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For Better or For Worse: Impacts of IoT Technology in e-Commerce Channel

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Internet of Things (IoT) technology utilizes sensors and other internet-enabled devices to collect and share data. It is widely regarded as a disruptive technology that brings tremendous opportunities to supply chain members. This study uses a game-theoretical model to study an e-commerce setting in which an online platform provides IoT infrastructure and a manufacturer sells its products on the platform. Our work examines the interaction among the manufacturer's IoT investment decision, the platform's choice of pricing models, and the platform's transfer payment strategy. We solve the model analytically and obtain several interesting findings. Our study shows that the manufacturer in a wholesale pricing model is more likely to invest, and invests more, in IoT technology than in an agency one. One surprising finding is that both the manufacturer and the channel performance could be hurt by an increase in IoT technology value in certain situations. Also surprisingly, even having the option of investing in IoT technology by the manufacturer can make both the manufacturer and the channel performance worse off. Therefore, the advancement of IoT technology might not benefit either manufacturers or the whole industry, although e-commerce platform giants and the news media have been advocating the benefits of IoT technology enthusiastically in recent years. Our results should concern both device manufacturers who contemplate adopting or have adopted IoT technology and policymakers who are interested in overall channel performance.

Key words: IoT technology; wholesale pricing; agency pricing; online platforms; transfer payment
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1. Introduction

Internet of Things (IoT) refers to the use of sensors and other internet-enabled devices to collect and share data. IoT technology is widely regarded as a disruptive technology that is increasingly attracting the attention of many industries, such as e-commerce and healthcare. Worldwide IoT spending on hardware and software is expected to maintain a double-digit growth and exceed the $1 trillion US dollar mark in 2022 (IDC Inc. 2019). The market revenue of IoT technology reached $100 billion US dollars in 2017, and this figure is forecast to grow to around $1.6 trillion US dollars by 2025 (Statistica Inc. 2020). Also, smart devices, that is, IoT-enabled devices, are becoming more popular, and the number of such devices is estimated to increase fivefold in 10 years from 2015, reaching 75 billion worldwide by 2025 (Statistica Inc. 2016).

With more and more data being pushed to the cloud, IoT technology enables innovations in smart devices and applications such as location intelligence (Amazon Inc. 2020b). In the e-commerce area, it brings tremendous opportunities to the supply chain members, from manufacturers to online retail platforms. By using data gathered through smart devices, supply chain members can interact with customers on an individual basis. For example, manufacturers can design devices such as smart refrigerators and smart fitness systems (Griffith and Colon 2019, Rawes 2021) that can adjust the settings in the home environment based on the owner's preferences. Because of the high cost and complexity of developing and maintaining *IoT infrastructure* such as security, data centers, and IoT analytics, it might not be cost-effective for device manufacturers to build their own IoT infrastructure. Instead, a device manufacturer can rely on existing artificial intelligence and Internet of Things (AIoT) ecosystems provided by online platform giants such as Amazon and Alibaba (the largest e-business platform in China) to create devices that gather, analyze, and act on data (Alibaba Inc. 2020, Amazon Inc. 2019). For example, LG Electronics saved 80% on its development cost by using Amazon Web Services (AWS)

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Figure 1 **A Smart Printer with Amazon Dash Replenish Service [Color figure can be viewed at wileyonlinelibrary.com]**

for its IoT platform (Amazon Inc. 2020a). Furthermore, online retail platforms can generate new sources of revenue by aggregating the data from smart devices to gain insights into customer behavior and recommend personalized products and services. Figure 1 shows an example of a smart printer available at amazon.com which can order toner cartridges automatically using the Amazon Dash Replenish service. In summary, we consider an e-commerce platform that not only acts as retailer but also provides IoT infrastructure and benefits through the effect of cross-selling brought by IoT technology.

In this research, we study two broad issues related to IoT strategies in a decentralized setting involving a manufacturer and a platform. First, who will benefit from the arrival of IoT technology in a decentralized channel? Second, how should an online platform incentivize a manufacturer to invest resources in building a smart device?

These two issues are challenging because of the complex interactions among all the supply chain members. Although customers can benefit from the smart devices, not all customers are willing to share their usage data due to privacy concerns. Without such data, the smart devices are not able to provide value-added service enabled by the IoT technology, which means that customers can only use the basic functionality that does not require IoT technology. This could result in less incentive for manufacturers to use IoT technology in smart devices. Similarly, online platforms might not be able to recommend new products to customers accurately if customers do not share usage data. Also, to bring smart devices to the market, device manufacturers need to make substantial investments in R&D, application development, and system integration. Depending on the level of functionality desired, the cost could easily surpass $1 million US dollars, an amount significant to small smart device manufacturers and start-ups (Mathew 2020). Given that such an investment also benefits the platform, from the perspective of the platform, the device manufacturers might under-invest if they do not receive proper compensation. Therefore, on the one hand, IoT technology creates new opportunities such as more accurate product recommendations via IoT-enabled customer data. On the other hand, to benefit from such opportunities, platforms should examine the incentives of supply chain members and carefully design pricing models (wholesale or agency) in the presence of IoT technology. Under a wholesale pricing model, a manufacturer sells its product to a platform at the wholesale price, and then the platform sells the product to customers at the retail price; while with an agency pricing model, a manufacturer sells its product at the retail price on the platform and pays the platform a proportion of the revenue as a commission fee. For example, commission fee is 8% for consumer electronics and cellphones sold at Amazon (Amazon Inc. 2020c) and 5% for electronics at Tmall (Tmall.com 2021), a platform operated by Alibaba.

In this study, we focus on addressing the following research questions:

1. What are the manufacturer's equilibrium decisions (pricing and IoT technology investment) under a wholesale and an agency model, respectively?
2. What are the platform's equilibrium decisions, such as transfer payment under a wholesale and an agency pricing model, respectively?
3. How does the strategic interaction between the manufacturer's and the platform's decisions affect the platform's choice of a pricing model (wholesale vs. agency)?
4. How do factors such as IoT technology value impact the manufacturer, the platform, and the whole channel?
5. Will the manufacturer, the platform, and the whole channel always benefit from the arrival of IoT technology?
6. Can channel coordination between a platform and a manufacturer improve system performance?

To answer these research questions, we develop a game-theoretical model in which a manufacturer produces a smart device to be sold on an online platform. While the past platform pricing literature has studied the pricing decision by a manufacturer (Geng et al. 2018, Kwark et al. 2017, Tian et al. 2018), one novel feature of our model is that a manufacturer can invest in IoT technology to gather usage data from customers by utilizing a platform's existing IoT infrastructure. Through such data, the manufacturer can benefit from the *demand-expansion* effect: IoT technology embedded in a smart device creates values for customers with personalized services and increases the demand for the device. With customer usage data gathered through its IoT infrastructure, a platform can benefit as well through the effect of *cross-selling* brought by IoT technology: more accurate recommendation using IoT data leads to more selling of other products to customers. In addition to choosing a pricing model, the platform can use transfer payments to further improve its profit in the presence of IoT technology. The transfer payment can take either the form of *license fee* or *subsidy*, that is, the platform can charge the manufacturer a license fee or provide a subsidy for using its IoT infrastructure. Our paper is the first to study the strategic behaviors of supply chain members (a manufacturer and a platform) in a platform pricing model with IoT technology and the impacts of IoT technology on supply chain members.

By analyzing the closed-form solutions obtained from the model, we reveal several interesting results and managerial insights, which are summarized in section 6. For example, one might expect from common intuition that a manufacturer would benefit from the arrival of IoT technology. Surprisingly, our result shows that in certain situations, a manufacturer will be worse off when it has an option of investing in this new IoT technology. Furthermore, the total supply chain profit could also decrease. The results imply that a coordination scheme is needed to fully realize the potential of IoT technology.

To summarize, our research makes several contributions. First, despite the importance of IoT technology to the economy, there has been no rigorous analysis of the economic implication of IoT technology in the context of online platforms. Our work attempts to fill this gap. Second, our research studies the interaction among IoT technology investment, transfer payment, and choice of pricing models, yielding results that are new and counter-intuitive. Third, our study has identified areas of IoT technology investment inefficiency due to the lack of proper coordination schemes. The finding has important practical implications for reaping the benefits of IoT technology.

The rest of this study is organized as follows. We review the related literature in section 2 and build a game-theoretical model with an upstream manufacturer, a downstream platform, and a continuum of customers in section 3. Then we solve the model with and without IoT technology and analyze the closed-form solutions in sections 4 and 5. We conclude the paper in section 6.

2. Literature Review

This study studies the problem of IoT technology investment by a manufacturer that produces a smart device to be sold on an online platform such as amazon.com. Our research is related to the following two streams of literature.

The first stream of literature studies pricing models in online platforms, specifically, wholesale and agency pricing models. In this stream of research, quite a few papers have studied the effect of competition on the pricing model choice. Abhishek et al. (2016) investigate whether an e-tailer should adopt an agency pricing model or a wholesale pricing model to deal with suppliers and find that e-tailers prefer agency pricing models when the electronic channel's sales negatively affect the traditional channel's demand. Tan and Carrillo (2017) analyze a model of vertically differentiated goods and find that a revenue-sharing scheme together with the upstream publisher's pricing right contributes to the advantage of an agency pricing model over a wholesale one. Tian et al. (2018) show that in the case of high order fulfillment cost and intensive competition, an online retailer prefers a wholesale pricing model, challenging the conventional wisdom that an agency pricing model can mitigate the double-marginalization effect and benefit both the supplier and online retailer.

The second group of papers in this stream studies the pricing of multiple products and the choice of pricing models in online platforms. Hao and Fan (2014) study e-book and e-reader pricing strategies for a publisher and a retailer under wholesale and agency models. They show that the publisher could be worse off under an agency model. Geng et al. (2018) analyze the interaction between an upstream firm's add-on strategy and a downstream online platform's pricing model choice. They find that the upstream firm chooses bundling under a wholesale pricing model but prefers a separate add-on under an agency pricing model.

The third group of papers in the first stream incorporates the strategic role of information. Mukhopadhyay et al. (2008) study the optimal pricing model design when both agency and wholesale pricing models exist. They determine the optimal pricing decisions and the amount of value added by the retailer when the manufacturer has incomplete information about the value adding cost. Hagiu and Wright (2015) examine pricing model preference by intermediaries in the presence of marketing activity. The preference is shown to depend on whether suppliers or intermediaries have better information about the optimal choice of marketing activities. Kwark et al. (2017) investigate how online retailers benefit from third-party information, such as product reviews. They show that retailers can benefit from third-party information by using the upstream pricing model as a strategic tool. Li et al. (2021) investigate a model where an upstream manufacturer and a reseller sell on an online platform using agency model. They find that the platform's information sharing decision depends on competition intensity and demand variability.

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In contrast to each of the three groups in the first stream, our paper studies the interaction between a pricing model and IoT technology investment. We focus on the impacts of IoT technology on the manufacturer's and the platform's profits, which has not been studied previously.

The second stream of literature is related to transfer payment. We classify the literature into two parts. The first part examines how governments or non-profit organizations use transfer payments to enhance social welfare. From a policymaker's perspective, Cohen et al. (2016) investigate government subsidy policies for green technology adoption. The paper finds that when policymakers subsidize customers directly, they will significantly miss the desired adoption target level if they ignore demand uncertainty. Levi et al. (2017) study a central planner's optimal policy of subsidizing producers to increase the consumption of products, such as new drugs, under a budget constraint and endogenous market response. They find that a uniform subsidy policy is optimal and obtain the best social welfare solution in many cases. Bai et al. (2021) study the optimal government subsidy decision to speed up consumer trade-ins of used products. They show that a sharing subsidy scheme is more effective than a fixed-amount one in encouraging consumer trade-ins. Among the papers studying the subsidy from a non-profit organization's perspective, Taylor and Xiao (2014) study whether a donor should subsidize the purchases or the sales of medical drugs in a distribution channel and show that the donor should only subsidize purchases. Yu et al. (2020) analyze the subsidy problem faced by donors who plan to subsidize products for sale to low-income families and show that donors achieve the same result when they allocate the subsidies by using different schemes, as long as the total subsidy per unit across manufacturers, retailers, or customers is at the optimal level.

The second part of this stream studies how supply chain members design transfer payment schemes to improve their profits. Cachon (2003) reviews the literature about supply chain coordination through transfer payment schemes such as revenue sharing contracts, sales-rebate contracts, and quantity discount contracts. Sieke et al. (2012) study how a manufacturer coordinates the supply chain through two types of service level-based supply contracts (flat penalty and unit penalty contracts) and obtain the structures of optimal contract parameters. Cho et al. (2016) study an internet service provider's problem of optimally managing content providers' customer subsidy policies and find that end customers' content fit cost can affect how service providers allow the subsidy policies. Ji et al. (2019) investigate the problem of joint marketing investment and in-app advertising adoption decisions. They show that a central planner should adopt a mixed transfer payment scheme to coordinate the system with or without competition.

Different from studies in the second stream, in our model the platform can use transfer payment either as a subsidy to encourage the manufacturer to invest in IoT or as a license fee to capitalize on its IoT infrastructure, depending on the sales commission rate.

3. Model of IoT Technology in e-Commerce Channel

We consider an e-commerce channel with an upstream manufacturer, a downstream platform, and a continuum of customers. Table 1 contains the notation used in this study.

3.1. The Manufacturer

The manufacturer produces a smart device which has an existing base quality q. To focus on the IoT technology's impact, we assume that the base product quality q is fixed. In addition, the manufacturer can invest in IoT technology based on the platform's IoT infrastructure and use the technology to collect customer usage information. Then, smart devices can use the collected information to adjust settings in order to suit the customers' needs and directly benefit the customers.

Table 1 Summary of Notation

Notation	Description
Parameters	
q	Base product quality
c	Marginal production cost of base product
θ	Customers' marginal valuation of base quality
α	Proportion of privacy-indifferent customers
k	IoT technology development cost
β	Utility of IoT functionality embedded in a smart device
γ	Marginal information value of cross-selling for the platform
η	Cost of embedding IoT functionality in a smart device
λ	Commission rate under an agency pricing model
Intermediate variables	
D_i	Privacy-indifferent customer's demand
D_s	Privacy-sensitive customer's demand
U	Customer's net benefit
π_p	Platform's profit
π_m	Manufacturer's profit
Decision variable	
p	Retail price for the product
w	Wholesale price for the product
a	Level of IoT functionality created by a manufacturer
s	Platform's transfer payment to a manufacturer
Superscripts	
WB	Benchmark case of wholesale pricing model without IoT technology
AB	Benchmark case of agency pricing model without IoT technology
WS	Case of wholesale pricing model with IoT technology investment
AS	Case of agency pricing model with IoT technology investment

Let a denote the additional functionality embedded in the device due to IoT technology. The IoT technology cost includes two parts: the fixed cost of technology development and the variable production cost of IoT functionality. Consider a smart refrigerator, for example. When the manufacturer invests in IoT technology, it needs to design the corresponding chips and software. For simplicity, we use a quadratic function ka^2 to model the development cost. This quadratic form captures the idea that it is more costly to add functionality to a more sophisticated device (i.e., a is higher) since the new functionality needs to be integrated with existing IoT functionality. After the chips and software have been developed, the manufacturer needs to embed them in each device. The higher the level of IoT functionality a, the higher the production cost. We use c to represent the cost of producing a device with base quality q, and a linear function ηa to represent the cost of incorporating IoT functionality into the device. In this study, we focus on the case where the manufacturer sells only a smart product, instead of both a smart product and a base product, with justifications provided in Appendix C.

3.2. Customers

All customers can enjoy the base product value when they purchase the smart device. For example, a customer can use a smart refrigerator just like a regular refrigerator: simply to store food. However, a smart refrigerator has additional features that can remind its owner to reorder food if the level of stock is low in the refrigerator or recommend new food more suitable for the owner. Similarly, smart treadmills can help owners exercise more effectively (Charles 2017). However, customers can gain such value due to IoT technology only if they use the IoT features embedded in the smart device and share the usage data.

To reflect reality, we let customers be heterogeneous in both their valuation of the smart device's base quality q and sensitivity to sharing usage information. Denote a customer's valuation of base quality as θ, which is uniformly distributed between 0 and 1. The parameter θ is private knowledge to each customer. Consistent with the platform pricing literature (Dey et al. 2019, Dou et al. 2017, Geng et al. 2018, Guan et al. 2020, Shulman and Geng 2019), we assume that there are just two types of customers according to their sensitivity to sharing usage information; this keeps the model tractable without affecting the key insights. The first type of customer is highly sensitive about sharing usage information and will not use the smart device's IoT functionality. As a result, such customers cannot enjoy the value brought by IoT functionality a. We call such customers *privacy-sensitive customers*. The second type of customer willingly shares usage information and will use the additional IoT functionality to gain additional value. Such customers are called *privacy-indifferent customers*. Denote the proportion of privacy-indifferent customers as α, so the proportion of privacy-sensitive customers is $1 - \alpha$.

We further assume that before customers use a smart device, their type is private information. Therefore, both types of customers pay the same price for the smart device. On the one hand, the utility of a privacy-indifferent customer who purchases a smart device at price p and uses IoT functionality a is given by:

$$U_i = \theta q + \beta a - p, \tag{1}$$

where β is the marginal utility of IoT technology embedded in a smart device. On the other hand, the utility of a privacy-sensitive customer who purchases a smart device at price p and does not use any IoT functionality is simply:

$$U_s = \theta q - p. \tag{2}$$

Compared with Equation (1), there is no βa in Equation (2), since all privacy-sensitive customers are not willing to share their usage information and therefore do not benefit from any IoT functionality.

Then, the utility of a privacy-indifferent customer who is indifferent between buying and not buying the product is given by $U_i = 0$. Therefore we can get this customer's marginal valuation $\theta = (p - \beta a)/q$. The demand for the product from the privacy-indifferent customers is given by

$$D_i = \left(1 - \frac{p - \beta a}{q}\right)\alpha. \tag{3}$$

Similarly, the demand from privacy-sensitive customers is the following:

$$D_s = \left(1 - \frac{p}{q}\right)(1 - \alpha), \tag{4}$$

and the total demand is

$$D_t = D_i + D_s = \frac{q + a\alpha\beta - p}{q}. \tag{5}$$

From Equation (3), we see the first effect of IoT technology: *demand expansion*. With IoT functionality, the device becomes more attractive to customers. The term $a\alpha\beta/q$ represents the magnitude of additional demand due to the IoT functionality.

3.3. The Platform

A platform such as Amazon or Alibaba provides IoT infrastructure as well as an e-commerce platform to sell products to customers. Accordingly, the platform

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has significantly more market power than the manufacturer so that the platform determines the form of the pricing model to be a wholesale or an agency one.

The platform can also implement a transfer payment mechanism to maximize its profit. Specifically, an amount s per device sold is transferred from the platform to the manufacturer. We do not restrict s to being positive. When s is positive, such transfer payment is considered as the platform providing a subsidy to the manufacturer (Amazon Inc. 2021b). The effect of a subsidy in this case is to encourage investment in IoT technology by the manufacturer. However, when s is negative, it can be interpreted as the platform charging the manufacturer a license fee per device for using the IoT infrastructure (Alibaba Inc. 2021, Amazon Inc. 2021a).

Since only privacy-indifferent customers who have purchased the device will share usage information, the platform can generate additional sales only from these customers by using the shared IoT information. Such a benefit to the platform should be proportional to both the number of privacy-indifferent customers and the level of IoT functionality in a device. We use a term $\gamma a D_i$ to represent this benefit, where γ is the marginal value of information. This is the second effect of IoT technology: *cross-selling*. This cross-selling effect only applies to customers who share their usage information through smart devices.

3.4. Pricing Models

In this study, we study two predominant pricing models (Geng et al. 2018, Tan and Carrillo 2017, Tian et al. 2018): wholesale and agency pricing models. We now describe a manufacturer's and a platform's profits under these two pricing models.

3.4.1. Profit Functions under Wholesale Pricing Model. Under a wholesale pricing model, a manufacturer determines the wholesale price w of selling its product to a platform (the manufacturer acts as a wholesaler). In turn, the platform sells the product to customers at the retail price p. Then the manufacturer's profit π_m and the platform's profit π_p are given by:

$$\pi_m = (w - \eta a - c + s)D_t - ka^2, \tag{6}$$

and

$$\pi_p = (p - w - s)D_t + \gamma a D_i, \tag{7}$$

where D_i and D_t are the privacy-indifferent and total customer demands that are defined in Equations (3) and (5). Then we have the channel profit

$$\pi_c = \pi_m + \pi_p = D_t(p - a\eta - c) + \gamma a D_i - ka^2. \tag{8}$$

3.4.2. Profit Functions under Agency Pricing Model. Under an agency pricing model, instead of the platform setting the retail price, the manufacturer sets the product retail price p. The manufacturer needs to pay a proportion λ of the revenue as a commission rate to the platform. E-Commerce platforms such as Amazon charge fixed commission rates, depending on product categories. For example, commission rate is 8% for the category of customer electronics sold at Amazon and 15% for home and garden (Amazon Inc. 2020c). Therefore, we consider λ as a parameter in this study, which is also consistent with previous literature (Abhishek et al. 2016, Geng et al. 2018, Tan and Carrillo 2017).

The manufacturer's profit π_m and the platform's profit π_p under an agency pricing model are given by:

$$\pi_m = ((1 - \lambda)p - \eta a - c + s)D_t - ka^2, \tag{9}$$

and

$$\pi_p = (\lambda p - s)D_t + \gamma a D_i. \tag{10}$$

The channel profit π_c is the same as Equation (8) under the wholesale pricing model.

3.5. Assumptions about Parameter Values

To gain insights without complicating the discussion, we focus on the interior solutions in this study and summarize the assumptions about parameter values below. A full list of constraints is defined in the online Appendix B, which includes a more detailed discussion in mathematical form.

1. The IoT technology development cost (k) is sufficiently large. If the IoT technology development cost (k) is too small, then the level of IoT functionality a will be too high, leading to a retail price so high that the demand of the privacy-sensitive customers becomes 0. Such an outcome is not reasonable since not all customers share information in reality. Therefore we assume that k is larger than a threshold so that the demand of privacy-sensitive customers is positive.
2. The marginal benefit of IoT technology is sufficiently large: $\alpha(\beta + \gamma) - \eta > 0$. When customers buy the product, the proportion of customers sharing information is α, so the total marginal benefit from IoT investment is $\alpha(\beta + \gamma)$, where β is the customers' benefit and γ is the platform's marginal cross-selling value. From the perspective of the manufacturer, it might invest in IoT under the condition $\alpha(\beta + \gamma) - \eta > 0$, instead of $\alpha\beta - \eta > 0$, because the platform would subsidize the manufacturer

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for the IoT investment due to the benefit of cross-selling.

3. The base product quality is sufficiently large. To ensure that the manufacturer produces the product when an agency pricing model is used, we assume $q(1-\lambda) > c$.

3.6. Time Sequence

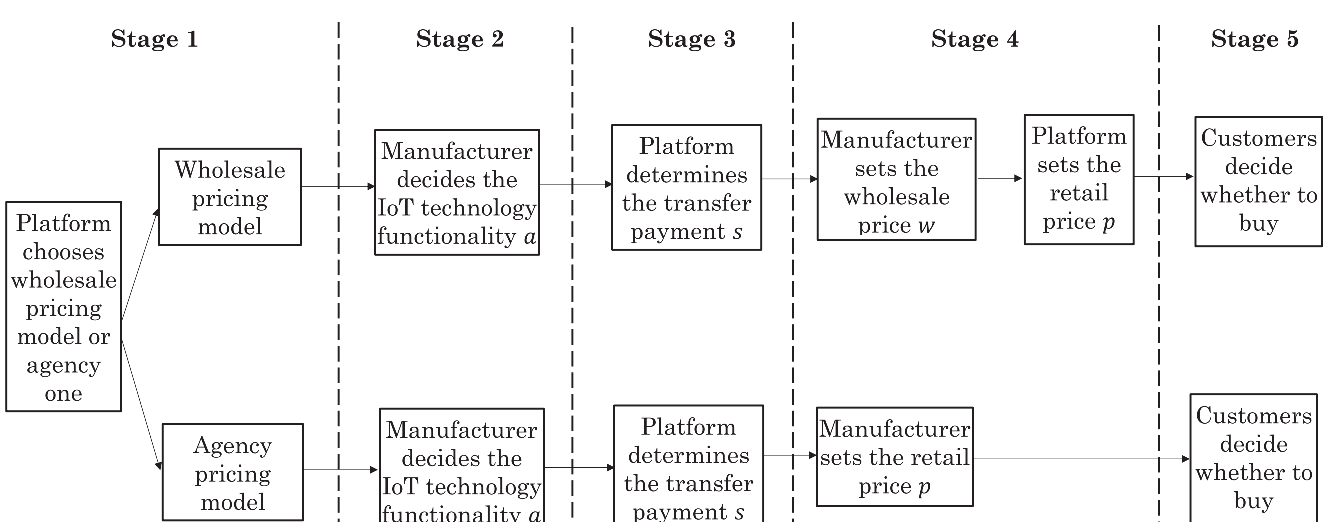
We study a five-stage game without information asymmetry between the platform and the manufacturer (see Figure 2 for the complete time sequence). In the first stage, the platform chooses a pricing model, which will be either a wholesale or an agency one. In the second stage, the manufacturer invests in building the level of IoT functionality a. In the third stage, the platform determines the transfer payment amount s, which could depend on the level of IoT functionality created by the manufacturer. In the fourth stage, if the platform has chosen the wholesale pricing model in Stage 1, the manufacturer first sets the wholesale price w, and then the platform sets the retail price p; if the platform has chosen the agency pricing model in Stage 1, the manufacturer decides the retail price p. In the fifth stage, customers decide whether to buy the product.

We set the time sequence as above for the following reasons. In our model, the manufacturer produces an IoT product that relies on the platform's IoT infrastructure. Therefore we can assume e-Commerce platforms such as Amazon have more market power and determine the type of the pricing model first in this game. If the manufacturer does not accept the pricing model, the platform can threat to introduce a similar product and the manufacturer could be worse off than if it accepts the pricing model. Also, if the platform makes transfer payment after the manufacturer has set price and sold the products, then the transfer payment will have no impact on customer demand. So we consider the case of the transfer payment decision (in reaction to the manufacturer's IoT investment) being made in Stage 3. Additionally, we assume that the platform's IoT decision has already been made before the game begins, since the platform's IoT infrastructure can be considered as a long-term strategic decision, and is not affected by a single manufacturer's IoT technology investment decision. However, the quality of the platform's IoT infrastructure does affect the manufacturer's IoT technology investment decision. When the quality increases, customers can benefit more from the same amount of manufacturer's IoT investment. Then the utility of IoT functionality embedded in a smart device (β) will increase. At the same time the platform can gain more cross-selling opportunities due to better data analysis capability, that is, γ increases. We will study how β and γ affect the manufacturer's IoT investment.

4. Nash Equilibria with and without IoT Technology

In section 4.1, we study the scenario without IoT technology. This serves as a benchmark for studying the impact of IoT technology on both the platform and the manufacturer. We then proceed to find the subgame perfect Nash equilibria in the presence of IoT technology. To do so, we first use backward induction to find the subgame equilibria for a given pricing model. After that, we characterize the platform's equilibrium choice of pricing model in Stage 1.

Figure 2 Time Sequence of the Game



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In the following analysis, we study both the wholesale and agency pricing models with and without IoT technology. We use superscripts to denote these four cases: *WB* refers to the benchmark case without IoT under a whole pricing model and *AB* the benchmark case under an agency one; *WS* the case with IoT under a wholesale pricing model and *AS* the case with IoT under an agency one.

4.1. Benchmark: The Case without IoT Technology

In this subsection, we investigate the subgame perfect Nash equilibrium when there is no IoT technology. In this case, the level of IoT functionality $a = 0$, and the transfer payment $s = 0$.

4.1.1. Subgame Equilibrium under Wholesale Pricing Model. This subgame can be solved as a special case of wholesale pricing model with IoT investment (section 4.2.2) when the cost of IoT technology k goes to infinity. We summarize the equilibrium results in Appendix D.1.

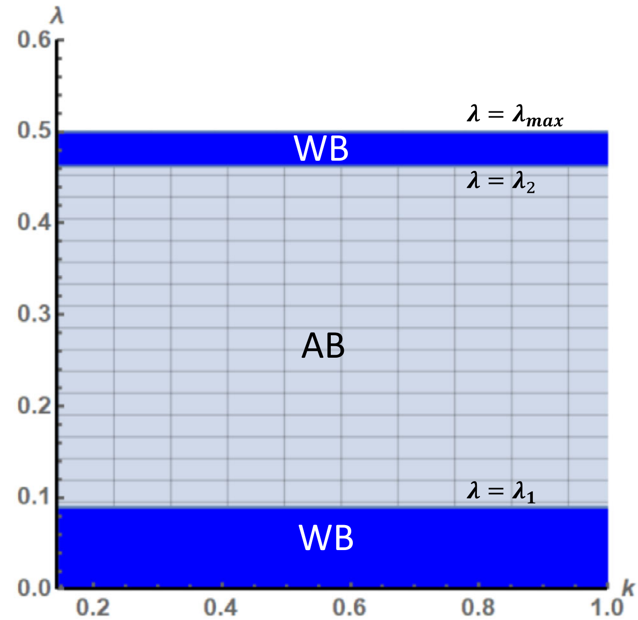
4.1.2. Subgame Equilibrium under Agency Pricing Model. This subgame ($a = 0, s = 0$) cannot be solved as a special case of agency pricing model with IoT investment (section 4.3) since the transfer payment s in the case of IoT technology investment will not become zero when IoT functionality a approaches zero. Plugging the total demand D_t in Equation (5) with $a = 0$ into the manufacturer's profit function (9), we can solve for the equilibrium retail price that maximizes this profit function. We summarize the equilibrium retail price, and the corresponding total demand and profits in Appendix D.2.

4.1.3. Platform's Pricing Model Choice in the Absence of IoT Technology. Now we can study the platform's Stage 1 pricing model choice by comparing its profits under a wholesale pricing model and an agency one. We summarize the findings in the following lemma as well as in Figure 3. To better contrast the results with and without IoT technology in a later part of the paper (section 5.2), we plot the regions of pricing model choice in two dimensions: λ and k.

LEMMA 1 (Equilibrium pricing model choice without IoT technology). *In the case without IoT technology,*

- *when the commission rate is small or large, that is,* $0 < \lambda < \lambda_1$ *or* $\lambda_2 < \lambda < \lambda_{max}$, *the equilibrium pricing model is a wholesale one;*
- *when the commission rate is medium, that is,* $\lambda_1 < \lambda < \lambda_2$, *the equilibrium pricing model is an agency one.*

Figure 3 Equilibrium Strategy without IoT Technology ($\alpha = \frac{1}{2}$, $\beta = \frac{1}{6}$, $\gamma = 1$, $\eta = \frac{1}{8}$, $q = 2$, $c = 1$) [Color figure can be viewed at wileyonlinelibrary.com]



The expressions of λ_{max}, λ_1, *and* λ_2 *are defined in online Appendices A, F.1, and F.1.*

We can explain the results in Lemma 1 in the following way. On the one hand, when the commission rate is small enough ($\lambda < \lambda_1$), the platform's profit will be low in adopting an agency pricing model relative to a wholesale one. Then it would like to choose a wholesale pricing model. On the other hand, the retail price increases with λ. When the commission rate is large enough ($\lambda > \lambda_2$) under an agency pricing model, the manufacturer needs to set a very high price in order to earn enough revenue to cover its production cost. In this case, the customer demand will be so low that the platform's profit will be lower than that under a wholesale pricing model. Thus, the platform will also choose a wholesale pricing model when the commission rate is high enough. When the commission rate is medium, the platform prefers the agency pricing model since the wholesale one suffers from the double-marginalization problem, while the agency one does not have this problem.

In the next subsection, we examine the main case when IoT technology is available. In this scenario, the manufacturer needs to make an investment decision in IoT functionality jointly with its pricing decision.

4.2. Wholesale Pricing Model When IoT Technology is Available

In this subsection, we investigate the subgame equilibria under a wholesale pricing model in the presence of IoT technology. We first investigate the case that the manufacturer does not invest in IoT technology, followed by the case that the manufacturer does invest. We compare the manufacturer's profits in these two cases to derive the manufacturer's optimal IoT technology investment strategy.

4.2.1. Wholesale Pricing Model without IoT Technology Investment. When the manufacturer does not invest in IoT technology, the results are the same as those without IoT technology in Lemma D.1, section 4.1.1.

4.2.2. Wholesale Pricing Model with IoT Technology Investment. In this case, we first show that the platform does not need a transfer payment to maximize its profit. To see that, suppose that the equilibrium wholesale price, retail price, and transfer payment are given by w_0, p_0, and s_0. Then, without any transfer payment (i.e., $s = 0$), the manufacturer can set a new wholesale price $w = w_0 + s_0$, so that the profits remain the same. Therefore, in the remainder of the paper, we let $s = 0$ for the wholesale pricing model. We state the result in Lemma 2:

LEMMA 2 (Payment transfer under wholesale pricing model with IoT technology). *Under a wholesale pricing model with IoT technology investment, the platform does not need to implement a transfer payment, that is,* $s = 0$.

We solve this sequential subgame by backward induction. We find the retail price p^{WS} from the platform's profit function (7), plug it into the manufacturer's profit function (6), and solve for the equilibrium a^{WS} and w^{WS}. We summarize the equilibrium level of IoT technology functionality, wholesale price, and retail price, and the corresponding demands and profits under a wholesale pricing model in Appendix D.3. We compare the retail and wholesale prices as well as the manufacturer's and the platform's profits in the *WS* case. The results are shown in the following lemma:

LEMMA 3. *In the WS case that the platform adopts a wholesale pricing model and the manufacturer invests in IoT technology,*

- *when the marginal value of cross-selling* γ *is large, the retail price is less than the wholesale price; otherwise, the retail price is greater than the wholesale price. That is, when* $\gamma > \gamma'$, $p^{WS} < w^{WS}$; *otherwise,* $p^{WS} > w^{WS}$.
- *when the marginal value of cross-selling* γ *is large, the manufacturer's profit is less than the platform's profit; otherwise, the manufacturer's profit is greater than the platform's profit. That is, when* $\gamma > \gamma''$, $\pi_m^{WS} < \pi_p^{WS}$; *otherwise,* $\pi_m^{WS} > \pi_p^{WS}$.

The expressions of γ' *and* γ'' *are defined in the online Appendix F.2.*

In the benchmark case *WB* (section 4.1.1), we can see that the retail price is larger than the wholesale price and the manufacturer's profit is higher than the platform's profit. However, from Lemma 3, we can see that the results do not hold when the manufacturer invests in IoT technology. Specifically, when comparing the wholesale price and the retail price, we find that the retail price can be less than the wholesale price. When the marginal value of cross-selling is large, the wholesale price is greater than the retail price. Such a result could be surprising at first sight. The reason is that with data from smart devices, the platform can benefit from exploiting the information value by cross-selling, so it has incentive to decrease the retail price in order to expand the total demand and benefit more from IoT information. When the marginal information value is sufficiently large, the gain from cross-selling becomes so important to the platform that the platform will set the retail price lower than the wholesale price. In other words, the platform subsidizes the customers indirectly in order to boost customer demand.

For the same reason, the platform's profit can be higher than the manufacturer's profit in the *WS* case, in contrast to the benchmark case. When the marginal information value of cross-selling for the platform is large enough, the platform's profit could be greater than the manufacturer's profit. The platform could benefit more from IoT technology than the manufacturer does, due to the role of information for cross-selling.

When either the customer's marginal benefit β or marginal cross-selling value γ increases, or the development cost k decreases, we can show that the manufacturer will increase the level of IoT functionality a. As a increases, the product becomes more attractive to customers, and cross-selling also becomes more valuable. In this sense, we say that the *IoT technology value* increases when β or γ increases, or k decreases. We can obtain the impact of IoT technology value on profits in the following lemma:

LEMMA 4 (Impact of IoT technology value on profits under wholesale pricing model). *Under a wholesale pricing model, with an increase in IoT technology value (i.e., an increase in either customer's marginal benefit* β *or marginal cross-selling value* γ*, or a decrease in IoT development cost* k*), the platform's profit* π_p*, the* *manufacturer's profit π_m, and the channel profit π_c all increase.*

From Lemma 4, it is intuitive to see that IoT technology value positively affects both the manufacturer's and the platform's profits, and as a result, the channel profit increases with IoT technology value.

4.2.3. Impacts of the Arrival of IoT Technology under Wholesale Pricing Model. We also study how the arrival of IoT technology affects the equilibrium outcomes by comparing the results between the *WB* and *WS* cases. We summarize the findings as a lemma:

LEMMA 5 (Comparison of equilibrium solutions in *WS* and *WB* cases). *In the WS case that the manufacturer invests in IoT technology under a wholesale pricing model,*

- *the total demand is greater than that in the WB case, that is, $D_t^{WS} > D_t^{WB}$.*
- *the wholesale price is greater than that in the WB case, that is, $w^{WS} > w^{WB}$.*
- *when the marginal cross-selling value γ is large relative to the customer's marginal benefit β, the retail price is less than that in the WB case; otherwise, the retail price is greater than that in the WB case, that is, when $\gamma > (3\alpha\beta + \eta)/\alpha$, $p^{WS} < p^{WB}$; otherwise, $p^{WS} > p^{WB}$.*
- *the profits are greater than those in the WB case, that is, $\pi_m^{WS} > \pi_m^{WB}$ and $\pi_p^{WS} > \pi_p^{WB}$.*

Lemma 5 shows additional interesting results which are different from Lemma 3. We can see that in the IoT technology investment case, the wholesale price is always higher than that in the non-IoT technology investment case regardless of the value of the cross-selling parameter γ. Therefore, the manufacturer gains *pricing power* through investing in IoT technology; it can increase price without hurting the demand for its product. In fact, the demand also increases as the product becomes more attractive due to IoT technology investment. However, the platform does have to balance the two effects of demand expansion and cross-selling when setting the retail price. When the gain from cross-selling is not sufficiently large, the platform should set a price higher than the benchmark case ($p^{WS} > p^{WB}$) to focus on the direct sales revenue. However, when cross-selling becomes more appealing, it will reduce the retail price to generate more demand, similar to the case in Lemma 3. In this case, the platform focuses more on the revenue from cross-selling than that from the direct sales. Thus, our results provide useful insights on how a manager should set the retail price, depending on the interaction between demand expansion and cross-selling.

In Lemma 5, we find that the platform can benefit from the manufacturer's IoT technology investment. The reason is that the platform can gain from IoT technology investment through two effects: demand expansion and cross-selling. Both effects can benefit the platform as well as the manufacturer when the wholesale pricing model is used. Lemma 5 also shows that the manufacturer's profit is higher when it invests in IoT technology. With IoT technology investment, the smart device will become more valuable for privacy-indifferent customers, and the manufacturer can charge a higher wholesale price. Accordingly, the manufacturer's profit will be higher. Otherwise, the manufacturer can at least earn the same profit as that without IoT technology. In other words, for a wholesale pricing model, the manufacturer is always better off by investing in IoT technology. Thus we obtain the manufacturer's decision on whether to invest in IoT technology under a wholesale pricing model in the following corollary:

COROLLARY 1 (Manufacturer's IoT technology investment decision under wholesale pricing model). *Under a wholesale pricing model, the manufacturer will always invest in IoT technology, that is, $a^{WS} > 0$.*

In a wholesale pricing model, the manufacturer captures the full marginal benefit (β) of IoT investment. Therefore, it will always invest in IoT technology, as Corollary 1 shows. Furthermore, Lemma 5 shows that the incentives of the platform and the manufacturer are aligned: both embrace the IoT technology under a wholesale pricing model. Will these two results still hold under an agency pricing model? This is one of the questions we are going to examine next.

4.3. Agency Pricing Model When IoT Technology is Available

In this subsection, we investigate the subgame equilibria under an agency pricing model when IoT technology is available. We compare the manufacturer's profits with and without IoT technology investment and identify its optimal IoT technology investment strategy.

4.3.1. Agency Pricing Model without IoT Technology Investment. When the manufacturer does not invest in IoT technology, the results are the same as those in the case of *AB* in section 4.1.2.

4.3.2. Agency Pricing Model with IoT Technology Investment. When the manufacturer invests in IoT technology, we can use backward induction to solve this subgame using the time sequence given in Figure 2. We summarize the equilibrium level of IoT technology functionality, transfer payment, and retail price, and the corresponding demands and profits under an agency pricing model with IoT technology investment in Appendix D.4. We can show that IoT technology value can increase the profits (Lemma 6), in addition to increasing the equilibrium level of IoT technology functionality.

LEMMA 6 (Impact of IoT technology value on profits under agency pricing model). *Using an agency pricing model, with an increase in IoT technology value (i.e., an increase in customer marginal benefit β, an increase in marginal cross-selling value γ, or a decrease in IoT development cost k), the platform's profit π_p^{AS}, manufacturer's profit π_m^{AS}, and channel profit π_c^{AS} all increase.*

The results in Lemma 6 are the same as the counterpart under a wholesale pricing model (see Lemma 4): an increase in IoT technology value can benefit both supply chain members. From Lemmas 4 and 6, we see that after the platform has chosen the pricing model, both the platform's and the manufacturer's profits increase as IoT technology becomes more valuable. Such intuitive results from subgames lead us to ask the following question: Will the results still hold when we examine the impact of IoT technology value in the full game? We delay addressing this important question until we have found the subgame perfect equilibrium.

Now we discuss the property of the transfer payment under the agency pricing model. The platform uses transfer payments, in the form of a subsidy or license fee, to increase its profit. On the one hand, the platform could use the transfer payment as a subsidy ($s > 0$) to the manufacturer to increase the customer demand and therefore, the amount of customer information for cross-selling. On the other hand, the platform could also use the transfer payment as a license fee ($s < 0$) to monetize its IoT infrastructure. The platform needs to balance cross-selling with monetization in order to maximize its overall profit. The following proposition identifies the conditions under which the form of transfer payment should be subsidy or license fee, if the manufacturer uses the IoT infrastructure:

PROPOSITION 1 (Platform's choice of transfer payment form). *In the case of AS, where the manufacturer invests in IoT technology under an agency pricing model,*

- *when the commission rate is small, the platform should use transfer payment in the form of a license fee, that is, when $0 < \lambda < \lambda'$, $s^{AS} < 0$;*
- *otherwise, the platform should use transfer payment as a subsidy, that is, $s^{AS} > 0$.*

The expression of λ' is defined in the online Appendix F.7.

The choice of transfer payment form by the platform in Proposition 1 results from the effect of the commission rate (λ). On the one hand, when λ is low, the manufacturer can keep most of the revenue. Then the manufacturer does not have to set a high retail price to recoup its production cost. Therefore, the demand will be relatively high to begin with, and the platform can compensate for a low share of sales revenue by charging the manufacturer for using its IoT infrastructure. On the other hand, when λ is high, the manufacturer needs a high retail price to cover its manufacturing cost, and the total demand will be low if the platform does not take any action. In that situation, if the platform lowers the manufacturer's effective marginal production cost by subsidizing the manufacturer, the total demand will expand since the retail price under subsidy decreases. The net result is that it is cost-effective for the platform to subsidize the manufacturer to increase IoT technology investment. As a result, the platform's profit will increase through a higher gain from cross-selling.

4.3.3. IoT Technology Investment Decision under Agency Pricing Model. For a given agency pricing model, we can determine the manufacturer's optimal investment decision by comparing its profits with and without IoT technology investment, that is, under the cases of *AS* and *AB*. The results appear in the following proposition:

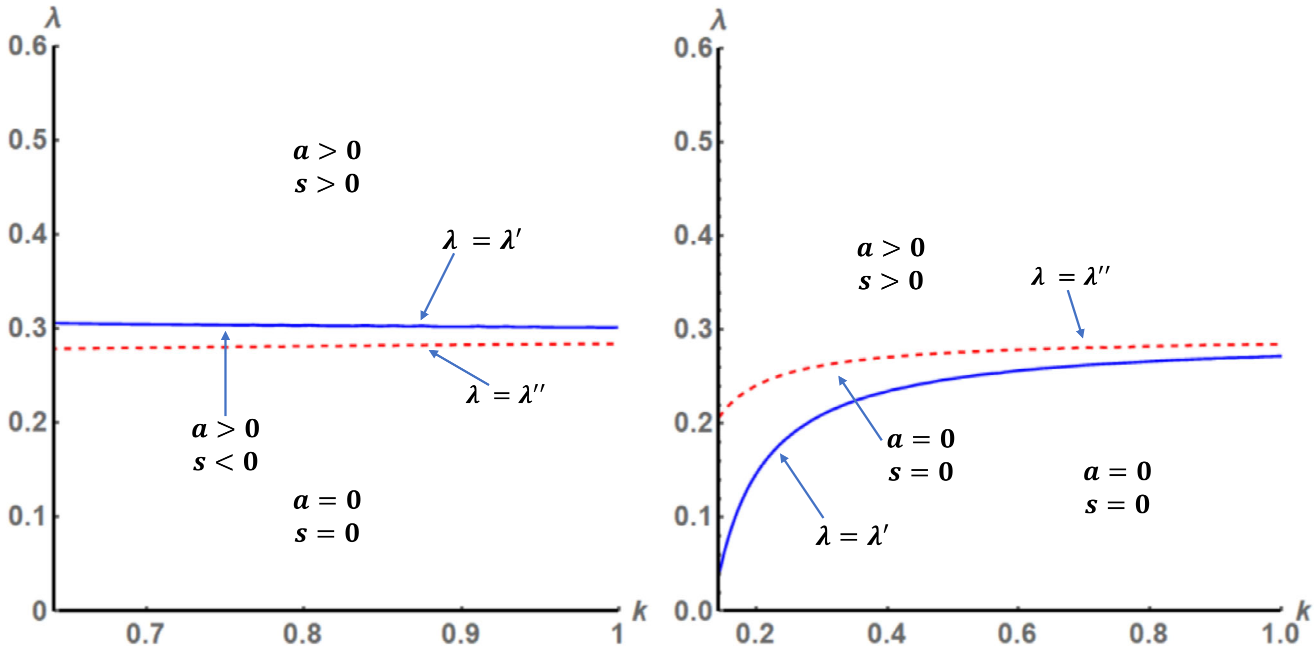
PROPOSITION 2 (Manufacturer's IoT technology investment decision under agency pricing model). *After the platform has chosen an agency pricing model,*

- *when the commission rate is small, the manufacturer chooses not to invest in IoT technology, that is, $a = 0$ when $\lambda < \lambda''$. We have the case of AB.*
- *otherwise, the manufacturer invests in IoT technology, that is, $a > 0$. We have the case of AS.*

The expression of λ'' is defined in the online Appendix F.8.

To explain the intuition behind the results in Proposition 2, we note that the manufacturer makes its IoT technology investment decision in anticipation of the platform's transfer payment decision in the subsequent stage. Thus, the platform's transfer payment will change the manufacturer's incentive to invest in IoT technology. Therefore, to understand the results

Figure 4 **Subgame Equilibrium Investment (*a*) and Transfer Payment (*s*) Decisions ($\alpha = \frac{1}{2}$, $\eta = \frac{1}{3}$, $q = 2$, $c = 1$). [Color figure can be viewed at wileyonlinelibrary.com]**



(a) Small γ/β ($\beta = 3.5$, $\gamma = 0.1$) **(b)** Large γ/β ($\beta = 0.5$, $\gamma = 3$)

in Proposition 2, it is natural to jointly examine the platform's transfer payment decision in Proposition 1 and the manufacturer's IoT technology investment decision in Proposition 2. Figure 4 displays the subgame equilibrium strategies under an agency pricing model, that is, the manufacturer's investment decision (a) in Stage 2 and the platform's transfer payment decision (s) in Stage 3.

For the reasons stated right after Proposition 1, on the one hand, when λ is small, the platform will charge a fee if the manufacturer uses the IoT infrastructure. The manufacturer is then less likely to invest in this parameter region, and we have $a = 0$ and $s = 0$. On the other hand, when λ is large, the platform will provide a subsidy for using the IoT infrastructure. As a result, the manufacturer tends to invest in this area, leading to $a > 0$ and $s > 0$.

Besides displaying the results from Propositions 1 and 2, Figure 4 also shows some interesting results due to the effect of cross-selling γ. From Figure 4a, we can see that in the region between the curves $\lambda = \lambda'$ and $\lambda = \lambda''$, the subgame equilibrium decisions are $a > 0$ (investment) and $s < 0$ (license fee). Here, since the cross-selling effect γ is small (relative to β), the platform does not benefit much by boosting demand. Therefore, it chooses to charge the manufacturer a fee for using the IoT infrastructure. However, in the counterpart region between the curves $\lambda = \lambda'$ and $\lambda = \lambda''$ of Figure 4b, a different picture emerges when γ is high (relative to β). Even though the platform would offer a subsidy due to a high cross-selling potential in this region if the manufacturer invests in IoT technology, the manufacturer chooses not to invest. The reason is that the manufacturer has to bear the IoT technology development cost but the benefit of IoT technology β is relatively small. To further see the implication of this, we can obtain the impact of IoT technology investment on the platform's profits from the cases of *AB* and *AS*, leading to the following lemma:

Lemma 7 (Profit comparison between *AS* and *AB* cases). *Under an agency pricing model, the platform's profit is higher when the manufacturer invests in IoT technology, that is,* $\pi_p^{AS} > \pi_p^{AB}$.

Therefore, different from the case of wholesale pricing, the platform and the manufacturer could have misaligned incentives. Specifically, in the region between the curves $\lambda = \lambda'$ and $\lambda = \lambda''$ of Figure 4b, the manufacturer does not invest in IoT while the platform would wish the manufacturer to do so. This is one region where an additional coordination mechanism would help to improve the overall channel profit and make both members better off, although a detailed study of the coordination mechanism is beyond the scope of this study.

4.4. Subgame Perfect Equilibria in the Presence of IoT Technology

In the previous subsections, we studied the subgame equilibria after the platform has chosen a wholesale or agency pricing model in the presence of IoT technology. By comparing the platform's profits under a wholesale pricing model (section 4.2) and under an agency one (section 4.3), we can obtain the platform's equilibrium pricing model choice together with the manufacturer's IoT technology investment decision under different conditions. We first prove the following lemma:

LEMMA 8 (IoT investment comparison between *AS* and *WS* cases). *For the IoT technology investment,*

- *the investment in WS strategy is larger than that in AS strategy, that is,* $a^{WS} > a^{AS}$.
- *the difference of the two investments decreases in the development cost k, that is,* $\frac{d(a^{WS} - a^{AS})}{dk} < 0$.

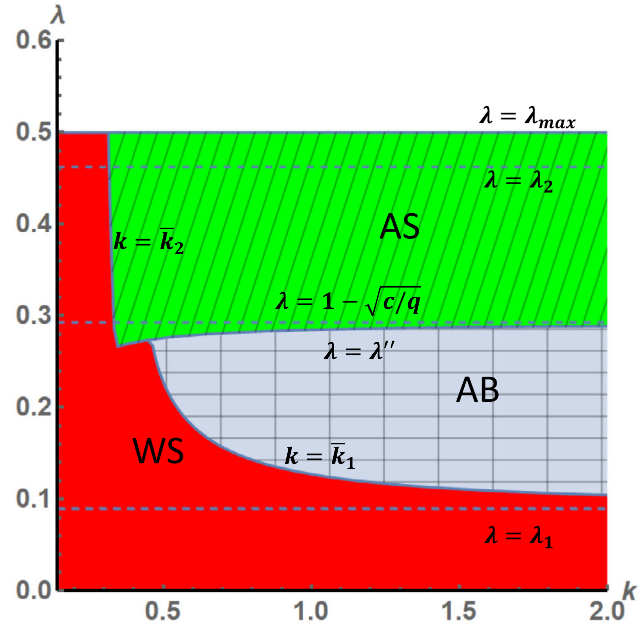
The intuition behind Lemma 8 is that the marginal benefit of IoT technology investment is reduced because of the sales commission. Specifically, under an agency pricing model, since the manufacturer invests in IoT technology when the sales commission is high, the IoT technology investment is lower than that under a wholesale pricing model. Moreover, the difference is magnified when the development cost reduces. We will use Lemma 8 to explain the intuition behind the following proposition. We also characterize the equilibrium strategies in Figure 5, to contrast with the scenario without IoT technology (shown in Figure 3).

PROPOSITION 3 (Equilibrium Strategies with IoT technology). *In the presence of IoT technology, the subgame perfect equilibrium strategies are the following:*

- *when the commission rate is large and the development cost is high, that is,* $\lambda'' < \lambda < \lambda_{max}$ *and* $k > \bar{k}_2$, *the subgame perfect equilibrium is the AS strategy.*
- *when the commission rate is medium and the development cost is high, that is,* $\lambda_1 < \lambda < \lambda''$ *and* $k > \bar{k}_1$, *the subgame perfect equilibrium is the AB strategy.*
- *otherwise, the subgame perfect equilibrium is the WS strategy.*

The expressions of λ_{max}, $\bar{k}_1$, *and* $\bar{k}_2$ *are defined in the online Appendices A, F.11, and F.11, respectively. Also,* $\bar{k}_1 > \bar{k}_2$ *and* $\lim_{k\to\infty} \lambda'' = 1 - \sqrt{c/q}$.

Figure 5 Equilibrium Strategy in the Presence of IoT Technology ($\alpha = \frac{1}{2}$, $\beta = 0.5$, $\gamma = 3$, $\eta = \frac{1}{3}$, $q = 2$, $c = 1$) [Color figure can be viewed at wileyonlinelibrary.com]



From Corollary 1, we see that the manufacturer always chooses to invest in IoT technology under a wholesale pricing model. Then the only subgame equilibrium strategies under a wholesale pricing model are represented by the case *WS*. When the commission rate is small ($\lambda < \lambda_1$), the platform can only get a low proportion of the manufacturer's revenue, so the platform chooses a wholesale pricing model, which is the same as the case without IoT technology (shown in Figure 3).

However, when the commission rate λ is large ($\lambda > \lambda''$), the platform chooses an agency pricing model for a large IoT development cost parameter k. Note that the platform can use transfer payment to change the manufacturer's effective marginal production cost under an agency pricing model, so the manufacturer invests in IoT technology even when the development cost is large. Then it is attractive for the platform to choose an agency pricing model to avoid the double-marginalization problem associated with a wholesale pricing model. Therefore, we have *AS* when both λ and k are large, contrasting with the strategies of either *WS* or *AB* in the case without IoT technology. Lemma 8 points out that when the development cost k decreases, the gap between IoT technology investments under an agency pricing model and a wholesale one becomes larger, causing the platform to benefit more from IoT technology investment under a wholesale pricing model. When k becomes sufficiently small ($k < \bar{k}_2$), the benefit of cross-selling dominates the loss due to double marginalization, and the platform chooses a wholesale pricing model, leading to the case *WS*.

In the intermediate range of λ ($\lambda_1 < \lambda < \lambda''$), when the development cost k is large, the investment in IoT will not be high. Then the platform chooses an agency pricing model to avoid the double-marginalization problem, even though the manufacturer does not invest in IoT technology. This leads to the *AB* case. When k is small ($k < \bar{k}_1$), the benefit of cross-selling is high. Then the platform offers a wholesale pricing model and in turn the manufacturer invests in IoT technology, so we have the *WS* case.

To examine the role of transfer payment, we have also studied the equilibrium results without transfer payment (see Appendix E). One key difference is that with transfer payment, *AB* dominates *AS* in some region and emerges as a new equilibrium strategy. In such region, the manufacturer has no incentive to invest in IoT technology.

5. Impacts of IoT Technology

In this section, we first study the impacts of the IoT technology improvement and the arrival of IoT technology on the supply chain. Then we study how to improve social welfare, consumer surplus, or channel profit through channel coordination between the platform and the manufacturer.

5.1. Impacts of IoT Technology Improvement on Supply Chain Performance

In this subsection, we study the question whether the improvement of IoT technology will always benefit the supply chain. Specifically, we study whether an increase in IoT value (i.e., a decrease in k, or an increase in either β or γ) will always increase the platform's and the manufacturer's profits as well as the channel profit. The following proposition shows how the profits change when the value of IoT technology increases:

Proposition 4 (Profit discontinuities with an increase in IoT value). *Consider the case of a change in subgame perfect equilibrium due to an increase in IoT value.*

- *The platform's profit π_p increases (with a discontinuity) if the subgame perfect equilibrium moves from AB to AS or from WS to AS.*
- *The manufacturer's profit π_m increases (with a discontinuity) if the subgame perfect equilibrium moves from AB to WS for a small development cost (i.e., $k < \bar{k}_3$) or from AS to WS, and decreases (with a discontinuity) if the equilibrium moves from WS to AS or from AB to WS for a large development cost (i.e., $k > \bar{k}_3$).*
- *The channel profit π_c increases (with a discontinuity) if the subgame perfect equilibrium moves from AB to WS for a small development cost (i.e., $k < \bar{k}_3$), from WS to AS for a large development cost (i.e., $k > \bar{k}_4$), or from AS to WS, and decreases (with a discontinuity) if the equilibrium moves from WS to AS for a small development cost (i.e., $k < \bar{k}_4$) or from AB to WS for a large development cost (i.e., $k > \bar{k}_3$).*

The expressions of $\bar{k}_3$ and $\bar{k}_4$ are defined in the online Appendix F.11 and F.12 respectively.

We can use Figure 5 to explain Proposition 4. The platform's profit will increase with a finite jump when k decreases and crosses the line $\lambda = \lambda''$. In this case, the equilibrium strategy moves from *AB* to *AS* through the line segment to the right of $k = \bar{k}_1$ or from *WS* to *AS* through the segment to the left of $k = \bar{k}_1$. An explanation is as follows. In the first scenario, when the development cost k decreases and the strategy moves from *AB* to *AS*, the platform's profit increases since the manufacturer starts to invest in the IoT technology, directly benefiting the platform. In the second scenario, when k decreases and crosses the line $\lambda = \lambda''$ to the left of $k = \bar{k}_1$, the IoT technology investment becomes cost-effective for the manufacturer, the platform switches to an agency pricing model to avoid double marginalization; the strategy will move from *WS* to *AS*. In this scenario, the platform is also better off. Overall, with such changes in these parameter values (k, β, and γ), the platform can either keep the same pricing model or switch to a different pricing model. As a result, the platform's profit increases with the value of IoT technology.

The effect of strategy change on the manufacturer's profit is more intricate. We find surprising results when the equilibrium outcome moves from *WS* to *AS* or from *AB* to *WS* as the IoT technology value increases. We can use Figure 5 as an example to understand the results. In the first scenario, where the development cost k decreases and crosses the curve $\lambda = \lambda''$ from the right side, the platform switches to an agency pricing model to avoid double marginalization, knowing that k is low enough for the manufacturer to invest in IoT technology under an agency pricing model. In the end, the platform's profit improves, and the manufacturer's profit worsens when the equilibrium outcome moves from *WS* to *AS*. In the second scenario, for the area below the curve

$\lambda = \lambda''$, as the development cost k decreases and just crosses the curve $k = \bar{k}_1$ from the right side, the development is not low enough for the manufacturer to invest in IoT technology if the pricing model remains as an agency pricing model, that is, $\pi_m^{AS} < \pi_m^{AB}$. However, the development cost is low enough for the platform to benefit from IoT technology. Therefore, the platform switches to a wholesale pricing model. Then, without the option of *AB*, the manufacturer can only choose option *WS* over *WB*, according to Corollary 1. The manufacturer is better off with the new option *WS* than with *AB* if the IoT development cost is sufficiently low ($k < \bar{k}_3$). However, if the development cost is high ($k > \bar{k}_3$), such switching is costly to the manufacturer since it does not benefit much from the IoT technology investment. Then it is worse off when being forced to invest, as the value of IoT technology increases.

An interesting question arises from the above discussion: How will the channel profit change when the strategies move from *WS* to *AS* or from *AB* to *WS*? In the first case, where the strategy moves from *WS* to *AS* when crossing the curve $\lambda = \lambda''$, there is a finite increase in the platform's profit, and a finite decrease in the manufacturer's profit. Such a decrease is larger than the increase when the development cost k is small ($k < \bar{k}_4$), leading to a decrease in the channel profit. In the second case, where the strategies move from *AB* to *WS*, the curve $k = \bar{k}_1$ is the platform's profit indifference line. In other words, the platform's profit remains the same when we just move to the other side of the curve. Therefore, the channel profit will increase in the upper part of the curve $k = \bar{k}_1$ (i.e., $k < \bar{k}_3$) and decrease in the bottom part of the curve, where $k > \bar{k}_3$.

5.2. Impacts of the Arrival of IoT Technology on Profits and Welfares

In this subsection, we study how the arrival of IoT technology affects the manufacturer's and the platform's profits as well as the consumer surplus and the social welfare based on the results from the previous sections. Negative impact of IoT technology could lead to important implication of IoT technology management. We summarize the findings in the following proposition. To make the proposition easier to understand, we separate the results according to the initial equilibrium strategies *WB* and *AB* in the absence of IoT technology.

Proposition 5 (Effects of adopting IoT technology on supply chain profits and welfares). *With the arrival of IoT technology, when the manufacturer adopts it,*

1. *in the region where the initial equilibrium strategy without IoT is WB,*
   - *the manufacturer's profit decreases if the equilibrium strategy becomes AS; otherwise, the manufacturer's profit increases.*
   - *the platform's profit, channel profit, consumer surplus, and the social welfare always increases.*
2. *in the region where the initial equilibrium strategy without IoT is AB,*
   - *the platform's profit always increases.*
   - *the manufacturer's profit decreases if the equilibrium strategy becomes WS in the area of large development cost ($k > \bar{k}_3$); otherwise, the manufacturer's profit increases.*
   - *the channel profit decreases if the equilibrium strategy becomes WS in the area of large development cost ($k > \bar{k}_8$); otherwise, the channel profit increases.*
   - *the consumer surplus and the social welfare decreases if the equilibrium strategy changes to WS in the area of large development cost ($k > \bar{k}_5$) and to AS in the area of $\lambda < 1 - \sqrt{\frac{c}{q}}$ and large development cost ($k > \bar{k}_7$).*

The expressions of $\bar{k}_3$, $\bar{k}_5$, $\bar{k}_7$, and $\bar{k}_8$ are defined in the online Appendix F.11, F.13, F.13, and F.13 respectively.

From Proposition 5, we see that when the pricing model changes due to the arrival of IoT technology, the platform's profit will always increase; otherwise, the platform will not change the pricing model. However, the impact of IoT technology on the manufacturer could be surprising: contrary to what one might intuitively expect, the manufacturer could be worse off when adopting IoT technology even with a subsidy from the platform. When the equilibrium strategy moves from *WB* to *AS*, or from *AB* to *WS* in the area of large development cost ($k > \bar{k}_3$), the manufacturer's profit decreases (also shown in Figure 6a). The intuition is as follows. When IoT technology becomes available, the platform can change the pricing model to exploit the IoT technology. Then for the changed pricing model, the manufacturer is better off in investing in IoT technology than not. However, the manufacturer could still be worse off than the case of no IoT technology investment under the previous pricing model. In other words, the manufacturer's investment in IoT technology only reduces the degree of profit loss.

With the arrival of IoT technology, not only could the manufacturer's profit decrease, but the channel profit could also decrease in the area of large

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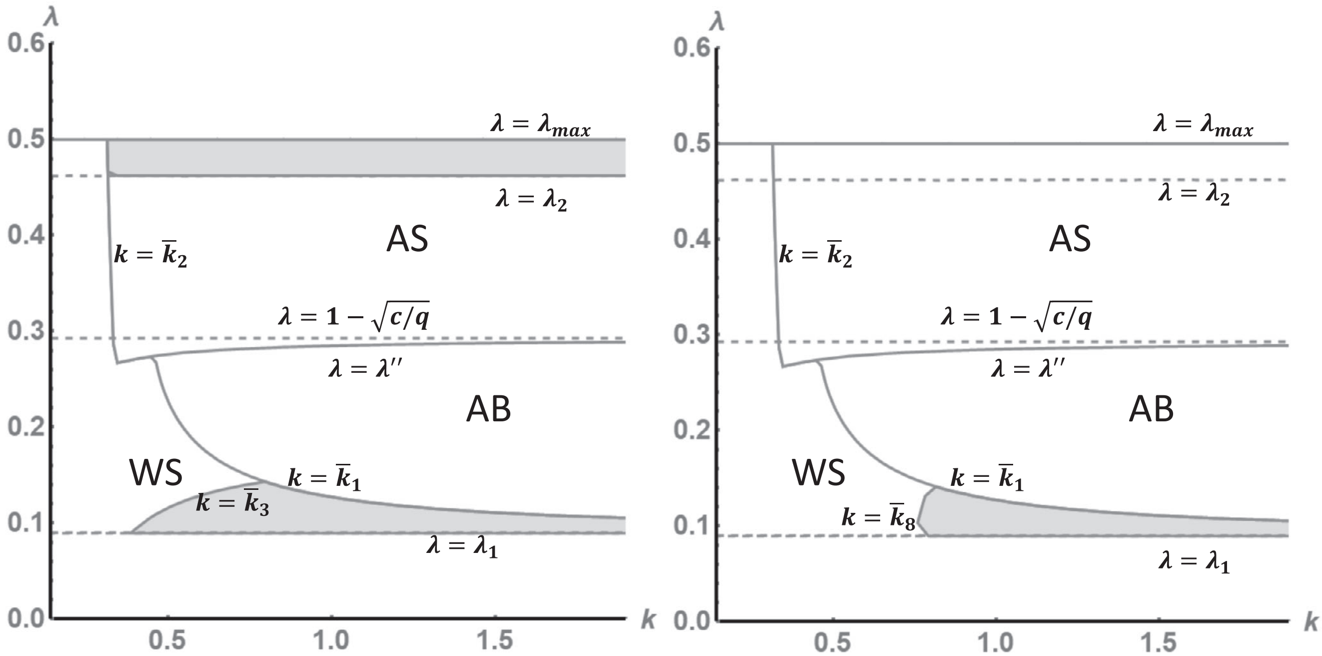
Figure 6 Negative Impacts of IoT Technology Arrival on the Manufacturer and the Channel



(a) Manufacturer's profit deceases in the shaded regions **(b)** Channel profit decreases in the shaded regions

development cost ($k > \bar{k}_8$) if the equilibrium strategy moves from *AB* to *WS* (also shown in Figure 6b). Here, the increase in the platform's profit is less than the decrease in the manufacturer's profit. To improve the channel profit, the platform should refrain from inducing the manufacturer to invest in IoT technology by changing the original pricing model. The platform could wait until IoT technology becomes more mature and the development cost further decreases. Another possibility is that the platform could work with the manufacturer to reduce the development cost. From Proposition 5, we can see that similar results hold for consumer surplus and social welfare when the equilibrium strategy moves from *AB* to *AS* or *AB* to *WS*.

From Propositions 4 and 5, the manufacturer could be worse off with an improvement in or the arrival of IoT technology. We can understand the results using demand-expansion or cross-selling effect as an example. On the one hand, a higher demand-expansion effect β or cross-selling effect γ can benefit a manufacturer for a given pricing model. On the other hand, a change of pricing model due to a higher β or γ, can generate negative impact on the manufacturer's profit. Then the net impact of an increase in β or γ on the manufacturer's profit could be negative if the positive demand-expansion or cross-selling effect is smaller than the negative effect of pricing model change.

5.3. Channel Coordination and Social Welfare Analysis

In the previous section, we have seen that social welfare, consumer surplus, and channel profit could decrease with the arrival of IoT technology. In this section, we want to explore whether channel coordination between a platform and a manufacturer can improve social welfare, consumer surplus or channel profit. We compare the first-best (*FB*), Nash bargaining (*NB*), *AS* and *WS* cases.

In the first-best case, a social planner maximizes the overall social welfare while in the Nash bargaining case (Nash 1953), a platform and a manufacturer share the channel profit according to their bargaining powers. Let Λ be the bargaining power of the manufacturer and that of the platform $1 - \Lambda$. Then in the Nash bargaining case, we have

$$\pi_m^{NB} = \Lambda \pi_c^{NB}, \tag{11}$$

and

$$\pi_p^{NB} = (1 - \Lambda)\pi_c^{NB}. \tag{12}$$

A platform can use a revenue sharing scheme under a wholesale pricing model to achieve the Nash bargaining outcome. Specifically, the manufacturer charges w as wholesale price; at the same time, the platform shares proportion ϕ_1 of its revenue with the manufacturer and proportion ϕ_2 of the manufacturer's IoT investment cost (ka^2). Then the Nash bargaining problem becomes

$$\max_{w, a, p, \phi_1, \phi_2} \pi_c^{NB}. \tag{13}$$

We can obtain the values of variables that achieve the Nash bargaining outcome:

LEMMA 9. *The Nash bargaining solution is achieved when* $w^{NB} = a\eta + c$, $\phi_1^{NB} = \Lambda$, *and* $\phi_2^{NB} = 1 - \Lambda$.

In other words, the manufacturer should get the share of sales revenue proportional to its bargaining power and similarly the platform shares the IoT investment cost proportional to the platform's bargaining power. In addition, the manufacturer should charge the wholesale price at the marginal production cost $a\eta + c$. Then the supply chain profit will be maximized.

Next we compare the social welfare, consumer surplus and channel profit among the *FB*, *NB*, *AS* and *WS* cases and have the following proposition.

PROPOSITION 6. *Social welfare, channel profit, and consumer surplus among the FB, NB, AS and WS cases can be ranked as follows.*

- $SW^{FB} > SW^{NB}$, $SW^{NB} > SW^{WS}$, *and* $SW^{NB} > SW^{AS}$.
- $\pi_c^{NB} > \pi_c^{AS} > \pi_c^{FB}$ *and* $\pi_c^{NB} > \pi_c^{WS} > \pi_c^{FB}$.
- $CS^{FB} > CS^{NB}$, $CS^{NB} > CS^{WS}$, *and* $CS^{NB} > CS^{AS}$.

The proposition shows that in the first-best (*FB*) case, a social planner maximizes the social welfare by increasing consumer surplus which becomes the largest among these four cases. However the channel profit reduces and becomes the smallest. As a result, the channel's incentive for IoT technology investment could be reduced and the society could suffer from less innovation in the long run. Interestingly, channel coordination through Nash bargaining can not only increase the channel profit but also improve both consumer surplus and social welfare over the decentralized cases (*AS* and *WS*). From the policymaker's perspective, channel coordination through Nash bargaining between the platform and the manufacturer should be encouraged since consumers will benefit as a whole and so does the social welfare.

6. Conclusion

This study is the first work that studies the problem of IoT technology investment, where a platform can use transfer payment to either encourage IoT technology investment or capitalize on its IoT infrastructure. In this work, we analyze the strategic interaction between the platform's choice of pricing model and the manufacturer's IoT technology investment, showing how this interaction affects both members' profits and the overall chain profit.

Under a wholesale pricing model, we find an interesting result that the retail price can be lower than the wholesale price when the marginal value of cross-selling is high. In this case, the platform subsidizes customers indirectly to attract demand since the gain from cross-selling outweighs the subsidy.

We also find that the platform does not have to implement any transfer payment under a wholesale pricing model; while under an agency one, the platform's strategic use of transfer payment, as a subsidy or license fee, depends on the sales commission. When the potential benefit from a sales commission is high, the platform should further stimulate the demand through a subsidy. Otherwise, if revenue from sales commission is low, the platform should use the license fee as another source of revenue.

In contrast to the results under a wholesale pricing model, under an agency one, the platform and the manufacturer could have misaligned incentives in the region where the commission rate is intermediate: the manufacturer does not want to invest in IoT technology while the platform wishes the manufacturer to do so. The platform could offer additional rewards based on the IoT functionality or adjust the commission rate so that the manufacturer would invest in IoT technology, and the channel performance could improve. In the end, both members could be in a win–win situation through profit sharing. Also compared with an agency pricing model, under a wholesale one, the manufacturer has a higher incentive in investing in IoT technology and consequently will have a better chance of improving IoT technology through "learning by doing." Therefore the platform could use a wholesale pricing model which might mean a temporary reduction in profit, but benefit more from better IoT technology in the long run. Policymakers should also encourage the platform to do so since developing IoT technology has increasingly become a national strategy in many countries (European Commission 2021).

A cautionary note is in order in the face of growing enthusiasm about IoT technology. Our research shows that when the value of IoT technology increases due to a lower development cost, a higher customer valuation of IoT functionality, or a more effective use of IoT data in cross-selling, the manufacturer's profit can decrease in certain scenarios. One scenario is that the platform switches to an agency pricing model from a wholesale one when the value of IoT technology increases. The manufacturer still invests in IoT technology, but it earns less profit than it would under a wholesale pricing

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model. In the second scenario, an increase in IoT value causes the platform to switch from an agency pricing model to a wholesale one. Then the manufacturer switches to investing in IoT technology in the new (wholesale) pricing model while it would not invest under an agency one. When the development cost is high, such a switch is costly for the manufacturer and makes it worse off. In both scenarios, the channel profit could also decrease, depending on the development cost.

Furthermore, when the manufacturer has the option of IoT technology investment due to the arrival of IoT technology, it can become worse off, contrary to what one might expect. This happens because the platform strategically changes the pricing model type in certain parameter regions, knowing that the manufacturer's subsequent equilibrium strategy is to invest. As a result, the platform is always better off while the manufacturer and the channel performance could suffer. Policymakers who want to maximize the overall supply chain profits should offer incentives for platforms to stay with pricing models that are beneficial for the overall supply chain or provide regulations to empower upstream device manufacturers in the choice of pricing model. Additionally, channel coordination between the platform and the manufacturer should be encouraged since both consumers and the social welfare will also benefit.

We now discuss avenues for future work. First, it will be interesting to consider a case in which a manufacturer co-develops IoT infrastructure with the platform and opens it to other competing manufacturers. In this case, one can study the equilibrium form of transfer payment and its impact on channel performance. Second, future research can explore the problem of a two-sided platform, one where system developers can build software components and manufacturers develop smart devices using the software components. The question of how the platform should price its service in the presence of IoT technology has not been studied in the existing research. In addition, a manufacturer could have private information about the demand of smart devices. An interesting direction for future research would be to study how such information asymmetry affects the platform's choice of pricing model and whether it is in the manufacturer's interest to share such information.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix A: Expressions for Simplifying Derivations.
Appendix B: Constraints.
Appendix C: Reasons for Focusing on the Case of One Smart Product Only.
Appendix D: Equilibrium Results in *WB*, *AB*, *WS* and *AS* Cases.
Appendix E: Equilibrium Outcome without Transfer Payment.
Appendix F: Proofs of Lemmas and Propositions.

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