositions and corollaries in this paper.

5.2.1. The manufacturer's overconfidence factor α_m

Table 2 shows the optimal decisions and the expected profits for the manufacturer and the supplier with different values of α_m, i.e., the overconfidence factor of the manufacturer. We let $0.0 \leqslant \alpha_m \leqslant 1.0$ and use a step size of 0.1.

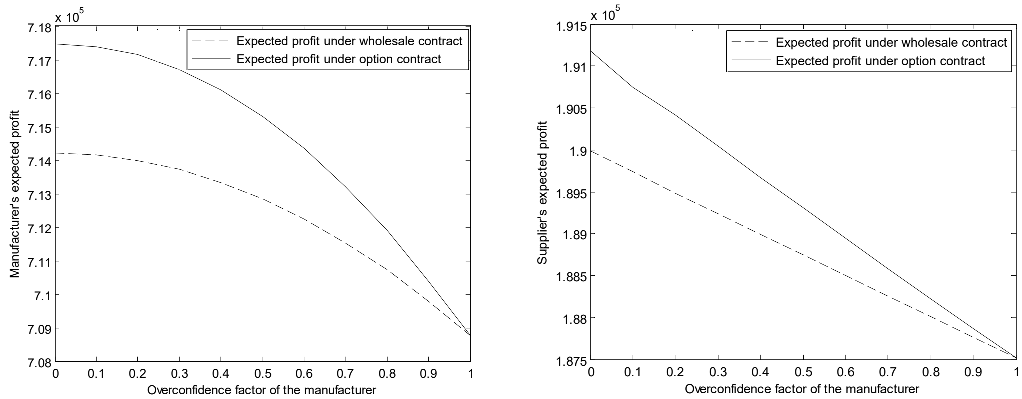
As can be seen from Table 2, the order quantity under the wholesale price contract is always between the initial order quantity and the total order quantity under the option contract. As the manufacturer's overconfidence increases, the manufacturer's order quantity under wholesale price contract and the total order quantity under the option contract decreases in an almost linear fashion. On the other side, the manufacturer's initial order quantity under the option contract increases almost linearly as the overconfidence factor increases. When the manufacturer is extremely confident (i.e., $\alpha_m = 1.0$), the order quantity under the wholesale price contract equals the initial order quantity under the option contract, and the option order quantity is 0.

Figure 4 plots the expected profits for the manufacturer and the supplier with different value of α_m. We can see from Figure 4(a) that the manufacturer's expected profit under the option contract is higher than that of the wholesale price contract. As the manufacturer's overconfidence level increases, the profits of the manufacturer under both types of contracts decrease. The manufacturer's expected profit under the wholesale price contract equal-

Contract	α_m	Q_0	Q_1	$Q_0 + Q_1$	I	$E(\pi_m)$	$E(\pi_s)$	$E(\pi_{ms})$
Wholesale	0.0	5389	0	5389	5729	714,226	189,981	904,207
	0.1	5382	0	5382	5721	714,158	189,981	903,892
	0.2	5375	0	5375	5714	713,995	189,488	903,483
	0.3	5368	0	5368	5706	713,723	189,241	902,964
	0.4	5361	0	5361	5699	713,342	188,994	902,336
	0.5	5354	0	5354	5692	712,851	188,747	901,598
	0.6	5347	0	5347	5684	712,250	188,500	900,750
	0.7	5340	0	5340	5677	711,539	188,254	899,793
	0.8	5333	0	5333	5669	710,717	188,007	898,724
	0.9	5326	0	5326	5662	709,784	187,760	897,544
	1.0	5319	0	5319	5654	708,753	187,513	896,266
Option	0.0	5251	148	5399	5582	717,480	191,176	908,656
	0.1	5258	132	5390	5590	717,385	190,750	908,135
	0.2	5265	118	5383	5597	717,147	190,420	907,567
	0.3	5272	103	5375	5604	716,711	190,047	906,758
	0.4	5279	88	5367	5612	716,096	189,675	905,771
	0.5	5286	73	5359	5619	715,303	189,307	904,610
	0.6	5292	59	5351	5626	714,353	188,944	903,297
	0.7	5299	44	5343	5633	713,208	188,581	901,789
	0.8	5306	29	5335	5641	711,887	188,221	900,108
	0.9	5313	14	5327	5648	710,391	187,863	898,254
	1.0	5319	0	5319	5654	708,753	187,513	896,266

Table 2: Relationship between optimal decisions and the manufacturer's overconfidence factor

s the profit under the option contract when the manufacturer is extremely confident. In Figure 4(b), we can see that the expected profit of the supplier under the option contract is higher than that of the wholesale price contract.



(a) The manufacturer

(b) The supplier

Figure 4: Relationship between expected profits and the manufacturer's overconfidence factor under different contracts

The two profits decrease approximately in a linear way as the manufacturer's overconfidence level increases, and gradually converge when the manufacturer is extremely confident. The above observations reveal that manufacturer's overconfidence not only negatively impacts on it own profits, but also has adversarial effects on its upstream partners in the supply chain.

5.2.2. The option price o and option execution price e

The option price o can certainly affect the decisions on Q_0, Q_1 and I. We allow the option price o to change between 40 and 90 with a step size of 5 to check its impact on these decisions. In doing so, we fix other parameters as described at the beginning of Section 5. The results are listed in Table 3, from which we can observe that Q_0 increases as o increases, while Q_1 behaves in the opposite way when the manufacturer is either rational or overconfident. Overall, $Q_0 + Q_1$ slightly decreases as the option price o increases. The supplier's initial production plan I increases alongside the increase of the

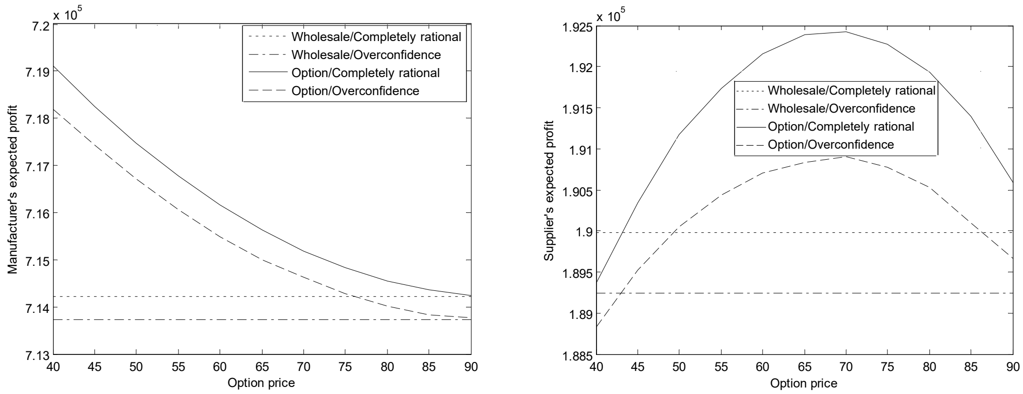
	Expect.	40	45	50	55	60	65	70	75	80	85	90
Q_0	Rational	5220	5235	5251	5266	5281	5297	5313	5329	5345	5361	5377
	Overconf.	5250	5261	5272	5283	5294	5305	5316	5327	5338	5350	5361
Q_1	Rational	180	164	148	131	115	98	81	64	47	30	12
	Overconf.	126	115	103	91	79	67	56	44	32	19	8
$Q_0 + Q_1$	Rational	5400	5399	5399	5397	5396	5395	5394	5393	5392	5391	5389
	Overconf.	5376	5376	5375	5374	5373	5372	5372	5371	5370	5369	5369
I	Rational	5549	5565	5582	5598	5614	5631	5648	5665	5682	5699	5716
	Overconf.	5581	5593	5604	5616	5628	5639	5651	5663	5675	5687	5699

Table 3: The relationship between Q_0, Q_1, I and option price o

option price o.

Figure 5 plots the relationships between the expected profits and the option price under the two types of contracts based on Propositions 5 and 6. It can be seen from Figure 5(a) that as the option price increases, the manufacturer's expected profit decreases, but the rate of decline gets slower and slower. When $o = 90$, profits under the option contract are about equivalent to the profits under the wholesale price contract when the manufacturer is either completely rational or overconfident. The manufacturer's expected profit under the wholesale price contract with complete rationality is higher than the profit under the option contract with overconfidence when $o > 77$.

In Figure 5(b), we can see that as o increases, the supplier's expected profits under the option contract first increase and then decrease. The expected profits of the supplier reach their maxima when $o = 70$. This indicates that the supplier will only benefit from increasing option price until a certain value. The manufacturer's option order quantity will be adversely affected when the option price is too high, which in turn reduces the supplier's profit. Figure 5(b) also demonstrates that the supplier's expected profit under the



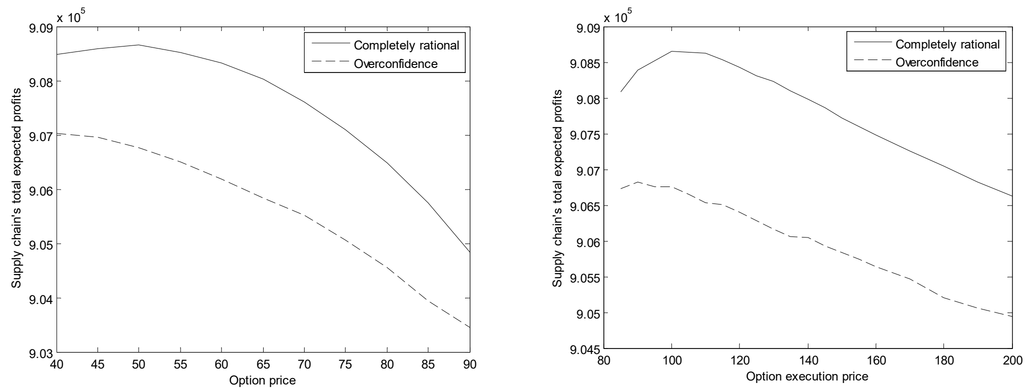
(a) The manufacturer

(b) The supplier

Figure 5: Relationships between expected profits and the option price under different contracts

wholesale price contract with complete rationality is higher than the profit under the option contract when the option price is either too low or too high. Therefore, it is important for the supplier to select a suitable option price to encourage the supply chain to adopt the option contract approach.

We note that the option execution price e has similar sensitivity analysis results, and therefore put its sensitivity analysis in Appendix A.7. Apparently, under the option contract, the total expected profit across the two-echelon supply chain is affected by both o and e, which is plotted in Figure 6. It can be seen from Figure 6 that regardless of whether the enterprise is completely rational or overconfident, the total expected profit across the supply chain is a concave function regarding the option price and the option execution price. When $o = 50$ and $e = 100$, the supply chain achieves the highest profit of 908,656 with complete rationality. When $o = 40$ or $e = 90$, the supply chain reaches the highest profits of 907,018 or 906,817 in the case of overconfidence.



(a) Relationship with option price (b) Relationship with option execution price

Figure 6: Relationship between total supply chain expected profits and the option price or option execution price with different levels of overconfidence

From the sensitivity analyses on o and e, we can conclude that apart from the option price and the option execution price, whether the option contract has a positive effect on both companies in the supply chain will also depend on the overconfidence level. In order to maximize the profit across the supply chain, companies should negotiate the option price and the option execution price. As can be seen from Figure 6, lower o and e in general are more favorable for the two-echelon supply chain. In this case, the supplier has lower-than-expected profit and therefore the manufacturer should propose revenue sharing or yield risk sharing to compensate for the supplier, in order to coordinate the supply chain to perform at its best configuration.

5.2.3. *The wholesale price* w_s

In the same vein, a reasonable wholesale price is critical for both the wholesale price contract and the option contract. The wholesale price has a great impact on the profits of the upstream and downstream companies of

	Contract	85	90	95	100	105	110	115	120	125	130
Q_0	Wholesale	5405	5403	5401	5398	5396	5394	5391	5389	5387	5385
	Option	5370	5353	5335	5318	5301	5284	5267	5251	5234	5218
Q_1	Wholesale	0	0	0	0	0	0	0	0	0	0
	Option	37	53	69	85	101	117	132	148	163	178
$Q_0 + Q_1$	Wholesale	5405	5403	5401	5398	5396	5394	5391	5389	5387	5385
	Option	5407	5406	5404	5403	5402	5401	5399	5399	5397	5396
I	Wholesale	5746	5744	5742	5738	5736	5734	5731	5729	5727	5725
	Option	5709	5690	5671	5653	5635	5617	5599	5582	5564	5547

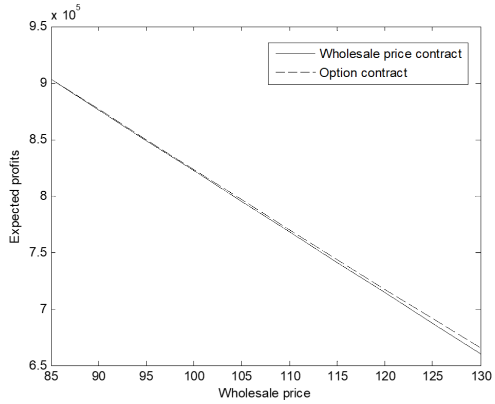
Table 4: The relationship between Q_0, Q_1, I and wholesale price w_s

the supply chain, and directly affects whether the transaction can proceed. We list the results for Q_0, Q_1, and I in Table 4, and plot the expected profits of both companies when w_s changes between 85 and 130 in Figure 7. We choose this range because if w_s is too small, there will be no profit for the supplier; if w_s is too large, the order quantity from the manufacturing will be too small to be meaningful. We also assume the manufacturer is completely rational to illustrate the impact of wholesale price as the difference between complete rationality and overconfidence does not affect observing the trends of wholesale price on expected profits.

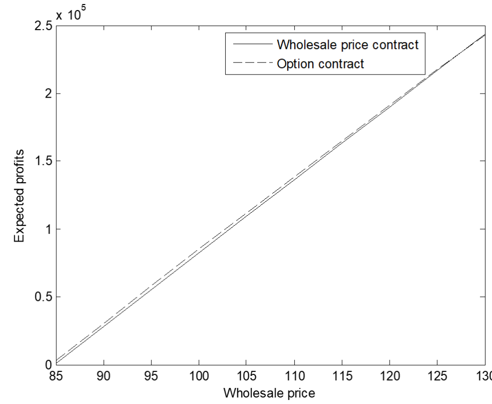
We can see from Table 4 that as w_s increases, Q_0 decreases, Q_1 increases under option contract, and Q_0+Q_1 and I gently decrease. From Figure 7(a), we can see that as the wholesale price increases, the profits for the manufacturer under both wholesale price and option contracts decrease in an almost linear way. The gap between the two widens as the wholesale price increases. This indicates that the manufacturer should use option contract, especially when the wholesale price is high, to offset the adverse impact of high wholesale price. From Figure 7(b), we see that the supplier's profits increase as the wholesale price increases for both wholesale price and option contracts, and the option contract profit dominates the wholesale price contract profit. This shows that the supplier will benefit from the option contract, as the wholesale price increases. In Figure 7(c), we see that as the wholesale price increases, the supply chain profit decreases under wholesale price contract. Under option contract, the overall profit first increases and then decreases after reaching a peaking value.

Overall, under wholesale price contract, while the supplier's profit increases as the wholesale price increases, the manufacturer's profit is impacted by higher wholesale price. The two combined, as the overall supply chain profit, decreases as wholesale price increases. Under option contract, as the wholesale price increases, the supplier's profit increases, and the initial ordering quantity of the manufacturer decreases, the option ordering quantity increases. The manufacturer reduces initial ordering cost, lowers the risk of not meeting the demand, and therefore makes the overall supply chain profit increase. When the wholesale price reaches a certain level, the manufacturing's initial ordering quantity will decrease, and therefore increase the option purchasing cost and emergency manufacturing, which leads to decreased profit. This results in the decrease of the overall supply chain profit.

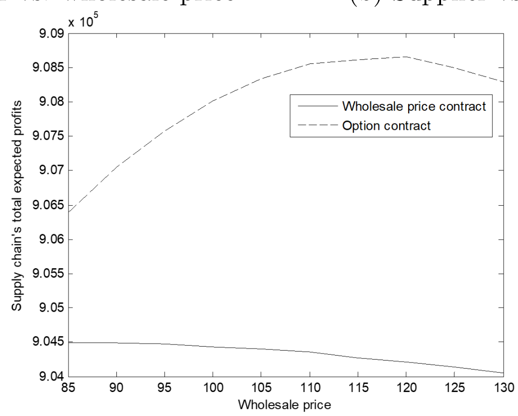
Therefore, from the perspective of supply chain coordination, if a wholesale price contract is to be signed between the manufacturer and the supplier, they may consider to reduce the wholesale price as much as possible. The manufacturer should share its revenue with the supplier to compensate the supplier's loss of revenue/profit. If an option contract is to be signed between the manufacturer and the supplier, the wholesale price could be set at



(a) Manufacturer vs. wholesale price



(b) Supplier vs. wholesale price



(c) The supply chain vs. wholesale price

Figure 7: Relationship between expected profits and the wholesale price under different contracts

a moderate level. Depending on how much the set price deviating from the optimal level, the manufacturer can consider sharing some revenue with the supplier when the set price is lower than the optimal level; the supplier could consider offering discounts on option and option execution prices when the set price is higher than the optimal level.

5.2.4. *The expected yield rate $\bar{\lambda}_m$ and its variability*

Table 5 lists the values for Q_0, Q_1, Q_0+Q_1, I, $E(\pi_m)$, $E(\pi_s)$, and $E(\pi_{ms})$ when the expected yield rate $\bar{\lambda}_m$ changes between 0.92 and 0.98 with a step size of 0.1. We can observe that as $\bar{\lambda}_m$ increases, Q_0, Q_1, $Q_0 + Q_1$ and I decrease accordingly. The manufacturer's expected profit and the total profit across the supply chain increase, while the supplier's expected profit decreases. Table 6 shows the corresponding values when the yield rate variability changes. We use $\Delta_\lambda = \bar{\lambda}_m - \lambda_m^1$ to denote the variability. We let Δ_λ changes between 0.00 and 0.06 with a step size of 0.01 and fix λ_m at 0.94 (if $\Delta_\lambda = 0.00$, $\lambda_m = 0.94$ as a constant; if $\Delta_\lambda = 0.01$, $\lambda_m \sim U(0.93, 0.95)$, etc.). We can see that as Δ_λ increases, Q_0 and I increase under the wholesale contract; Q_0 and I decreases while Q_1 and $Q_0 + Q_1$ increase under the option contract. In any case, the manufacturer's expected profit and the supply chain profit decreases while the supplier's expected profit increases.

These results are rather expected as the higher the yield rate, the less the production cost and hence higher profit for the manufacturer; the supplier on the other side, will have less demand which reduces its expected profit. On the contrary, when the expected yield rate variability increases, which means there are quality control issues for the manufacturer, we see exactly the opposite.

5.2.5. *The expedited production cost c_m^1*

Since $c_m^1 > c_m^0$, we let $k = c_m^1/c_m^0$. Therefore we know $k > 1.0$. When k changes, c_m^1 changes in respect of c_m^0. We set k between 1.6 and 3.1, considering that if c_m^1 is too close to c_m^0, there is no motivation for the manufacturer to commit to the initial order, and on the other side, k is limited by p.

Contract	Expect.	$\bar{\lambda}_m$	Q_0	Q_1	$Q_0 + Q_1$	I	$E(\pi_m)$	$E(\pi_s)$	$E(\pi_{ms})$
Wholesale	Rational	0.92	5505	0	5505	5852	685,905	194,070	879,975
		0.93	5447	0	5447	5790	700,218	192,026	892,244
		0.94	5389	0	5389	5729	714,226	189,981	904,207
		0.95	5333	0	5333	5669	727,938	188,007	915,945
		0.96	5278	0	5278	5611	741,363	186,068	927,431
		0.97	5224	0	5224	5553	754,511	184,164	938,675
		0.98	5171	0	5171	5497	767,389	182,296	949,685
	Overconf.	0.92	5484	0	5484	5830	685,414	193,330	878,744
		0.93	5426	0	5426	5768	699,810	191,285	191,285
		0.94	5368	0	5368	5706	713,723	189,241	902,964
		0.95	5312	0	5312	5647	727,458	187,267	914,725
		0.96	5257	0	5257	5588	740,886	185,328	926,214
		0.97	5203	0	5203	5531	754,019	183,424	937,443
		0.98	5150	0	5150	5475	766,871	181,555	948,426
Option	Rational	0.92	5345	167	5512	5682	690,013	195,124	885,137
		0.93	5297	157	5454	5631	703,881	193,088	896,969
		0.94	5251	148	5399	5582	717,480	191,176	908,656
		0.95	5204	138	5342	5532	730,819	189,149	919,968
		0.96	5159	129	5288	5484	743,903	187,247	931,150
		0.97	5114	121	5235	5436	756,739	185,376	942,115
		0.98	5069	113	5182	5389	769,335	183,489	952,824
	Overconf.	0.92	5373	116	5489	5712	689,153	194,070	883,223
		0.93	5322	110	5432	5658	703,099	192,065	895,164
		0.94	5272	103	5375	5604	716,711	190,047	906,758
		0.95	5223	96	5319	5552	730,055	188,059	918,114
		0.96	5174	90	5264	5500	743,147	186,106	929,253
		0.97	5127	84	5211	5450	756,036	184,229	940,265
		0.98	5080	78	5158	5400	768,633	182,341	950,974

Table 5: The relationship between optimal decisions and the expected yield rate $\bar{\lambda}_m$

Contract	Expect.	Δ_λ	Q_0	Q_1	$Q_0 + Q_1$	I	$E(\pi_m)$	$E(\pi_s)$	$E(\pi_{ms})$
Wholesale	Rational	0.00	5319	0	5319	5654	723,440	187,513	910,953
		0.01	5354	0	5354	5692	718,845	188,747	907,592
		0.02	5389	0	5389	5729	714,226	189,981	904,207
		0.03	5424	0	5424	5766	709,546	191,215	900,761
		0.04	5459	0	5459	5803	704,804	192,449	897,253
		0.05	5495	0	5495	5841	700,000	193,718	893,718
		0.06	5530	0	5530	5879	695,133	194,952	890,085
	Overconf.	0.00	5319	0	5319	5654	723,440	187,513	910,953
		0.01	5344	0	5344	5681	718,655	188,395	907,050
		0.02	5368	0	5368	5706	713,723	189,241	902,964
		0.03	5393	0	5393	5733	708,878	190,122	899,000
		0.04	5417	0	5417	5759	703,830	190,968	894,798
		0.05	5442	0	5442	5785	698,868	191,849	890,717
		0.06	5466	0	5466	5811	693,706	192,696	886,402
Option	Rational	0.00	5319	0	5319	5654	723,440	187,513	910,953
		0.01	5286	73	5359	5619	720,423	189,344	909,767
		0.02	5251	148	5399	5582	717,480	191,176	908,656
		0.03	5214	223	5437	5543	714,576	192,912	907,488
		0.04	5177	298	5475	5503	711,711	194,649	906,360
		0.05	5138	374	5512	5462	708,886	196,336	905,222
		0.06	5098	450	5548	5419	706,102	197,974	904,076
	Overconf.	0.00	5319	0	5319	5654	723,440	187,513	910,953
		0.01	5296	51	5347	5630	720,026	188,778	908,804
		0.02	5272	103	5375	5604	716,711	190,047	906,758
		0.03	5247	155	5402	5578	713,397	191,270	904,667
		0.04	5222	207	5429	5551	710,132	192,494	902,626
		0.05	5195	261	5456	5523	706,940	193,721	900,661
		0.06	5169	313	5482	5495	703,729	194,900	898,629

Table 6: The relationship between optimal decisions and the expected yield rate variability

Contract	Expect.	k	Q_0	Q_1	Q_0+Q_1	I	$E(\pi_m)$	$E(\pi_s)$	$E(\pi_{ms})$
Wholesale	Rational	1.6	5388	0	5388	5728	714,259	189,946	904,205
		1.9	5391	0	5391	5731	714,117	190,052	904,169
		2.2	5394	0	5394	5734	713,991	190,157	904,148
		2.5	5396	0	5396	5736	713,879	190,228	904,107
		2.8	5398	0	5398	5738	713,779	190,298	904,077
		3.1	5400	0	5400	5740	713,689	190,369	904,058
	Overconf.	1.6	5368	0	5368	5706	713,839	189,241	903,080
		1.9	5370	0	5370	5709	713,629	189,311	902,940
		2.2	5371	0	5371	5710	713,315	189,346	902,661
		2.5	5373	0	5373	5712	713,196	189,417	902,613
		2.8	5374	0	5374	5713	712,955	189,452	902,407
		3.1	5376	0	5376	5715	712,911	189,523	902,434
Option	Rational	1.6	5228	168	5396	5558	718,096	190,998	909,094
		1.9	5301	101	5402	5635	716,099	191,237	907,336
		2.2	5336	69	5405	5672	715,155	191,198	906,353
		2.5	5357	50	5407	5695	714,606	191,136	905,742
		2.8	5370	37	5407	5709	714,246	191,020	905,266
		3.1	5379	28	5407	5718	713,992	190,931	904,923
	Overconf.	1.6	5256	118	5374	5587	717,301	190,008	907,309
		1.9	5307	70	5377	5642	715,360	190,046	905,406
		2.2	5332	47	5379	5668	714,428	190,008	904,436
		2.5	5346	34	5380	5683	713,843	189,959	903,802
		2.8	5355	26	5381	5693	713,447	189,936	903,383
		3.1	5362	19	5381	5700	713,109	189,877	902,986

Table 7: The relationship between optimal decisions and expedited production cost c_m^1

Table 7 shows the corresponding decisions when k changes. It can be seen that as k increases, Q_1 decreases but $Q_0 + Q_1$ slightly increases under the option contract. Overall, the manufacturer's expected profit decreases and the supplier's expected profit increases under both types of contracts.

We conduct sensitivity analyses for other parameters such as the spot market purchase cost r_m and the residual value v_m. The results are similar to those presented in this section and therefore omitted.

Using the case and the consequent sensitivity analyses on parameters, we see the conclusions drawn from the propositions and corollaries hold. In any setting, the option contract has a clear advantage when compared with its wholesale price contract counterpart. Similarly, decisions under complete rationality dominates those with overconfidence. While the trends shown in the figures and tables are only relying on a single case, the sensitivity analyses offer a wide range of scenarios. Furthermore, these trends provide referential value for practical operations as the parameters are set within reasonable ranges.

6. Conclusion

This paper investigated a two-echelon supply chain for MTO productions and examined the optimal decision-making for both companies and the supply chain when yield randomness and overconfidence are presented. Both wholesale price and option contracts were analyzed when the manufacturer is complete rational and overconfident, i.e., in the cases of wholesale price contract/complete rationality, wholesale price contract/overconfidence, option contract/complete rationality, and option contract/overconfidence.

If a manufacturer is overconfident about its yield estimations, it means that the manufacturer's material ordering decisions and actual profits will deviate from reality, which have a direct impact on the upstream supplier. Compared with the wholesale price contract that is often signed between companies, the advantage of the option contract is that the manufacturer has two ordering opportunities. This can transfer the risk of future supply and demand mismatch to the supplier. The supplier gets the option to sell and execute in return. Therefore, if the option contract is structured properly, it will be a win-win situation for both companies.

Our analytical and numerical results suggest that the greater the overconfidence level of the manufacturer is, the lower the expected profit for each company will be. Under the option contract, the initial order quantity of the manufacturer increases and the option order quantity decreases along with the increase of its overconfidence level. For the option and option execution prices, the manufacturer will benefit from lower of these prices; however, the supplier does not always benefit from higher prices. From the perspective of a supply chain, the profit across the supply chain will be higher when the option and the option execution prices are relatively small. The manufacturer should consider compensating the supplier for doing so through revenue sharing. Under wholesale price contracts, the lower the wholesale price is, the higher the supply chain profit will be. Under the option contracts, the optimal supply chain profit will depend on a moderately selected wholesale price. Therefore, in both types of contracts, compensation mechanisms will need to be in place to encourage both companies to negotiate the proper prices for the wholesale price, the option price and the option execution price.

This paper can be extended to cases where the supply chain consists of multiple echelons, or there is competition among companies in the same echelon. In these cases, demand uncertainty and overconfidence in demand will need to be considered on top of yield uncertainty and yield overconfidence to make the relevant research more practical.

Acknowledgement

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Appendix A. Proofs of Propositions and Corollaries

Appendix A.1. Proof of Proposition 1

Proof. By taking the first and second order derivatives of $E\left(\pi_m^d(Q)\right)$ with respect to Q, we have:

$$\frac{\mathrm{d}E\left(\pi_m^d(Q)\right)}{\mathrm{d}Q} = (p + c_m^1 + r_m - \varphi p - v_m)\frac{\mathrm{d}V_1(Q)}{\mathrm{d}Q} - (w_s + c_m^0 - v_m\bar{\lambda}_m), \quad \text{(A.1)}$$

$$\frac{\mathrm{d}^2E(\pi_m^d(Q))}{\mathrm{d}Q^2} = (p + c_m^1 + r_m - \varphi p - v_m)\frac{\mathrm{d}^2V_1(Q)}{\mathrm{d}Q^2}.$$

Based on the definition of $V_1(Q)$, we have:

$$V_1(Q) = \int_0^{\frac{D}{Q}} xQf(x)\,\mathrm{d}x + \int_{\frac{D}{Q}}^1 Df(x)\,\mathrm{d}x,$$

and its first and second order derivatives with respect to Q are:

$$\frac{\mathrm{d}V_1(Q)}{\mathrm{d}Q} = \int_0^{\frac{D}{Q}} xf(x)\,\mathrm{d}x,$$

$$\frac{\mathrm{d}^2V_1(Q)}{\mathrm{d}Q^2} = -\frac{D^2}{Q^3}f\left(\frac{D}{Q}\right).$$

As $p > v_m$, $c_m^1 + r_m - \varphi p > c_m^0 > 0$, we have:

$$\frac{\mathrm{d}^2 E\left(\pi_m^d(Q)\right)}{\mathrm{d}Q^2} < 0.$$

That is, $E\left(\pi_m^d(Q)\right)$ is a concave function of Q. As $p\bar{\lambda}_m > w_s + c_m^0$, we have:

$$0 < \frac{w_s + c_m^0 - v_m\bar{\lambda}_m}{p + c_m^1 + r_m - \varphi p - v_m} < \bar{\lambda}_m,$$

while

$$0 < \int_0^{\frac{D}{Q_d^r}} x f(x)\,\mathrm{d}x < \bar{\lambda}_m,$$

we get Equation (6) by letting Equation (A.1) equal zero.

Once Q_d^r is determined, we can prove that $E(\pi_s^d(I))$ is a concave function about I in a similar way, and therefore obtain Equation (7). □

Appendix A.2. Proof of Proposition 2

Proof. When the manufacturer is overconfident about its yield rate, it will only affect the cumulative distribution function of λ_m, and has no impact on the concavity or convexity of $E\left(\pi_m^d(Q)\right)$. Therefore, there must exist a certain order quantity that maximizes $E\left(\pi_m^d(Q)\right)$. Let $f'(x)$ and $F'(x)$ be the probability density function and the cumulative distribution function of λ_m'. If we can express $f'(x)$, we will be able to express Q_d^c based on Equation (6):

$$\begin{aligned} F'_{\lambda_m'}(x) &= P_r(\lambda_m' \leqslant x) = P_r(\alpha_m\bar{\lambda}_m + (1-\alpha_m)\lambda_m \leqslant x) \\ &= P_r\left(\lambda_m \leqslant \frac{x - \alpha_m\bar{\lambda}_m}{1-\alpha_m}\right) = F_{\lambda_m}\left(\frac{x - \alpha_m\bar{\lambda}_m}{1-\alpha_m}\right), \end{aligned}$$

$$f'_{\lambda_m'}(x) = \frac{\mathrm{d}F'_{\lambda_m'}(x)}{\mathrm{d}x} = \frac{1}{1-\alpha_m} f\left(\frac{x - \alpha_m\bar{\lambda}_m}{1-\alpha_m}\right).$$

Since $0 \leqslant \lambda_m \leqslant 1$, we have $\alpha_m\bar{\lambda}_m \leqslant \lambda_m' \leqslant \alpha_m\bar{\lambda}_m + (1-\alpha_m)$, which leads to Equation (12). For the supplier, if the order quantity from the manufacturer changes, its production quantity will change accordingly. The ratio between the two remains unchanged, that is, Equation (13) is identical to Equation (7). □

Appendix A.3. Proof of Corollary 1

Proof. According to the definition of uniform distribution, we have $\lambda_m^2 - \lambda_m^1 = 2(\bar{\lambda}_m - \lambda_m^1)$. From Equation (14), let

$$R_1(\alpha_m) = \left(\frac{D}{Q_d^c}\right)^2 = \left[\alpha_m \bar{\lambda}_m + (1-\alpha_m)\lambda_m^1\right]^2 + 2a_1(\lambda_m^2 - \lambda_m^1)(1-\alpha_m).$$

Take the first and second order derivatives of $R_1(\alpha_m)$ with respect to α_m:

$$\frac{\mathrm{d}R_1(\alpha_m)}{\mathrm{d}\alpha_m} = 2(\bar{\lambda}_m - \lambda_m^1)(\alpha_m \bar{\lambda}_m + (1-\alpha_m)\lambda_m^1 - 2a_1),$$

$$\frac{\mathrm{d}^2 R_1(\alpha_m)}{\mathrm{d}(\alpha_m)^2} = 2(\bar{\lambda}_m - \lambda_m^1)^2.$$

Since $\dfrac{\mathrm{d}^2 R_1(\alpha_m)}{\mathrm{d}(\alpha_m)^2} > 0$, we have:

$$\frac{\mathrm{d}R_1(\alpha_m)}{\mathrm{d}\alpha_m} > \frac{\mathrm{d}R_1(\alpha_m)}{\mathrm{d}\alpha_m}\Big|_{\alpha_m=0} = 2(\bar{\lambda}_m - \lambda_m^1)(\lambda_m^1 - 2a_1).$$

When $a_1 \leqslant \lambda_m^1/2$, $\dfrac{\mathrm{d}R_1(\alpha_m)}{\mathrm{d}\alpha_m} > 0$. Therefore, as α_m increases, $\left(\dfrac{D}{Q_d^c}\right)^2$ increases, Q_d^c decreases. Hence, we have $Q_d^c(\alpha_m) < Q_d^c(\alpha_m = 0) = Q_d^r$. By comparing Equations (10) and (15), we notice that when a company is overconfident, its optimal ordering decision is shifted, which results in a loss of expected profit compared with the case with full rationality. As Q_d^r is the only optimal decision for the manufacturer to actually expect the maximum profit, $Q_d^c < Q_d^r$ leads to $E(\pi_m^{dc}) < E(\pi_m^{dr})$. The shift (the difference between

Q_d^c and Q_d^r) becomes larger as α_m increases. According to Propositions 1 and 2, $E\left(\pi_m^d(Q)\right)$ is a concave function, therefore $E\left(\pi_m^{dc}(\alpha_m)\right)$ is continuously decreasing. For the supplier, the ratio of their production decisions to the manufacturer's order quantity remains the same, and thus it has the same pattern of change with I_d^c and Q_d^c. $\square$

Appendix A.4. Proof of Propositions 3 and 4

Proof. Take the first and second order derivatives of $E(\pi_m^o(Q_0, Q_1))$ (referred to as $E(\pi_m^o)$ below) with regard to Q_0 and Q_1:

$$\begin{aligned}\frac{\mathrm{d}E(\pi_m^o)}{\mathrm{d}Q_0} = &\left(p + b_m - e - c_m^1 + \varphi p\right)\frac{\mathrm{d}V_3}{\mathrm{d}Q_0} + \\ &\left(e + c_m^1 - \varphi p - v_m\right)\frac{\mathrm{d}V_1}{\mathrm{d}Q_0} - (w_s + c_m^0 - v_m\bar{\lambda}_m),\end{aligned} \tag{A.2}$$

$$\frac{\mathrm{d}E(\pi_m^o)}{\mathrm{d}Q_1} = \left(p + b_m - e - c_m^1 + \varphi p\right)\frac{\mathrm{d}V_3}{\mathrm{d}Q_1} - p_0, \tag{A.3}$$

$$\begin{aligned}\frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}(Q_0)^2} = &\left(p + b_m - e - c_m^1 + \varphi p\right)\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_0)^2} + \\ &\left(e + c_m^1 - \varphi p - v_m\right)\frac{\mathrm{d}^2V_1}{\mathrm{d}(Q_0)^2},\end{aligned}$$

$$\frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}(Q_1)^2} = \left(p + b_m - e - c_m^1 + \varphi p\right)\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_1)^2},$$

$$\frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}Q_0\,\mathrm{d}Q_1} = \frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}Q_1\,\mathrm{d}Q_0} = \left(p + b_m - e - c_m^1 + \varphi p\right)\frac{\mathrm{d}^2V_3}{\mathrm{d}Q_1\,\mathrm{d}Q_0}.$$

The first and second order derivations, based on the definition of $V_3(Q_0, Q_1)$, for $V_3(Q_0, Q_1)$ with regard to Q_0 and Q_1 are:

$$\frac{\mathrm{d}V_3}{\mathrm{d}Q_0} = \int_0^{\frac{D-Q_1}{Q_0}} x f(x)\,\mathrm{d}x,$$

$$\frac{\mathrm{d}V_3}{\mathrm{d}Q_1} = \int_0^{\frac{D-Q_1}{Q_0}} f(x)\,\mathrm{d}x,$$
$$\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_0)^2} = -\frac{(D-Q_1)^2}{(Q_0)^3} f\left(\frac{D-Q_1}{Q_0}\right),$$
$$\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_1)^2} = -\frac{1}{Q_0} f\left(\frac{D-Q_1}{Q_0}\right),$$
$$\frac{\mathrm{d}^2V_3}{\mathrm{d}Q_1\,\mathrm{d}Q_0} = -\frac{D-Q_1}{Q_0^2} f\left(\frac{D-Q_1}{Q_0}\right).$$

Based on the relationships among parameters, we have $p + b_m - e - c_m^1 + \varphi p > 0$, $e + c_m^1 - \varphi p - v_m > 0$. As $\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_0)^2} < 0$, $\frac{\mathrm{d}^2V_1}{\mathrm{d}(Q_0)^2} < 0$, $\frac{\mathrm{d}^2V_3}{\mathrm{d}(Q_1)^2} < 0$, we have $\frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}(Q_0)^2} < 0$, $\frac{\mathrm{d}^2E(\pi_m^o)}{\mathrm{d}(Q_1)^2} < 0$.

From here we can calculate the determinant of the Hessian matrix about $E(\pi_m^o)$ with regard to Q_0 and Q_1:

$$\det(H) = (p + b_m - e - c_m^1 + \varphi p)^2 \frac{D^2}{(Q_0)^4} f\left(\frac{D}{Q_0}\right) f\left(\frac{D-Q_1}{Q_0}\right) > 0$$

Therefore, $E\left(\pi_m^0(Q_0, Q_1)\right)$ is a concave function of Q_0 and Q_1. Thus we obtain Equation (21) by letting Equations (A.2) and (A.3) equal zero, thus proving the first half of Proposition 3. Once Q_0^{or} and Q_1^{or} are determined, the second half of Proposition 3 can be proved in a similar way. □

We omit the proof of Proposition 4 as it can be proved in a similar way to Proposition 3.

Appendix A.5. Proof of Corollary 2

Proof. First, we consider the case when the manufacturer is completely rational. Let $z(t) = \int_0^t x f(x)\,\mathrm{d}x$. Obviously, $z(t)$ is an increasing function with regard to t. Therefore,

$$z\left(\frac{D-Q_1^{or}}{Q_0^{or}}\right) < z\left(\frac{D}{Q_0^{or}}\right).$$

Let

$$z\left(\frac{D-Q_1^{or}}{Q_0^{or}}\right)=z\left(\frac{D}{Q_0^{or}}\right)-\Delta.$$

From Proposition 3, we have:

$$(p+b_m-v_m)z\left(\frac{D}{Q_0^{or}}\right)=(p+b_m-e-c_m^1+\varphi p)\Delta+w_s+c_m^0-v_m\bar{\lambda}.$$

As $b_m=c_m^1+r_m-\varphi p$, we have $p+b_m-e-c_m^1+\varphi p>0$, hence:

$$z\left(\frac{D}{Q_0^{or}}\right)>\frac{w_s+c_m^0-v_m\bar{\lambda}_m}{p+c_m^1+r_m-\varphi p-v_m}=z\left(\frac{D}{Q_d^r}\right).$$

Similarly,

$$(p+b_m-v_m)z\left(\frac{D-Q_1^{or}}{Q_0^{or}}\right)=-(p+b_m-e-c_m^1+\varphi p)\Delta+w_s+c_m^0-v_m\bar{\lambda}.$$

Therefore:

$$z\left(\frac{D-Q_1^{or}}{Q_0^{or}}\right)<\frac{w_s+c_m^0-v_m\bar{\lambda}_m}{p+c_m^1+r_m-\varphi p-v_m}=z\left(\frac{D}{Q_d^r}\right).$$

Thus we prove that $\frac{D-Q_1^{or}}{Q_0^{or}}<\frac{D}{Q_d^r}<\frac{D}{Q_0^{or}}$. We can, in a similar way, prove that $\frac{D-Q_1^{oc}}{Q_0^{oc}}<\frac{D}{Q_d^r}<\frac{D}{Q_0^{oc}}$ when the manufacturer is overconfident based on Propositions 2 and 4. □

Appendix A.6. Proof of Corollary 3

Proof. Based on Equations (27) to (30), let

$$R_2(\alpha_m)=\frac{D-Q_1^{oc}}{Q_0^{oc}}=k_m(\alpha_m)+\frac{o}{b_1}l_m(\alpha_m),$$

$$R_3(\alpha_m)=\left(\frac{D}{Q_0^{oc}}\right)^2=[k_m(\alpha_m)]^2+2a_4(\alpha_m)l_m(\alpha_m),$$

where,

$$a_4(\alpha_m) = \frac{2(b_3 - k_m(\alpha_m)o)b_1 - o^2 l_m(\alpha_m)}{2b_1b_2}.$$

Take the first order derivatives of $R_2(\alpha_m)$ and $R_3(\alpha_m)$,

$$\frac{\mathrm{d}R_2(\alpha_m)}{\mathrm{d}\alpha_m} = (\bar{\lambda}_m - \lambda_m^1) - \frac{o(\lambda_m^2 - \lambda_m^1)}{b_1} = \frac{(\bar{\lambda}_m - \lambda_m^1)(b_1 - 2o)}{b_1}, \tag{A.4}$$

$$\frac{\mathrm{d}R_3(\alpha_m)}{\mathrm{d}\alpha_m} = 2\Bigg[k_m(\bar{\lambda}_m - \lambda_m^1) + \frac{2o(1-\alpha_m)(o-b_1)(\bar{\lambda}_m - \lambda_m^1)^2}{b_1b_2} - 2a_4(\alpha_m)(\bar{\lambda}_m - \lambda_m^1)\Bigg].$$

Take the second order derivative of $R_3(\alpha_m)$ with regard to α_m,

$$\frac{\mathrm{d}^2R_3(\alpha_m)}{\mathrm{d}(\alpha_m)^2} = 2(\bar{\lambda}_m - \lambda_m^1)^2\frac{b_1b_2 + 4o(b_1 - o)}{b_1b_2}.$$

As $b_1 > o > 0$, we have $\frac{\mathrm{d}^2R_3(\alpha_m)}{\mathrm{d}(\alpha_m)^2} > 0$, therefore $\frac{\mathrm{d}R_3(\alpha_m)}{\mathrm{d}(\alpha_m)}$ is an increasing function with regard to α_m. Hence,

$$\frac{\mathrm{d}R_3(\alpha_m)}{\mathrm{d}\alpha_m} < \frac{\mathrm{d}R_3(\alpha_m)}{\mathrm{d}\alpha_m}\big|_{\alpha_m\to 1} = 2(\bar{\lambda}_m - \lambda_m^1)\frac{(b_2+2o)\bar{\lambda}_m - 2b_3}{b_2}.$$

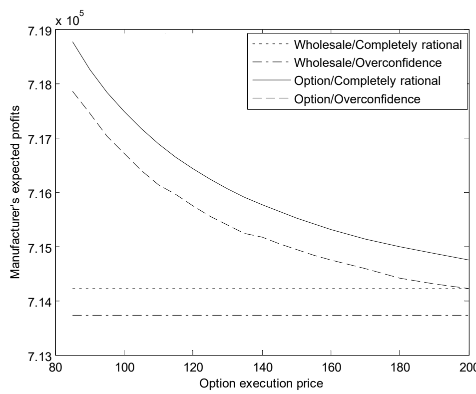
When $\bar{\lambda}_m \leqslant \frac{2b_3}{b_2+2p_0}$, we have $\frac{\mathrm{d}R_3(\alpha_m)}{\mathrm{d}\alpha_m} < 0$, that is, $\left(\frac{D}{Q_0^{oc}}\right)^2$ is a decreasing function with regard to α_m. Therefore, Q_0^{oc} is an increasing function with regard to α_m. When $b_1 > 2o$, $\frac{D - Q_1^{oc}}{Q_0^{oc}}$ is an increasing function with regard to α_m, therefore when α_m increases, Q_0^{oc} increases, and Q_1^{oc} decreases. From Proposition 3, when $\alpha_m = 0$, Q_0^{oc} and Q_1^{oc} are the only optimal solution for the manufacturer's expected profit under the option contract. As α_m increases, the differences between Q_0^{oc} and Q_1^{oc}, and between Q_0^{or} and Q_1^{or} get bigger and bigger. Since $E\left(\pi_m^o(Q_0,Q_1)\right)$ is a concave function, $E\left(\pi_m^o(Q_0,Q_1)\right)$ will get smaller and smaller. □

Appendix A.7. Sensitivity analysis on the option execution price e

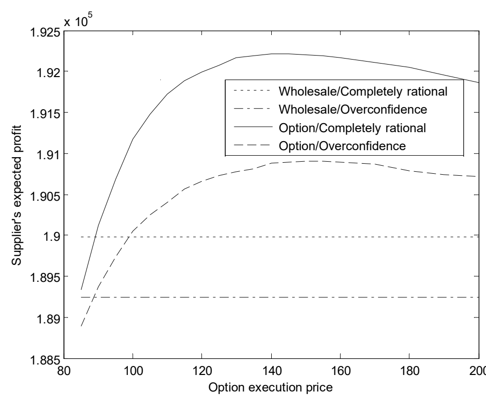
We allow the option execution price e to change between 90 and 190, while keep other parameters as described at the beginning of Section 5. Table A.8 shows how Q_0, Q_1 and I respond to e. Figure A.8 plots the relationships between the expected profits and the option execution price in a similar way to Figure 5.

	Expect.	90	100	110	120	130	140	150	160	170	180	190
Q_0	Rational	5222	5251	5273	5290	5304	5315	5325	5333	5340	5346	5352
	Overconf.	5251	5272	5287	5299	5309	5317	5324	5330	5335	5339	5343
Q_1	Rational	175	148	127	110	97	86	76	68	61	55	49
	Overconf.	123	103	88	77	67	60	53	47	42	37	33
$Q_0 + Q_1$	Rational	5397	5399	5400	5400	5401	5401	5401	5401	5401	5401	5401
	Overconf.	5374	5375	5375	5376	5376	5377	5377	5377	5377	5376	5376
I	Rational	5551	5582	5605	5624	5638	5650	5661	5669	5677	5683	5689
	Overconf.	5582	5604	5620	5633	5644	5652	5660	5666	5671	5676	5680

Table A.8: The relationship between Q_0, Q_1, I and option execution price e



(a) The manufacturer



(b) The supplier

Figure A.8: Relationships between expected profits and the option execution price under different contracts

It can be seen from Figure A.8(a) that as the option execution price increases, the profits of the manufacturer in the option contract continuously decrease, but remain higher than the profits under the wholesale price contract. When $e = 200$, the manufacturer's expected profit under the wholesale price contract with complete rationality is approximately equal to the profit under the option contract with overconfidence. From Figure A.8(b) we see that with the increase of the option execution price, the supplier's profits under the option contract first grow rapidly and then start to decline. This indicates that the marginal profit of the option execution price for the supplier decreases once it reaches a certain value. As the option execution price affects the manufacturer's order quantity decisions, it is not always beneficial for the supplier to have a higher option execution price.

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