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# COMPETITION OF PRICING AND SERVICE INVESTMENT BETWEEN IOT-BASED AND TRADITIONAL MANUFACTURERS

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ABSTRACT. This paper develops a multi-period product pricing and service investment model to discuss the optimal decisions of the participants in a supplier-dominant supply chain under uncertainty. The supply chain consists of a risk-neutral supplier and two risk-averse manufacturers, of which one manufacturer can provide real-time customer service based on the Internet of Things (IoT). In each period of the Stackelberg game, the supplier decides its wholesale price to maximize the profit while the manufacturers make pricing and service investment decisions to maximize their respective utility. Using the backward induction, we first investigate the effects of risk-averse coefficients and price sensitive coefficients on the optimal decisions of the manufacturers. We find that the decisions of one manufacturer are inversely proportional to both riskaverse coefficients and its own price sensitive coefficient, while proportional to the price sensitive coefficient of its rival. Then, we derive the first-best wholesale price of the supplier and analyze how relevant factors affect the results. A numerical example is conducted to verify our conclusions and demonstrate the advantages of the IoT technology in long-term competition. Finally, we summarize the main contributions of this paper and put forward some advices for further study.

1. Introduction. With the development of global information technology, upgrading speed of products has been accelerated and more types of IT-based customer service can be provided [24]. Advances in the emerging information technology, e.g. the IoT (internet of things) and big data, have significantly changed the market in co-competition mechanisms [21], integration and sharing modes of real-time information [29], and means of customer service [6]. For instance, the IoV (internet of vehicles) is a huge integration network with RFID (radio frequency identification devices) and executive devices embedded in vehicles to detect and record product

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life-cycle usage information. Based on the technical fusion of sensing, communication and data processing, multi-domain information can be comprehensively acquired and shared through vehicle-status or road-condition customer terminal, vehicle maintenance system, etc. [18, 19]. Other applications include but not limited to logistics, manufacturing, smart grid, intelligent building, and e-business.

There are two typical features of the IoT-based products compared to traditional products: (1) detection, analysis, and sharing of usage information can be realtimely realized; (2) more comprehensive and accurate information can be acquired by terminal customers [15]. The new customer services brought by these advantages have blurred the concept of traditional manufacturing. The IoT is an integration of various terminal devices, network services and cloud technologies, making the products perceptive and traceable. However, the great opportunity lies in predicting potential abnormal conditions based on product self-diagnoses, and providing resolutions timely via mobile technologies or social media. Imagine a scenario where your car alerts you of a specific problem and provides several service options before it breaks down on the way, or your air-conditioner manufacturer books a service appointment for you once the machine self-detected a potential issue. Guinard et al. [9] indicated that the IoT-based industries are deploying service-oriented integration technologies since investments in the new services will undoubtedly improve its market competitiveness. Besides, enterprises selling congeneric products often play price war to attract customers' attention. Product pricing is a powerful lever to improve business profits by matching supply and demand more reasonably [4]. As such, enterprises should make a trade-off between service investment and product pricing considering both market competition and the huge investment costs.

Pricing and investment models have been well developed by scholars in recent years. Xiao and Yang [28] developed a price-service model of two symmetric supply chains to investigate the decision-making equilibrium of players with different risk attitudes. However, most studies considered a single stage or single period competition between symmetric players and obtained their optimal decisions in different scenarios including uncertain market demand [11], different risk preferences [1], product substitutability [10], and profit compensation [13]. In this paper, a multi-period Stackelberg model is formulated to discuss the price-service investment competition between an IoT-based manufacturer and a traditional manufacturer in a duopoly market. In fact, our multi-period Stackelberg model is actually equivalent to a one-period static model considering similarities in different periods.

Extensive previous research has focused on oligopoly market competition concerning investment and pricing strategies of the participants. Different game models were built to address the optimal decisions and analyze how they were affected by factors such as negotiation power and risk preference. Giri and Sarker [8] considered a newsvendor setting in which the manufacturer faced a production disruption and two retailers competed on pricing and service level. They formulated this decentralized system as a manufacturer-Stackelberg game with customer demand influenced by the prices and service levels of both retailers. Wang and Ma [26] developed a mixed Cournot-Bertrand duopoly model with linear market demand and fixed marginal cost functions. They mainly investigated the existence and stability conditions of Nash equilibrium of two participants, who competed on output and price. Although there are some related work studying different sequential decision problems on pricing and investment optimization, the dynamic market share was seldom involved.



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With respect to the model, most existing studies formulated the customer demand as a linear function of retail price, service level and stochastic market base. Wu [27] investigated the bargaining equilibrium of two competing supply chains. The customer demand in each supply chain was formulated using the downwardsloping function with respect to both price and promotional effort. This paper is similar to the work of Dan et al. [5], who adopted the two-stage optimization technique and Stackelberg game to study the optimal decisions on retail services and prices in a dual-channel supply chain. However, they mainly focused on the impacts of retail service and customer loyalty on players' pricing behaviors. Our work is also related to Sinha et al. [23], who considered a multi-period multileader-follower Stackelberg competition model with non-linear cost and demand functions. Their objective function was to maximize the multi-stage total profit of each leader/follower, and an evolutionary strategy was then employed to solve this complex bi-level optimization problem. It should be noted that we obtain the optimal decisions of the two manufacturers by maximizing their periodical profits using backward induction [22], and the expected market bases for both manufacturers are assumed to be their customer demands in the latest period for simplicity.

To sum up, more and more different models were developed to investigate the price and service investment competition in duopoly markets. Most existing literature focused on the optimal decisions in different situations and analyzed how the results were affected by certain factors. Others compared duopoly equilibrium with coordinated cases where participants cooperate to maximize their total profits [7, 30], and then proposed appropriate mechanisms to promote the cooperation. However, few attempts were conducted considering multi-period market competition between traditional enterprises and the IoT-based enterprises, although this competition is much closer to the practical scenarios. Also, scholars have seldom studied the dynamic market shares of participants when examining their periodical customer demand, while the market share is an important indicator to evaluate enterprise's competitive position and profitability [14].

In this paper, we concern the multi-period price and service competition of two risk-averse manufacturers selling congeneric products, i.e., a traditional manufacturer and an IoT-based manufacturer. This duopoly market is dominated by a risk-neutral supplier, who provides raw materials for both manufacturers. Particularly, only the IoT-based manufacturer is expected to spend a certain amount of investment on IoT-service platforms and technologies in each selling season. The service level of the IoT-based products is therefore incessantly improving, which also helps to attract more market demand, while the traditional products cannot provide customer service. Such customer-oriented service can be interpreted as cloud storage, information sharing, and decision support [25]. The retail-demand uncertainty is described by demand variance and it is related to the risk preferences and utilities of the two manufacturers. Moreover, each manufacturer has its own reservation utility. Either manufacturer will guit the game once the expected utility is lower than its own reservation utility. In each period, the supplier decides its wholesale price to maximize its profit, the IoT-based enterprise determines its retail price and service investment to achieve periodical utility maximization and the traditional enterprise decides its retail price before withdrawing from the market. We find that both manufacturers' optimal decisions are affected by factors including risk-averse coefficients, price sensitive coefficients and product service level. Our numerical



example indicates that the traditional products will eventually be replaced by the IoT-based products with the passage of time.

Hereby, we conclude the main contributions of this paper as follows: (1) We propose a supplier-dominated Stackelberg model to study the optimal decisions of participants using backward induction. The duopoly market is asymmetric since we only consider the service investment of the IoT-based manufacturer. (2) To the best of our knowledge, this paper is the first time to extend such model to multiperiod competition, and we focus on the change of the market shares to see whether traditional products will eventually be replaced. (3) Our model is more adequate to the practical applications since most enterprises are conducting multi-period market competition to cultivate core competitiveness [2, 20].

The rest of the paper is organized into sections. Section 2 describes the problem and introduces a multi-period Stackelberg model considering both retail price and service investment competition. Section 3 derives the optimal decisions of the manufacturers given the wholesale price of the supplier, and analyzes how the results are affected by different factors. Section 4 goes into the optimal wholesale price decision of the supplier. A numerical example is conducted and discussed to verify our conclusions in Section 5. Finally, we summarize this paper and give further research directions in Section 6. Proofs of the propositions are given in the Appendix.

2. **Problem description and model formulation.** In this section, a multiperiod Stackelberg model is formulated to discuss the price-service investment competition between a traditional manufacturer and an IoT-based manufacturer in a duopoly market. The supplier acts as the Stackelberg leader who first determines its wholesale price to maximize the periodical profit, while the two manufacturers are regarded as followers and decide their retail price as well as service investment according to the supplier's optimal decision.



FIGURE 1. The structure of market competition between the IoTbased manufacturer and the traditional manufacturer

Figure 1 illustrates the structure of the market competition between the IoTbased manufacturer and the traditional manufacturer. Different from the traditional products, the IoT-based products are embedded with sensing devices, which are often regarded far cheaper than the production cost. In each competition period, the model illustrated in Figure 1 can be considered as a sequential dynamic game in which the supplier decides an optimal wholesale price based on the uncertain



TABLE 1. NOTATIONS

Symbol	Meaning
$\widetilde{a}_{i,n}$	manufacturer i's random market base in <i>n</i> th period with mean $q_{i,n-1}$ and variance $\sigma^2$ , where $q_{i,n-1}$ denotes the expected market demand in the previous period and $q_{2,0} > q_{1,0}$ ;
s	marginal production cost of the supplier;
$w_n$	unit wholesale price of the supplier in period $n$ ;
$p_{i,n}$	unit retail price of manufacturer $i$ in period $n$ ;
lpha,eta	price sensitive coefficients of demands of IoT-based and traditional products respectively;
$\lambda_i$	risk-averse coefficient of manufacturer $i, \lambda_i \ge 0;$
$I_n$	service investment of manufacturer 1 in the $nth$ period;
C	investment efficiency coefficient of service expenditure;
$\eta_n$	service improvement of manufacturer 1 in the <i>nth</i> period, $\eta_n > 1$ ;
$d_n$	service level of IoT-based product in period $n, d_n = d_{n-1}\eta_n$ ;
K	influence coefficient of service level on the demand of IoT-based product, $K > 0$ ;
$R_i$	reservation utility of manufacturer $i, R_i > 0$ .

market demand, and then the manufacturers generate their pricing and investment strategies accordingly. Thus, the actual decision sequences of the repeated game in each period are as follows:

**Step 1.** The supplier decides production and wholesale quantity of raw materials based on the uncertain total market demand;

Step 2. The supplier decides its optimal wholesale price;

**Step 3.** The IoT-based enterprise decides its retail price and service investment while the traditional enterprise decides its retail price.

We solve this problem of sequential dynamic game using backward induction. In each selling period, manufacturer 1 and 2 stand for the IoT-based manufacturer and the traditional manufacturer respectively. Notations used in this paper are given in Table 1.

In Table 1, i (i = 1, 2) denotes the index of the manufacturers and n ( $n = 1, 2, \dots$ ) represents the competition period of the Stackelberg game. We have  $I_n = C\eta_n^2$ , where the constant C reflects the degree of service level improvement brought by a certain amount of service investment, i.e., the investment has a decreasing effect on improving the service level.  $q_{2,0} > q_{1,0}$  means that the market demand of traditional product is initially greater than that of IoT-based product. This is intuitive for market demand substitution takes time. Manufacturers' risk-averse coefficients are assumed to be public information which is fundamentally different from the discussion of some articles [16], so we can analyze the effects of risk based on complete information dynamic game. As widely adopted in many previous studies, such as Huang and Swaminathan [12] and Chen et al. [3], the random market demands of two players are assumed to be linear functions of the retail prices, service level, and random market base. Similar to Xiao and Yang [28], we define the linear market demand function of two manufacturers in the following equations.

$$\begin{cases} \tilde{q}_{1,n} = \tilde{a}_{1,n} - \alpha p_{1,n} + \beta p_{2,n} + K d_n \\ \tilde{q}_{2,n} = \tilde{a}_{2,n} + \alpha p_{1,n} - \beta p_{2,n} \end{cases}$$
(1)

The manufacturer with larger  $\overline{a}_{in}$  has a better market prospect due to its good public praise, cost efficiency, brand, etc. The market demand of each manufacturer is positively related to the retail price of its rival, i.e., the other manufacturer, while



decreases with its own retail price. Besides, the coefficient K reflects the positive effect of the service level on the random demand of the IoT-based products. Our model can be extended to the case where the price sensitive coefficients  $\alpha$  and  $\beta$  are variables on the selling season because the customers' preference can be influenced by the service level  $d_n$ . Moreover, the market demand function can be extended to some nonlinear types on the certain factors.

Thus, according to Eqs. (1), the random profits of the manufacturers can be obtained as follows:

$$\begin{cases} \widetilde{\Phi}_{1,n} = (p_{1,n} - w_n)(\widetilde{a}_{1,n} - \alpha p_{1,n} + \beta p_{2,n} + Kd_n) - I_n \\ \widetilde{\Phi}_{2,n} = (p_{2,n} - w_n)(\widetilde{a}_{2,n} + \alpha p_{1,n} - \beta p_{2,n}) \end{cases}$$
(2)

As a result of the market demand uncertainty, manufacturers aim to maximize their utilities rather than profits given their risk attitudes. We define the utilities using Mean-Variance value function of their profits [17] as follows:

$$u_{i,n}(\widetilde{\Phi}_{i,n}) = E(\widetilde{\Phi}_{i,n}) - \lambda_i Var(\widetilde{\Phi}_{i,n}), \ i = 1, 2.$$
(3)

The first term represents the expected profits of the manufacturers and the second term represents the risk cost caused by uncertainty.  $\lambda_i$  reflects the subjective attitude of manufacturer *i* towards uncertainty, which is public information to all members. That is, the larger  $\lambda_i$  is, the more conservatively manufacturer *i* behaves. By maximizing the utilities of the manufacturers in Eq. (3), we derive their firstbest strategies given a known wholesale price decision, and analyze how various factors influence the optimal decisions in section 3.

Similarly, the profit of the supplier is determined by its wholesale price and the total order quantity of two manufacturers, i.e.,

$$\Phi_{s,n} = (w_n - s)(q_{1,n} + q_{2,n}) \tag{4}$$

The supplier determines its optimal wholesale price aiming at maximizing its periodical profit. Given the random market demand  $\tilde{q}_{i,n}$  (i = 1, 2) and the optimal pricing and investment strategies of the manufacturers, we derive the random periodical profit  $\tilde{\Phi}_{s,n}$  of the supplier and analyze how risk-averse coefficients and investment efficiency coefficient affect the optimal wholesale price in section 4.

3. Optimal retail price and service investment. To simplify our analysis without affecting our research conclusions, let K = 2 and C = 1 if not specified. Thus, according to Eqs. (2) and (3), the utility functions of the manufacturers can be derived as follows:

$$\begin{cases} u_{1,n} = (p_{1,n} - w_n)(q_{1,n-1} - \alpha p_{1,n} + \beta p_{2,n} + d_{n-1}\sqrt{I_n}) - I_n - \lambda_1 (p_{1,n} - w_n)^2 \sigma^2 \\ u_{2,n} = (p_{2,n} - w_n)(q_{2,n-1} + \alpha p_{1,n} - \beta p_{2,n}) - \lambda_2 (p_{2,n} - w_n)^2 \sigma^2 \end{cases}$$

(5)

Two manufacturers jointly determine their optimal retail price  $p_{i,n}^*$  and service investment  $I_n^*(n \ge 1)$  simultaneously. The utility function  $u_{1,n}$  is a concave function, i.e., there is only one maximum value on  $(p_{1,n}, I_n)$  if and only if Hessian matrix  $H_{1,n}$ is negative definite.

$$H_{1,n} = \begin{bmatrix} -2\alpha - 2\lambda_1 \sigma^2 & \frac{d_{n-1}}{\sqrt{I_n}} \\ \frac{d_{n-1}}{\sqrt{I_n}} & -\frac{1}{2}d_{n-1}(p_{1,n} - w_n)I_n^{-\frac{3}{2}} \end{bmatrix}, H_{2,n} = -2\beta - 2\lambda_2\sigma^2$$

Define  $A = (\alpha + \lambda_1 \sigma^2) - d_{n-1}^2$ ,  $B = \beta + \lambda_2 \sigma^2$ , and we get the following proposition from Eqs. (5) and the Hessian matrix. Proofs of all propositions are given in the Appendix.



**Proposition 1.** If (i)  $p_{i,n}^* - w_n > 0$ ; (ii)  $\frac{p_{1,n}^* - w_n}{\sqrt{I_n^*}} > \frac{d_{n-1}}{a + \lambda_1 \sigma^2}$ ; (iii)  $u_{i,n} > R_i$  are satisfied, then the optimal decisions of two manufacturers are given as

$$p_{1,n}^* = w_n + T_{1,n}, \ p_{2,n}^* = w_n + T_{2,n}, \ I_n^* = d_{n-1}^2 T_{1,n}^2$$
(6)

where  $T_{1,n} = \frac{2BM_{1,n} + \beta M_{2,n}}{4AB - \alpha\beta}$ ,  $T_{2,n} = \frac{2AM_{2,n} + \alpha M_{1,n}}{4AB - \alpha\beta}$  and  $M_{1,n} = -\alpha w_n + \beta w_n + q_{1,n-1}$ ,  $M_{2,n} = \alpha w_n - \beta w_n + q_{2,n-1}$ .

In Eqs. (6),  $q_{i,n-1}$  denotes the expected market demand of manufacturer *i* in the previous period and  $T_{i,n}$  represents the total unit profit of manufacturer *i*. Either manufacturer will withdraw from the market once its unit profit  $T_{i,n} < 0$ . The service investment of the IoT-based manufacturer  $I_n$  is proportional to its unit profit and the last-period service level. The preconditions for the establishment of proposition 1 including: (i)  $T_{i,n}$  should be positive; (ii)  $H_{1,n}$  is negative definite, i.e.,  $|H_{1,n}| > 0$ ; (iii) since both manufacturers are risk-averse,  $u_{i,n}$  should always be greater than the reservation utility  $R_i$ . An undo investment in service may end up with a low unit profit to the IoT-based manufacturer. Besides, from Eqs. (1) and the first derivative of Eqs. (5), it follows that the expected random order quantity of the manufacturers are

$$\begin{cases} E\widetilde{q}_{1,n} = T_{1,n}(\alpha + 2\lambda_1\sigma^2) \\ E\widetilde{q}_{2,n} = T_{2,n}(\beta + 2\lambda_2\sigma^2) \end{cases}$$
(7)

For convenience, we assume that the wholesale quantity is far larger than the wholesale price, i.e.,  $M_{i,n} \gg 0, (i = 1, 2)$  in each period. The following proposition analyzes the establishment condition of Proposition 1.

**Proposition 2.** If  $1 < d_{n-1} < d^*$ , then we have  $T_{i,n} > 0$  and  $|H_{1,n}| > 0$ , where

$$d^* = \sqrt{(\alpha + \lambda_1 \sigma^2) - \frac{\alpha \beta}{4(\beta + \lambda_2 \sigma^2)}}.$$

Proposition 2 gives a necessary condition to ensure the Stackelberg competition between two manufacturers. A critical value of the service level is given to guarantee positive marginal profits of the manufacturers. When the service level exceeds  $d^*$ , the traditional manufacturer will withdraw and the IoT-based manufacturer monopolizes the market. Thus, we assume the boundary condition is tenable throughout this paper.

Next, we qualitatively analyze how the wholesale price, risk-averse coefficients, and price sensitive coefficients affect the optimal decisions of the manufacturers in the following propositions.

**Proposition 3.** If  $1 < d_{n-1} < d^*$ , then the optimal decisions of the manufacturers satisfy

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(i) When 
$$\alpha < \beta$$
, then  $\frac{\partial p_{1,n}}{\partial w_n} > 1$ ,  $\frac{\partial I_n^*}{\partial w_n} > 0$  and  $\frac{\partial p_{2,n}}{\partial w_n} > 1$  if  $d_{n-1} > \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ ,  
 $\frac{\partial p_{2,n}^*}{\partial w_n} < 1$  if  $d_{n-1} < \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ ,  $\frac{\partial p_{2,n}^*}{\partial w_n} = 1$  if  $d_{n-1} = \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ .  
(ii) When  $\alpha > \beta$ , then  $\frac{\partial p_{1,n}^*}{\partial w_n} < 1$ ,  $\frac{\partial I_n^*}{\partial w_n} < 0$  and  $\frac{\partial p_{2,n}^*}{\partial w_n} > 1$  if  $d_{n-1} < \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ ,  
 $\frac{\partial p_{2,n}^*}{\partial w_n} < 1$  if  $d_{n-1} > \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ ,  $\frac{\partial p_{2,n}^*}{\partial w_n} = 1$  if  $d_{n-1} = \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ .  
(iii) When  $\alpha = \beta$ , then  $\frac{\partial p_{1,n}^*}{\partial w_n} = 1$ ,  $\frac{\partial I_n^*}{\partial w_n} = 0$  and  $\frac{\partial p_{2,n}^*}{\partial w_n} = 1$ .



Proposition 3 shows that the effects of the wholesale price on the optimal decisions of the manufacturers depend on the comparison of  $\alpha$  with  $\beta$ . When  $\alpha < \beta$ , with the increase of the wholesale price, the IoT-based manufacturer would appropriately increase its retail price and service investment to make a higher unit profit and a better product service to attract more demand. Since the traditional manufacturer is comparatively more risk-averse, however, when the service level  $d_{n-1}$ is sufficiently high, it tends to increase its retail price to gain a higher unit profit; when  $d_{n-1}$  is sufficiently small, it may reduce the price to attract market demands. On the contrary, when  $\alpha < \beta$ , the results are totally inversed.

**Proposition 4.** If  $1 < d_{n-1} < d^*$ , then the optimal decisions of the manufacturers satisfy

(i)  $\frac{\partial p_{1,n}^*}{\partial \lambda_1} < 0, \ \frac{\partial p_{2,n}^*}{\partial \lambda_1} < 0, \ \frac{\partial I_n^*}{\partial \lambda_1} < 0;$ (ii)  $\frac{\partial p_{1,n}^*}{\partial \lambda_2} < 0, \ \frac{\partial p_{2,n}^*}{\partial \lambda_2} < 0, \ \frac{\partial I_n^*}{\partial \lambda_2} < 0.$ 

The larger the risk-averse coefficient of one manufacturer, the lower both retail prices and service investment will be, thus bringing about a fierce price competition. A lower optimal service investment will compensate the decrease of the optimal retail price. A lower risk sensitivity helps to reduce the price competition and increase the unit profit as well as the service investment while a higher risk sensitivity brings about a greater sales market. Manufacturers have to reveal a balanced risk sensitivity value to solve this contradiction.

From proposition 1, the demand uncertainty  $\sigma^2$  has similar effects on the optimal retail price and service investment as that of risk-averse coefficients. So we omit the analysis of effects of demand uncertainty on manufacturers' decision equilibrium. **Proposition 5.** If the establishment conditions of proposition 2 hold, then,

- (i)  $\frac{\partial p_{1,n}^*}{\partial \alpha} < 0, \ \frac{\partial p_{2,n}^*}{\partial \alpha} > 0, \ \frac{\partial I_n^*}{\partial \alpha} < 0;$
- (ii)  $\frac{\partial p_{1,n}^*}{\partial \beta} < 0, \ \frac{\partial p_{2,n}^*}{\partial \beta} > 0, \ \frac{\partial I_n^*}{\partial \beta} < 0.$

This proposition shows that price sensitive coefficient of one manufacturer has a negative effect on its own optimal retail price but a positive effect on the rival's decision. This is because the increase of price sensitive coefficient will result in the decrease of its expected market demand which prompts the manufacturer to reduce price to attract customers. Moreover, the IoT-based manufacturer has to reduce service investment to compensate the loss of profit caused by the decrease of its optimal retail price.

4. The wholesale price of the supplier. In this section, we analyze the wholesale price of the supplier. Since the supplier is risk-neutral, we derive the optimal wholesale price that maximizes its expected profit. From Eqs. (7), the expected order quantity  $E\tilde{Q}_{s,n} = T_{1,n}(\alpha + 2\lambda_1\sigma^2) + T_{2,n}(\beta + 2\lambda_2\sigma^2)$ , so we have the expected profit of the supplier

$$E\Phi_{s,n} = (w_n - s)[T_{1,n}(\alpha + 2\lambda_1\sigma^2) + T_{2,n}(\beta + 2\lambda_2\sigma^2)]$$
(8)

Note that either manufacturer will withdraw from the market, thus the game ends, once its expected utility falls below the retained utility. Combine Eqs. (5-7),



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and yields

$$u_{1,n} = AT_{1,n}^2 \ge R_1 \tag{9}$$

$$u_{2,n} = BT_{2,n}^2 \ge R_2 \tag{10}$$

Inequalities (9) and (10) are IR (individually rationality) constraints. The wholesale price will be accepted by manufacturers only if their IR constraints are satisfied. Otherwise, the manufacturer will withdraw from the market and then only the other manufacturer keeps cooperating with the supplier. Specially, the game ends when neither (9) nor (10) holds. The total order quantity varies when either manufacturer quits the game. We derive the following proposition solving the first derivative of  $E\tilde{\Phi}_{s,n}$  with respect to  $w_n$ .

**Proposition 6.** Assume that  $d_{n-1} < \frac{\alpha}{2} + \lambda_1 \sigma^2$  and  $\frac{d_{n-1}}{(\alpha + \lambda_1 \sigma^2)} < \frac{p_{1,n}^* - w_n}{\sqrt{I_n^*}}$  are satisfied, then the optimal wholesale price of the supplier is

$$w_{n}^{*} = \begin{cases} w_{n}^{'}, & \text{if both (9) and (10) hold;} \\ w_{n}^{''}, & \text{if (9) holds while (10) doesn't;} \\ w_{n}^{'''}, & \text{if (10) holds while (9) doesn't;} \\ game ends, & neither (9) nor (10) holds. \end{cases}$$
(11)

where

$$\begin{split} w_n' &= \frac{s}{2} + \frac{(\alpha + 2\lambda_1 \sigma^2)(2Bq_{1,n-1} + \beta q_{2,n-1}) + (\beta + 2\lambda_2 \sigma^2)(2Aq_{2,n-1} + \alpha q_{1,n-1})}{2(\alpha + 2\lambda_1 \sigma^2)(2B - \beta)(\alpha - \beta) + 2(\beta + 2\lambda_2 \sigma^2)(2A - \alpha)(\beta - \alpha)}, \\ w_n'' &= \frac{s}{2} + \frac{2Bq_{1,n-1} + \beta q_{2,n-1}}{2(\alpha - \beta)(2B - \beta)} , \\ w_n''' &= \frac{s}{2} + \frac{2Aq_{2,n-1} + \alpha q_{1,n-1}}{2(\beta - \alpha)(2A - \alpha)} . \end{split}$$

In proposition 6, the wholesale price of the supplier is correlated with the retained utilities  $R_i$  of the two manufacturers. If the manufacturers' utilities are sufficiently large, the supplier has to adjust its wholesale price to accommodate the expected total order quantity. When the expected utility of one manufacturer falls below its retained utility, the supplier must decide the optimal wholesale price considering the decrease of order quantity. When neither of the manufacturers' utilities is satisfied, a great decrease of material order quantity may also bring about a massive loss to the supplier and thus the game ends.

The optimal wholesale price is complicatedly affected by related coefficients, but increases with the expected order quantity of the manufacturers in the previous period  $q_{i,n-1}$  and the unit production cost of the supplier s in different scenarios. In Eq. (8), the supplier may have an optimal wholesale price to maximize its expected profit if and only if  $E\widetilde{\Phi}_{s,n}$  is concave in  $w_n$ , i.e.,  $(\alpha+2\lambda_1\sigma^2)\frac{\partial T_{1,n}}{\partial w_n} + (\beta+2\lambda_2\sigma^2)\frac{\partial T_{2,n}}{\partial w_n} < 0.$ 

5. Numerical example. In this section, we conduct a numerical example to illustrate our conclusions. Consider two manufacturers producing and selling congeneric engineering vehicles in a duopoly market. All raw materials needed, such as steels, auto glasses and tires, are provided by a same integrated supplier. The IoT-based engineering vehicles are specifically equipped with sensing devices, which track, record and analyze the operation and status information, such as oil temperature and rotating speed of the vehicles for possible abnormal problems. Therefore, customers can be provided services of maintenance warning, emergency rescue, and so on.





FIGURE 2. The optimal retail price  $p_{i,1}^*$  versus the price sensitive coefficient  $\alpha$  and  $\beta$ 



FIGURE 4. First derivative of retail price  $\frac{\partial p_{i,1}^*}{\partial w_1}$ versus the service level  $d_0$ 



FIGURE 3. The optimal retail price  $p_{i,1}^*$  versus the price sensitive coefficient  $\alpha$  and  $\beta$ 



FIGURE 5. The optimal retail price  $p_{i,1}^*$  versus the risk-averse coefficient  $\lambda_i$ 

The default values of related parameters in our example are given as follows:  $\alpha = 0.2, \beta = 0.8, w = 40, q_{1,0} = 100, q_{2,0} = 200, d_0 = 1.2, \lambda_1 = \lambda_2 = 0.6$  and  $\sigma = 2$ , which satisfy the establishment conditions of proposition 2. The effects of the price sensitive coefficients, wholesale price, service level and risk-averse coefficients on the optimal retail prices of two manufacturers are evaluated in Figures 2-5.

Figures 2-3 show the effects of price sensitive coefficients on the optimal retail prices of both manufacturers, and  $p_{1,1}^*$  diminishes with  $\alpha$  while  $p_{2,1}^*$  opposites. Similarly, the optimal retail price  $p_{2,1}^*$  decreases with  $\beta$  while  $p_{1,1}^*$  opposites. This is in accordance with proposition 5 and it is also obvious that  $p_{1,1}^* > p_{2,1}^*$  when and only when  $\alpha < \beta$ . Thus, we can conclude that either manufacturer will achieve price advantage if its price sensitive coefficient is comparatively small. Figure 4 illustrates proposition 3 and reveals that when  $\alpha < \beta$  and  $d_0 > \sqrt{\frac{\alpha}{2} + \lambda_1 \sigma^2}$ , we have  $\frac{\partial p_{1,1}^*}{\partial w_1} > 1$  and  $\frac{\partial p_{2,1}^*}{\partial w_1} < 1$ . This indicates that the IoT-based manufacturer will obtain a larger unit profit as the wholesale price increases when its service level is sufficiently high. In Figure 5, the optimal retail price  $p_{i,1}^*$  decreases with both  $\lambda_1$  and  $\lambda_2$ . Intuitively, we have  $p_{1,1}^* > p_{2,1}^*$  when  $\lambda_1 > \lambda_2$  and vice versa, i.e., either manufacturer will raise its retail price if it is more risk-averse.





FIGURE 6. The optimal wholesale price  $w_n^*$  versus the service level  $d_n$ 



FIGURE 7. The optimal wholesale price  $w_n^*$  versus the price sensitive coefficients  $\alpha$  and  $\beta$ 



FIGURE 8. The optimal wholesale price  $w_n^*$  versus the risk-averse coefficients  $\lambda_i$ 

To further analyze how the two manufacturers' risk-averse coefficients and price sensitive coefficients affect the supplier's optimal decision, Figures 6-8 are given according to proposition 6 using the same default values of related parameters.

In Figure 6, the optimal wholesale price of the supplier decreases with the service level of the IoT-based manufacturer. According to proposition 1, both manufacturers will raise the retail prices with the improvement of the service level, and thus the market demand decreases. This indicates that the supplier will gradually reduce its wholesale price due to the periodical service investment. Figure 7 illustrates that the variation of price sensitive coefficients has little effects on  $w_n^*$ . Yet when  $\beta$  gets quite close to  $\alpha$ ,  $w_n^*$  increases dramatically. In this case,  $T_{i,n}$  is not related to  $w_n^*$  and the optimal retail prices are linear functions of  $w_n^*$ . Since the market demands are identically affected by the retail prices, either manufacturer will choose a higher retail price. The effect of the risk-averse coefficients on  $w_n^*$  is shown in Figure 8. When  $\alpha > \beta$ ,  $w_n^*$  only significantly increases with  $\lambda_2$ , thus the traditional manufacturer should reveal less risk aversion to reduce the purchase cost and improve its utility.



6. **Conclusions.** This paper studies the pricing and service investment competition between an IoT-based manufacturer and a traditional manufacturer under market demand uncertainty. The manufacturers are risk-averse and the supplier is risk-neutral. In each period of the multi-period Stackelberg model, the supplier acts as the leader and the manufacturers are followers. We solve the maximum periodical utilities of the manufacturers and the periodical profit of the supplier using backward induction. Then, we illustrate the effects of the price sensitive coefficients, wholesale price and risk-averse coefficients on the optimal decisions of the players, especially the two manufacturers.

We find that the effect of the wholesale price on the optimal decisions of the manufacturers depends on the comparison between their price sensitive coefficients. With the increase of the wholesale price, the IoT-based manufacturer would raise its retail price and improve the service level to make a higher unit profit and a better customer service to attract more customers. When the service level is sufficiently high, it may choose to raise its retail price to gain a higher unit profit. When the service level is sufficiently low, however, it may reduce the price to attract more market demand. The higher the risk-averse coefficient of one manufacturer, the lower both retail prices and service investment will be, which brings about a fierce price competition. A lower optimal service investment will compensate the decrease of the optimal retail price. Lower risk sensitivity helps to reduce the price competition and increase the unit profit as well as the service investment, while higher risk sensitivity makes a greater sales market. Manufacturers have to reveal a balanced risk sensitivity to deal with this contradiction. Price sensitive coefficient of one manufacturer has a negative effect on its own optimal retail price but a positive effect on the rival's decision. This is because the increase of price sensitive coefficient results in the decrease of its expected market demand and promotes the manufacturer to reduce price to attract more demand. In addition, the IoT-based manufacturer has to reduce service investment to compensate the loss of profit caused by the decrease of its optimal retail price.

This paper contributes to explore the optimal decisions of two asymmetric manufacturers in a duopoly market using backward induction, which is also practically meaningful for promoting the application of emerging information technologies during multi-period market competition. There are several directions for further study. Firstly, our model can be extended to the case where manufacturers lie in more powerful positions, i.e., two asymmetric manufacturers act as the Stackelberg leaders. Then, the risk sensitivities of the two manufacturers can also be private information. It is interesting but challenging to investigate how suppliers design incentive mechanisms that induce the manufacturers to reveal their private risk preferences. Furthermore, this paper considers a multi-period pricing and service competition that can actually be equivalent to a single period problem, it will be meaningful to discuss a multi-period problem in which the repeated game is played despite its complexity. Finally, this paper considers one supply chain in which two manufacturers keep a long-term relationship with a single supplier. Further study can also consider the problem that both manufacturers can replenish their raw material from separate suppliers.



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### Appendix

### Proof of Proposition 1.

*Proof.* From Eqs. (5), there always exists at least one optimal decision if and only if Hessian Matrix  $H_{1,n}$  on  $(p_{1,n}, I_n)$  is negative definite, i.e.,  $|H_{1,n}| > 0$  and then  $\frac{d_{n-1}}{(\alpha+\lambda_1\sigma^2)} < \frac{p_{1,n}^* - w_n}{\sqrt{I_n^*}}$  is derived. The solution satisfying the first order conditions of  $u_{i,n}$  is optimal, thus we have

$$\frac{\partial u_{1,n}}{\partial p_{1,n}} = -2Ap_{1,n} + \beta p_{2,n} + (2A - \alpha)w_n + q_{1,n-1} = 0$$
(A.1)

$$\frac{\partial u_{2,n}}{\partial p_{2,n}} = \alpha p_{1,n} - 2Bp_{2,n} + (2B - \beta)w_n + q_{2,n-1} = 0 \tag{A.2}$$

$$\frac{\partial u_{1,n}}{\partial I_n} = d_{n-1}(p_{1,n} - w_n)I_n^{-\frac{1}{2}} - 1 = 0$$
(A.3)

Eqs. (A.1) and (A.2) can be regarded as two linear equations on variables  $p_{1,n}$  and  $p_{2,n}$ . Simultaneous the two linear equations and we get the optimal retail prices,  $p_{i,n}^* = w_n + T_{i,n}, i = 1, 2$ , where  $T_{1,n} = \frac{2BM_{1,n} + \beta M_{2,n}}{4AB - \alpha\beta}$ ,  $T_{2,n} = \frac{2AM_{2,n} + \alpha M_{1,n}}{4AB - \alpha\beta}$  and  $M_{1,n} = -\alpha w_n + \beta w_n + q_{1,n-1}$ ,  $M_{2,n} = \alpha w_n - \beta w_n + q_{2,n-1}$ . Moreover, from (A.3), we have the first-best service investment of the IoT-based manufacturer  $I_n^* = d_{n-1}^2 T_{1,n}^2$ .

### Proof of Proposition 2.

*Proof.* In general, the sales volume is much greater than the wholesale price through dimensional transformation, thus we have  $M_{i,n} > 0$ . To satisfy the conditions  $T_{i,n} > 0$  and  $|H_{1,n}| > 0$ , we solve the following linear inequalities

$$4AB - \alpha\beta > 0 \tag{A.4}$$

$$|H_{1,n}| > 0, i.e., \frac{p_{1,n}^* - w_n}{\sqrt{I_n^*}} > \frac{d_{n-1}}{(\alpha + \lambda_1 \sigma^2)}$$
(A.5)

and it follows that  $d_{n-1} < \sqrt{(\alpha + \lambda_1 \sigma^2) - \frac{\alpha \beta}{4(\beta + \lambda_2 \sigma^2)}}$ .

#### Proof of Proposition 3.

Proof. Differentiating  $p_{i,n}^*(i = 1, 2)$  and  $I_n^*$  with respect to  $w_n$ , we have  $\frac{\partial p_{1,n}^*}{\partial w_n} = 1 + \frac{(\alpha - \beta)(-2B + \beta)}{4AB - \alpha \beta}$ ,  $\frac{\partial p_{2,n}^*}{\partial w_n} = 1 + \frac{(\alpha - \beta)(2A - \alpha)}{4AB - \alpha \beta}$  and  $\frac{\partial I_n^*}{\partial w_n} = 2d_{n-1}^2T_{1,n}\frac{\partial T_{1,n}}{\partial w_n}$ . Since  $4AB - \alpha\beta > 0$  and  $2B - \beta > 0$ , when  $\alpha < \beta$ , we get  $\frac{\partial T_{1,n}}{\partial w_n} > 0$ ,  $\frac{\partial p_{1,n}^*}{\partial w_n} > 1$  and  $\frac{\partial I_n^*}{\partial w_n} > 0$ . When  $d_{n-1} < \alpha/2 + \lambda_1 \sigma^2$ , namely  $2A - \alpha > 0$ , we have  $\frac{\partial p_{2,n}^*}{\partial w_n} < 1$ . Other results can be derived in the same way. Similarly, we can prove part (ii) and part (iii) of proposition 3.

### **Proof of Proposition 4.**

*Proof.* Take the first-order derivative of  $p_{i,n}^*$  and  $I_n^*$  with respect to  $\lambda_1$  and get

$$\frac{\partial p_{1,n}^*}{\partial \lambda_1} = \frac{\partial T_{1,n}}{\partial \lambda_1} = \frac{-4\sigma^2 B(2BM_{1,n} + \beta M_{2,n})}{(4AB - \alpha\beta)^2} \tag{A.6}$$

$$\frac{\partial p_{2,n}^*}{\partial \lambda_1} = \frac{\partial T_{2,n}}{\lambda_1} = \frac{-2\alpha\sigma^2(2BM_{1,n} + \beta M_{2,n})}{(4AB - \alpha\beta)^2} \tag{A.7}$$



$$\frac{\partial I_n^*}{\partial \lambda_1} = 2d_{n-1}^2 T_{1,n} \frac{\partial T_{1,n}}{\partial \lambda_1} \tag{A.8}$$

From proposition 2, we have  $\pm \alpha w_n \mp \beta w_n + q_{i,n-1} > 0$ , thus part (i) is proved. Part (ii) of Proposition 4 can be proved similarly.

#### **Proof of Proposition 5.**

*Proof.* We only prove part (i) of proposition 5 because of symmetry, part (ii) can be derived in the same way. Differentiating  $p_{i,n}^*$  and  $I_n^*$  with respect to  $\alpha$ , we have

$$\frac{\partial p_{1,n}^*}{\partial \alpha} = \frac{\partial T_{1,n}}{\partial \alpha} = \frac{w_n(-2B+\beta)}{(4AB-\alpha\beta)} - \frac{(4B-\beta)(2BM_{1,n}+\beta M_{2,n})}{(4AB-\alpha\beta)^2} < 0$$
(A.9)

$$\frac{\partial p_{2,n}^*}{\partial \alpha} = \frac{\partial T_{2,n}}{\partial \alpha} = \frac{w_n (2A - \alpha)}{(4AB - \alpha\beta)} + \frac{2(A - \alpha)(2BM_{2,n} + \beta M_{1,n})}{(4AB - \alpha\beta)^2} > 0$$
(A.10)

$$\frac{\partial I_n^*}{\partial \alpha} = 2d_{n-1}^2 T_{1,n} \frac{\partial T_{1,n}}{\partial \alpha} < 0 \tag{A.11}$$

Proposition 5 is proved.

## Proof of Proposition 6.

Proof. Note that the expected total order quantity of the supplier  $E\tilde{Q}_s = E(\tilde{q}_1 + \tilde{q}_2)$ , take the second-order derivative of  $E\tilde{\Phi}_{sn}$  in Eq. (8) with respect to  $w_n$  and we have  $\frac{\partial^2 E\tilde{\Phi}_{sn}}{\partial w_n^2} = 2(\alpha + 2\lambda_1\sigma^2)\frac{\partial T_1}{\partial w_n} + 2(\beta + 2\lambda_2\sigma^2)\frac{\partial T_2}{\partial w_n}$ . From proposition 3, when  $\alpha > \beta$ ,  $E\tilde{\Phi}_{s,n}$  is concave in  $w_n$ . Solve the first-order derivative of  $E\tilde{\Phi}_{s,n}$  when both (9) and (10) are satisfied, the optimal wholesale price of the supplier is  $w'_n$ . If Eq. (9) holds while (10) doesn't, then the traditional manufacturer will quit the game and  $E\tilde{Q}_s = E\tilde{q}_1$ . Solve the equation  $\frac{\partial E\tilde{\Phi}_{s,n}}{\partial w_n} = 0$  and we obtain  $w''_n$ , i.e., when the traditional manufacturer quits the game, the optimal wholesale price of the supplier is  $w''_n$ . The scenario when the IoT-based manufacturer quits the game can be considered in the same way. Specially, when neither (9) nor (10) holds, both manufacturers will withdraw from the market and thus the game ends.

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