

When Should Suppliers Adopt Augmented Reality Technology in a Dual-Channel Supply Chain?

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Abstract

In practical business, an increasing number of suppliers are adopting augmented reality (AR) technology in their online channels to provide consumers with virtual try-on experiences. While the adoption of AR technology is anticipated to enhance product matching levels in online channels, it may also intensify channel competition and raise costs for consumers' privacy concerns. Hence, the wisdom of suppliers embracing augmented reality technology in a dual-channel supply chain remains uncertain. To address this challenge, we have developed a stylized model to explore whether a supplier should embrace AR technology in a dual-channel supply chain, taking into account consumer returns and the cost of consumer privacy concerns. The main findings are as follows: First, the supplier is motivated to adopt AR technology if the improvement rate of product matching is high or if both the improvement rate of product matching and consumer's privacy concerns cost is low. Then, the implementation of AR technology does not invariably harm the retailer. When the improvement rate of product matching is low and the privacy concerns cost is high, AR technology can enhance both the marginal profit and demand in the offline channel, ultimately benefiting the retailer. Thus, there are specific circumstances under which the adoption of AR technology can create a mutually beneficial situation for both the supplier and the retailer.

Keywords

Supply Chain Management, AR Technology, Consumer Returns, Consumer's Privacy Concerns Cost, Dual-Channel Supply Chain

1. Introduction

In recent years, e-commerce has become intrinsic to the global retail landscape.

With a global internet user base exceeding five billion and a notable surge in online shopping activities, it is anticipated that global retail e-commerce sales will exceed 6.3 trillion U.S. dollars by 2024 (Statista, 2024). In the context of the rapid development of e-commerce, an increasing number of suppliers are establishing online channels to directly sell products to customers. Approximately 42% of top suppliers, including Nike, Zara, and Estee Lauder, are selling products to customers through an online channel in addition to their traditional retail channels (Soleimani et al., 2016; Zhang et al., 2021). Although online shopping provides customers with the convenience of time and space, allowing them to easily browse and purchase goods anytime and anywhere, at the same time, the return rate for online channels is also very high (Xu et al., 2023; Xu et al., 2024). This is because online channels can only display digital attributes (i.e., specifications, size, and performance) of products through web pages. This limitation makes it difficult for customers to fully evaluate the actual appearance and feel of goods, resulting in the item not being expected and then returned (Mehra et al., 2018; Zhang et al., 2023). Data from the National Retail Federation (NRF) and Appriss Retail shows that in 2023, online purchases had a return rate of 17.3%, higher than the 10% rate for in-store purchase (NRF, 2023). Moreover, return amounts are approximately \$743 billion, accounting for 14.5% of the total \$5.13 trillion in retail sales (NRF, 2024).

Consumer returns place a significant financial burden on retailers, resulting in lost profit and additional inspection and processing costs (Kwon et al., 2022; Ladd, 2018; Roy, 2013; Wu et al., 2019). According to the report by the NRF and Appriss Retail, the average retailer incurs \$145 million in merchandise returns for every \$1 billion in sales (NRF, 2023). The recent emergence of AR technology allows customers to virtually try out products in real time, either on their own faces or in their surroundings (Smink et al., 2019). It is estimated that this technology helps convert 12.4% of fitting consumers into purchasers and reduces the return rate of some brands by about 30% (Yang et al., 2022; You, 2017). Therefore, some firms are actively adopting AR technology on their websites to reduce pre-purchase consumer uncertainty about products and mitigate mismatches arising from individual preferences. For example, L'Oréal collaborates with the AR technology company Image Metrics to launch Makeup Genius. This app allows users to virtually test various makeup and beauty products, enabling them to better assess how these products suit their skin or appearance (Hilken et al., 2017). Similarly, Gucci has launched Snapchat AR filters, which allow users to virtually try on footwear products to enhance their understanding of the products' appearance and compatibility (Wang et al., 2024).

Despite the potential of AR technology to enhance the possibility of product matching and reduce the return rate in online channels, we have observed that some suppliers, such as Armani and Prada, have not yet integrated AR technology into their official websites or apps (Wang et al., 2021). There may be two reasons for this: first, the adoption of AR technology can reduce the uncertainty of

purchasing in online channels, which could intensify competition between the online and offline channels, leading to price wars, thereby potentially damaging the profits of suppliers themselves. What is more, AR adoption requires customers to activate cameras and provide personal data (i.e., height, weight, and dressing preferences), potentially giving rise to consumer' concerns regarding privacy breaches (Ameen et al., 2022; Dacko, 2017; Smink et al., 2019). Customers may experience discomfort upon realizing that these companies actively track their activities (Gal-Or et al., 2018; Zhu et al., 2017). For example, Snapchat's augmented reality filters use facial recognition technology to accurately apply filters to users' faces. Despite Snapchat's claims that it does not store users' facial data, privacy advocates worry about potential misuse of this technology, particularly if the data is hacked or used without users' consent (Smith, 2024). Therefore, customers may experience disutility when suppliers adopt AR technology in online channels.

Existing literature primarily characterizes the competition between online and offline channels in terms of price (Cai et al., 2009; Huang et al., 2013; Huang & Swaminathan, 2009; Soleimani et al., 2016), product quality (Chen et al., 2017; David & Adida, 2015; Zhang et al., 2021), and value-added service (Chen et al., 2008; Guo et al., 2020; Hua et al., 2010; Li et al., 2019b; Modak & Kelle, 2019), our research brings a new perspective to the competition between online and offline channels by emphasizing product matching, an aspect not previously explored in prior studies. Moreover, previous research examines whether suppliers should introduce virtual showrooms from the perspective of inconvenience costs associated with online and offline channels (Xu et al., 2023; Yang et al., 2022; Zhang et al., 2023). However, there is currently little research considering the combined impact of consumer returns and the cost of customers' privacy concerns on whether suppliers adopt AR technology. Therefore, this study aims to fill this gap by analyzing suppliers' adoption strategy of AR technology within dual-channel supply chains, particularly in light of factors such as consumer returns and customers' privacy concerns cost. Inspired by real-world practices and research gap, the following research questions emerge:

- 1) How does the supplier's AR adoption affect its decisions and when the supplier has an incentive to adopt AR technology in the dual-channel supply chain?
- 2) Is the supplier's AR adoption always detrimental to the retailer's profit? If not, under what conditions can the retailer benefit from the adoption of AR?
- 3) Under what conditions does the supplier's AR adoption lead to a win-win situation for both the supplier and retailer?

To address these questions, we consider a dual-channel supply chain consisting of a supplier and a physical retailer, where the supplier sells products through both the physical retailer and its own online channel. To alleviate the uncertainty faced by customers in the online channel who are unable to physically interact with products, the supplier can adopt AR technology to offer virtual try-on or fitting services. However, this initiative raises customers' concerns regarding privacy breaches. We develop two theoretical models for cases without and with the

adoption of AR technology. By comparing the equilibrium results and profits of these two models, we derive several interesting findings.

Firstly, we find that the adoption of AR leads the supplier to set a lower retail price, which seems counterintuitive. The underlying reasons are intense inter-channel competition and the negative impact of consumer's privacy concerns cost. Previous literature suggests that AR technology increases online prices but does not consider the cost of privacy concerns for consumers (Qiu et al., 2024). Additionally, an offline retail price may rise or fall, depending on the balance between the improvement rate in matching and the cost of the consumer's privacy concerns. The improvement rate in product matching in the online channel tends to lower the offline retail price, while the cost of consumer privacy concerns tends to rise.

Secondly, we find that AR adoption consistently increases the supplier's wholesale profit in the offline channel, while the direct profit in the online channel may either increase or decrease. Further analysis reveals the conditions under which the supplier has the motivation to adopt AR technology in a dual-channel supply chain: 1) when AR technology significantly enhances the likelihood of product matching in the online channel; 2) when the ability of AR technology to enhance the likelihood of product matching in the online channel is limited, but consumers have minimal privacy concerns when shopping online. On the contrary, when the effectiveness of AR technology in enhancing product matching in the online channel is limited, coupled with significant privacy concerns among consumers regarding online purchases, the decrease in direct profit surpasses the increase in wholesale profit. As a result, the supplier has no motivation to adopt AR technology.

Thirdly, we discovered that the supplier's adoption of AR could increase the retailer's profit. To be more specific, when the effectiveness of AR technology in improving product matching is limited and consumers experience significant privacy concerns during online shopping, the marginal profit and demand quantity of the offline channel increase, thus benefiting the retailer. Finally, we find that when the effectiveness of AR technology in improving product matching is limited and consumers' privacy concerns cost is in the moderate range, AR adoption results in a win-win situation for both the supplier and the physical retailer. This indicates that when AR technology can moderately improve product matching without causing excessive consumer's privacy concerns, all parties in the supply chain can benefit from its adoption.

The contributions and innovations of this paper are as follows:

1) We introduce a novel perspective to analyze competition between online and offline dual channels, focusing on the differences in product matching due to channel characteristics. This approach broadens the scope of existing research on dual-channel supply chain competition. 2) Our study offers valuable insights for suppliers to determine the conditions for adopting AR technology within a dual-channel supply chain framework. Notably, the most relevant studies to this paper are Qiu et al. (2024) and Yang et al. (2022). Qiu et al. (2024) emphasized the

impact of consumer web rooming behavior on whether a supplier opens virtual showrooms in a dual-channel supply chain but did not consider consumer returns. [Yang et al. \(2022\)](#) focused on a supply chain structure where a single retailer operates both online and offline channels. In contrast, this study investigates a dual-channel supply chain where a supplier sells products to customers through an independent physical retailer and its own online channel. To our knowledge, this is the first study to consider the application of AR technology in a dual-channel supply chain, incorporating key factors such as consumer returns and customer privacy concerns cost.

The structure of this paper is as follows: In Section 2, we conduct a review of related literature. Section 3 outlines the problem description and assumptions. Section 4 presents the theoretical models both without and with AR technology. Section 5 focuses on the equilibrium analysis. Section 6 concludes this paper and outlines avenues for future research. The proofs for all lemmas and propositions are available in the online appendix.

2. Literature Review

In recent years, the impact of supply chain management has become very popular ([Khatib et al., 2022](#)), especially, the competition between suppliers selling directly to consumers and traditional retail channels has attracted wide attention from scholars. The assertion that suppliers entering the online market may not necessarily threaten retailers' profits has been widely substantiated; in certain scenarios, this transition can lead to mutual benefits for both parties ([Arya et al., 2007](#); [Chiang et al., 2003](#); [Ha et al., 2016](#); [Liu et al., 2021](#); [Shi et al., 2023](#); [Tsay & Agrawal, 2004](#); [Zhang et al., 2020](#); [Zheng & Yu, 2021](#)). Dual-channel supply chains are increasingly prevalent in the practical business landscape, garnering significant attention from the academic community. Scholars have extensively delved into various facets of competition within dual-channel supply chains. For instance, research on pricing strategies considers factors such as price discounts ([Cai et al., 2009](#)), channel substitutability ([Hezarkhani et al., 2018](#)), production cost disruptions ([Huang et al., 2013](#); [Soleimani et al., 2016](#)), asymmetric product distribution ([Matsui, 2016](#)), and asymmetric information ([Zhou et al., 2019](#)). Moreover, certain studies are dedicated to enhancing product quality within dual-channel contexts ([Chen et al., 2017](#); [David & Adida, 2015](#); [Zhang et al., 2021](#)). There are also articles addressing value-added services in the offline channel ([Guo et al., 2020](#); [Li et al., 2019b](#)) and delivery lead time in the online channel ([Hua et al., 2010](#); [Modak & Kelle, 2019](#); [Xu et al., 2012](#)). The above literature review primarily characterizes the competition between online and offline channels in terms of pricing, product quality, and services. We focus on the disparities in product matching between online and offline channels. Considering that the adoption of AR technology can enhance the likelihood of product matching in online channels, potentially intensifying competition between channels, we further investigate pricing decisions and suppliers' strategies for adopting AR technology within an offline-online

supply chain.

Another research direction focuses on making optimal operational decisions regarding the adoption of virtual showrooms to increase the likelihood of product matching in online channels. Some scholars have conducted research on the adoption of virtual showrooms in online channels across various supply chain structures. Sun et al. (2020) examined whether an online retailer should adopt virtual showrooms in different market environments (monopolistic retailer/two independent retailers). They found that it is advantageous to adopt virtual showrooms when customers are less sensitive to travel costs. Sun et al. (2023) studied the adoption strategy of virtual showrooms in two dual-channel supply structures, concluding that it can be profitable for both the supplier and retailer when the online shopping cost is high. Qiu et al. (2024) analyzed whether a supplier should establish virtual showrooms in an online and offline channel structure, finding that virtual showrooms are beneficial when the experience cost is moderate and consumers are sensitive to the store visit cost. Most of the literature above emphasizes how consumer web rooming behavior affects the adoption of virtual showrooms, particularly in contexts where sellers don't offer a full refund policy, meaning consumers can't return dissatisfied products.

In recent years, some scholars have focused on the impact of introducing virtual showrooms on the profitability of supply chain members in the context of return policies. Gao and Su (2017) found that an omnichannel retailer is profitable only if the virtual showroom doesn't excessively steer offline customers to the online channel. Yang et al. (2022) proposed that the benefits of a virtual showroom for the supplier depend on the extent to which it enhances the likelihood of product matching and increases demand. Xu et al. (2023) examined the impact of adopting AI in different market models (agency/resale) on the profits of the supplier and platform when considering the role of network effects. Zhang et al. (2023) investigated the deployment of virtual showrooms on an online retail platform and proposed a pricing mechanism to achieve a win-win-win situation for the intermediary, the seller and customers. Xu et al. (2024) explored whether a live broadcasting platform should adopt AI to reduce mismatch probability under two sales models, concluding that the decision depends on the marginal cost of AI adoption and the effectiveness of live broadcasting. The literature mentioned above primarily explores whether suppliers should adopt virtual showrooms from the perspective of the inconvenience costs incurred by customers when shopping through different channels. However, this paper focuses on how the improvement rate of product matching and consumers' privacy concerns cost impact suppliers' decisions regarding the adoption of AR technology.

In summary, we find that the literature on existing dual-channel supply chains rarely discusses AR technology adoption strategies, and the literature that talks about AR technology adoption strategies does not take into account consumers' privacy concerns and different channel product matching probabilities. For the first time, our paper discusses whether to adopt AR technology in a dual-channel

supply chain, taking into account the customers' privacy concerns cost, consumer returns, and the probability of product matching across different channels.

Table 1 presents a comparison between this study and related studies from the literature review.

Table 1. Comparison between this study and related studies.

papers	Virtual showrooms/ AI/AR	Dual-channel supply chain	Consumer returns	Customers' privacy concerns cost	Difference in product matching between online and offline channels
Sun et al. (2020)	√				
Sun et al. (2023)	√	√			
Qiu et al. (2024)	√	√		√	
Gao & Su (2017), Yang et al. (2022), Xu et al. (2023)	√	√	√		
Zhang et al. (2023)	√		√		
Xu et al. (2024)	√	√	√		√
Li et al. (2019b), Chen et al. (2017), David & Adida (2015), Zhang et al. (2021)		√			
This paper	√	√	√	√	√

3. Problem Description and Assumptions

This paper considers a supply chain consisting of a supplier (M) and a physical retailer (R), where the supplier can sell products to customers through both the physical retailer and its own online channel. Consumers can assess both digital and non-digital attributes of products in offline channels, but only digital attributes online. Consequently, customers are more likely to find products that meet their needs offline than online (Li & Liu, 2021). In this paper, we use h to represent the likelihood of product matching when consumers shop in the offline channel and l to represent the likelihood of product matching when customers shop online, where $l < h \leq 1$, and we further assume that $1/2 \leq l < 1$, which aligns with reality. For instance, according to data from the National Retail Federation in the United States, the average return rate for online shopping in 2023 was 17.3% (NRF, 2024). To make the model tractable, we assume $h = 1$ in basic model. Note that, similar assumption is commonly used in Mehra et al. (2018).

In real-world scenarios, to reduce the risks associated with online shopping for consumers, merchants often offer full refund policies. Typically, customers have a 7-day window for full returns, fostering confidence and flexibility in their online shopping experience. Major companies embracing such customer-friendly practices include Amazon, Apple, Walmart, and eBay (Guo et al., 2023; Huang et al., 2018; Li et al., 2019a). Therefore, we assume that both the supplier and the retailer offer a full refund policy in their respective sales channels in this paper. For the online channel, customers can only evaluate whether a product matches their

needs and preferences after they receive it. If customers receive a product that doesn't match their needs and preferences, the perceived value of the product is 0, they will return it to the merchant for a full refund. Conversely, if customers receive a product that matches their needs and preferences, the perceived value is v and they will keep it. Similar to Choi et al. (2024), Cao and Choi (2022) and Cao et al. (2023), we assume consumers are heterogeneous, and v is uniformly distributed over the range $[0,1]$. To improve the likelihood of product matching in the online channels, some suppliers such as L'Oréal and Zara adopt AR technology to provide customers with online try-on services (Hilken et al., 2017). This enables customers to comprehensively assess product attributes (including both digital and non-digital) before purchasing products. In this paper, similar to Yang et al. (2022), we assume that the improvement rate of product matching after adopting AR technology is denoted as a , where $1 < a < h/l$. Therefore, the likelihood of product matching in the online channel after adopting AR technology is al . Note that this condition ensures that the likelihood of product matching in the offline channel remains superior to that in the online channel even after the adoption of AR technology, which is consistent with the practice. Additionally, considering that AR technology requires customers to use their cameras and record personal data, it may trigger consumers' privacy concerns about leaving a digital footprint (Dacko, 2017; Martin et al., 2017). Following Arora and Jain (2024) and Liu et al. (2023), we assume that customers incur privacy concerns cost when using AR technology, denoted by t . To ensure that all the scenarios result in non-negative profits, we focus on $0 < t \leq \bar{t}$ in our following analysis, where $\bar{t} = (al - l^2)/(2 - al)$.

In cases where the supplier has not adopted AR technology, customers can obtain a utility $u_m^N = l(v - p_m)$ if they purchase products from the online channel. Similarly, customers can obtain a utility $u_r^N = h(v - p_r)$ if they purchase products from the offline channel. Customers make purchasing decisions by maximizing their own utility. The indifference point for customers to purchase products from either the offline channel or online channel is $v_{rm}^N = (hp_r - lp_m)/(h - l)$, and the indifference point for consumers purchasing products at the online channel or not purchasing products is $v_m^N = p_m$. When $0 < v_m^N < v_{rm}^N < 1$, equivalently, $(p_r + l - 1)/l < p_m < p_r$, the demand function for the offline channel is $d_r^N = 1 - (p_r - lp_m)/(1 - l)$, the demand function for the online channel is $d_m^N = (p_r - lp_m)/(1 - l) - p_m$. If $p_m \leq (p_r + l - 1)/l$, all customers will shop from the online channel, and if $p_m \geq p_r$, all customers will shop from the offline channel.

In the case where the supplier has adopted AR technology, the consumer utility for the online channel is $u_m^A = al(v - p_m) - t$. Similarly, customers make purchasing decisions by maximizing their own utility. The indifference point for customers to purchase in either the offline or online channel is $v_{rm}^A = (p_m - alp_r - t)/(1 - al)$, and the indifference point for customers to shop online or not is $v_m^A = (alp_m + t)/al$. When $0 < v_m^A < v_{rm}^A < 1$, equivalently, $(p_r + al - t - 1)/al < p_m < (alp_r - t)/al$, the demand functions for the offline and online channels are:

$$d_r^A = 1 - \frac{p_m - alp_r - t}{1 - al} \quad \text{and} \quad d_m^A = \frac{p_m - alp_r - t}{1 - al} - \frac{alp_m + t}{al} \quad (1)$$

If $p_m \leq (p_r + al - t - 1)/al$, all customers will shop from the online channel, and if $p_m \geq (alp_r - t)/al$, all customers will shop from in the offline channel. To narrow down the scope of analysis regarding the adoption of AR technology by the supplier in a dual-channel context, this study specifically targets scenarios where demand is present in both channels (Li et al., 2024; Xu et al., 2024). All corresponding notations are succinctly outlined in **Table 2**.

Table 2. Notations.

Notation	Definition
v	Customer's valuation of product
l	Likelihood of product matching in the online channel
h	Likelihood of product matching in the offline channel
a	Improvement rate of product matching after the adoption of AR technology
t	Customers' privacy concerns cost
w	Wholesale price of the offline channel
p_m	Retail price of the online channel
p_r	Retail price of the offline channel
π_m^i	Profit of the supplier ($i = \{N, A\}$)
π_r^i	Profit of the physical retailer

Without loss of generality, we assume unit operational cost and unit production cost to be zero, and normalize the market size to one (Cao et al., 2023; Ji et al., 2023). Moreover, to focus on the impact of improvement rate of product matching and customers' privacy concerns cost on consumers' utility and supply chain members' pricing decisions and profits, we set the inconvenience cost for customers returning products and the cost for the merchant to process returned products to zero. Following Niu et al. (2023), Tian et al. (2018) and Lai et al. (2022), the decision sequence is illustrated in **Figure 1**. Since the adoption strategy for AR technology is a long-term decision, in the first stage, the supplier first

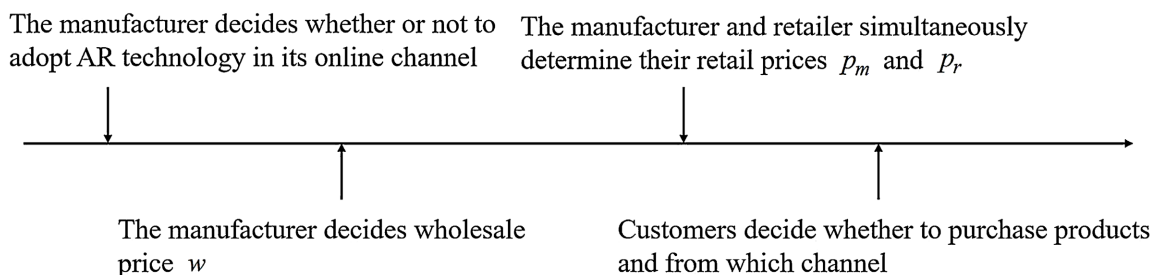


Figure 1. Decision sequence.

decides whether or not to adopt AR technology in its online channel. In the second stage, the supplier determines wholesale price w . In the third stage, the supplier and retailer simultaneously determine their retail prices p_m and p_r . Finally, customers decide whether to purchase products and from which channel.

4. Model

This section delves into the equilibrium results and examines cases both with and without AR technology.

4.1. Case without AR Technology

In cases where the supplier has not adopted AR technology, the profit functions for the supplier and the retailer are as follows:

$$\pi_m^N = wd_r^N h + p_m d_m^N l \quad \text{and} \quad \pi_r^N = (p_r - w) d_r^N h \quad (2)$$

We derive the equilibrium results in the case without AR technology by backward induction, and the results are presented in Lemma 1.

Lemma 1. *In the case without AR technology, the equilibrium prices of the supplier and retailer are*

$$w^{N*} = \frac{8+l^2}{2(8+l)}, \quad p_m^{N*} = \frac{10-l}{2(8+l)} \quad \text{and} \quad p_r^{N*} = \frac{12-2l-l^2}{2(8+l)};$$

the equilibrium demand quantities of two channels are

$$d_m^{N*} = \frac{2+l}{2(8+l)}, \quad d_r^{N*} = \frac{2+l}{8+l}.$$

Lemma 1 shows the equilibrium results are correlated with the likelihood of product matching in the online channel l . Intuition suggests that the supplier increases the wholesale price charged to the retailer as the likelihood of product matching in the online channel improves. This intuition is valid. A higher product match likelihood enhances customers' willingness to pay for goods from the online channel, where there is no double marginalization problem. To capitalize on this positive effect, the supplier raises the wholesale price, forcing more customers to switch to the online channel. In response, the retailer prices aggressively to retain their market segment, leading to a price war between the two channels., i.e., $\partial p_m^{N*} / \partial l < 0$ and $\partial p_r^{N*} / \partial l < 0$, consistent with the findings of Sun et al. (2023), Qiu et al. (2024) and Xu et al. (2023).

4.2. Case with AR Technology

In the case where the supplier has adopted AR technology, The profit functions for the supplier and the retailer are as follows:

$$\pi_m^A = wd_r^A h + p_m d_m^A al \quad \text{and} \quad \pi_r^A = (p_r - w) d_r^A h \quad (3)$$

Similarly, we derive equilibrium results for the case with AR technology by backward induction, presented in Lemma 2.

Lemma 2. *In the case of AR technology, the equilibrium prices of the supplier and retailer are $w^{A*} = \frac{8+al(al-t)}{2(8+al)}$, $p_m^{A*} = \frac{10al-a^2l^2-8t+alt}{2al(8+al)}$ and $p_r^{A*} = \frac{4(3+t)+al(-2-al+t)}{2(8+al)}$ the equilibrium demand quantities of two channels are $d_m^{A*} = \frac{-a^3l^3-a^2l^2(1-t)-8t+al(2+t)}{2al(1-al)(8+al)}$, $d_r^{A*} = \frac{(2+al)(1-al+t)}{(1-al)(8+al)}$.*

Lemma 2 shows that after the adoption of AR technology, the equilibrium results are related to the likelihood of product matching in the online channel l , the improvement rate of product matching a and the privacy concerns cost t . Since the impact of the likelihood of product matching in the online channel l on the equilibrium prices after adopting AR technology closely mirrors that described in Lemma 1, we will not provide a detailed discussion here.

After the supplier adopts AR technology, the equilibrium prices are further influenced by the improvement rate of product matching a and customers' privacy concerns cost t . Therefore, we summarize the impact of these two parameters on equilibrium prices in the case of AR technology in Lemma 3.

Lemma 3. (i) *The equilibrium wholesale price w^{A*} decreases in a if $1 < a \leq a_1$ and $t_1 \leq t \leq \bar{t}$; otherwise, it increases in a . Additionally, the equilibrium wholesale price w^{A*} decreases in t .*

(ii) *The equilibrium retail price of the online channel p_m^{A*} increases in a if $1 < a \leq a_2$ and $t_2 \leq t \leq \bar{t}$; otherwise, it decreases in a . Additionally, the equilibrium retail price of the online channel p_m^{A*} decreases in t .*

(iii) *The equilibrium retail price of the offline channel p_r^{A*} decreases in a , while it increases in t .*

Intuitively, an improvement in product matching a increases the competitiveness of the online channel, making the supplier more inclined to sell products through this channel due to the absence of double marginalization. As a result, the supplier tends to raise the wholesale price. However, Lemma 3(i) indicates when the adoption of AR technology only marginally improves product matching in the online channel while significantly raising consumers' privacy concerns cost, and the equilibrium wholesale price actually decreases as a increases. The reason behind this is that in this scenario, a high product match likelihood enhances customers' willingness to pay for goods from the online channel, but the privacy concerns weaken the customer's willingness to pay for the goods from this channel. When $1 < a \leq a_1$ and $t_1 \leq t \leq \bar{t}$, the negative impact of customers' privacy concerns cost on the online channel becomes dominant, reducing the marginal benefit for the supplier in the online channel. Therefore, as a increases, the supplier lowers the wholesale price to give the retailer room to reduce retail prices and encourage consumers to switch from the online channel to the offline channel. Additionally, it's evident that the equilibrium wholesale price decreases as the customers' privacy concerns cost t increases.

Lemma 3(ii) illustrates the impact of the improvement rate of product matching

a and customers' privacy concerns cost t on the equilibrium prices in the online channel. An increase in the improvement rate of product matching a has both a direct and an indirect impact on the retail price in online channel. The direct impact is that as a increases, it enhances the likelihood of product matching in the online channel, prompting the supplier to raise the retail price. The indirect impact is that an increase in a intensifies online-offline channel head-on price competition, leading the supplier to reduce the retail price. Specifically, when the improvement rate of product matching is high (i.e., $a_2 < a < 1/l$) or when both the improvement rate of product matching and customers' privacy concerns cost are low (i.e., $1 < a \leq a_2$ and $0 < t < t_2$), the indirect effect of a dominates the direct impact. As a result, the supplier sets a lower retail price as a increases. When the improvement rate of product matching is low and customers' privacy concerns cost is high (i.e., $1 < a \leq a_2$ and $t_2 \leq t \leq \bar{t}$), the direct effect of a dominates the indirect impact, thus the supplier sets a higher retail price as a increases. Additionally, the equilibrium retail price in the online channel decreases as the customers' privacy concerns cost t decreases. This phenomenon occurs because a higher customers' privacy concerns cost t compels the supplier to reduce the retail price in order to entice customers to make purchases through the online channel.

Lemma 3(iii) indicates that the retail price in the offline channel decreases with the improvement rate of product matching a but increases with the customers' privacy concerns cost t . This is because an increase in the improvement rate of product matching a enhances customers' willingness to purchase products through the online channel, prompting the retailer to set a lower retail price to attract customers. Conversely, a higher customers' privacy concerns cost t encourages the retailer to set a higher retail price to maximize its own profit.

5. Equilibrium Analysis

In this section, we discuss the impact of adopting AR technology on equilibrium prices, demand quantity, and profits of supply chain members and the overall supply chain profit. We first explore how the adoption of AR technology impacts equilibrium retail prices of online channel and offline channel, summarized as Proposition 1.

Proposition 1. (i) *The equilibrium wholesale price is lower with AR technology than without, that is, $w^{A*} \leq w^{N*}$, if $1 < a \leq a_3$ and $t_3 \leq t \leq \bar{t}$ and higher otherwise.*

(ii) *The equilibrium retail price of the online channel is always lower with AR technology than without, that is, $p_m^{A*} < p_m^{N*}$.*

(iii) *The equilibrium retail price of the offline channel is higher with AR technology than without, that is, $p_r^{A*} \geq p_r^{N*}$, if $1 < a \leq a_4$ and $t_4 \leq t \leq \bar{t}$ and lower otherwise.*

Proposition 1(i) demonstrates that after adopting AR technology, the supplier generally set a higher wholesale price in the offline channel. However, when the

improvement rate of product matching is low and the consumers' privacy concerns cost is high (i.e., $1 < a \leq a_3$ and $t_3 \leq t \leq \bar{t}$), the wholesale price decreases. This occurs because the combination of a low improvement rate and high privacy concerns drives the wholesale price down in the offline channel, as indicated by Lemma 3(i).

Proposition 1(ii) shows that after the adoption of AR technology, the supplier consistently set a lower retail price in online channel. This result contradicts our intuition that AR adoption would raise the retail price in the online channel due to the improvement in the likelihood of product matching. According to Lemma 3(ii), when the improvement rate of product matching is high, or when the improvement rate of product matching and the consumers' privacy concerns cost are low, both a and t lead to a decrease in retail price in online channel after the adoption of AR technology. When the improvement rate of product matching is low and the consumers' privacy concerns cost is high, the impact of t in driving down retail price in online channel outweighs the effect of a in driving up retail price in online channel. Thus, due to intense inter-channel competition and the negative impact of consumers' privacy concerns cost, the supplier consistently set a lower retail price in the online channel after the adoption of AR technology.

Proposition 1(iii) shows that when the improvement rate of product matching is low and privacy concerns cost is high (i.e., $1 < a \leq a_4$ and $t_4 \leq t \leq \bar{t}$), the retailer sets a higher retail price after the adoption of AR technology. Otherwise, the retailer sets a lower retail price after the adoption of AR technology. Analyzing this result in light of Lemma 3(iii), we find that the customers' privacy concerns cost t drives the retail price in the offline channel upward, while the improvement rate of product matching a drives it downward. When a is sufficiently high (i.e., $a_4 < a < 1/l$), or when both a and t are low (i.e., $1 < a \leq a_4$ and $0 < t \leq t_4$), the negative impact of a outweighs the positive impact of t , causing the retailer to set a lower price after the adoption of AR technology. Conversely, when a is low and t is relatively high (i.e., $1 < a \leq a_4$ and $t_4 < t \leq \bar{t}$), the positive impact of t outweighs the negative impact of a , the retailer set a higher retail price after the adoption of AR technology.

Next, we analyze the impacts of the supplier adopting AR technology on the equilibrium demand quantity of online channel and offline channel and present Proposition 2.

Proposition 2. (i) *The equilibrium demand quantity of the online channel is higher with AR technology than without, that is, $d_m^{A*} \geq d_m^{N*}$, if $0 < t \leq t_5$, and lower otherwise.*

(ii) *The equilibrium demand quantity of the offline channel is always higher with AR technology than without, that is, $d_r^{A*} > d_r^{N*}$.*

Proposition 2(i) indicates the demand quantity of the online channel increases after the adoption of AR technology when customers' privacy concerns cost t is low. When consumers' privacy concerns are high, the demand quantity for the

online channel decreases after the adoption of AR technology, which aligns with real-world observations (Dick, 2021). A low value of t implies that customers bear low privacy disclosure risks to enjoy the price advantage and improved product matching in the online channel. Thus, customers are more inclined to purchase goods in the online channel after the adoption of AR technology. Conversely, with a high value of t , the drawbacks introduced by the privacy concerns outweigh the benefits derived from the price advantage and improved product matching. Consequently, customers are less willing to make purchases in the online channel after the adoption of AR technology.

Proposition 2(ii) indicates that the demand quantity for the offline channel always increases after the adoption of AR technology. This contradicts the intuition that the adoption of AR technology will attract more customers to the online channel, leading to less demand for the offline channel. By calculating the first-order derivatives of the demand for the offline channel, we find $\partial d_r^{A^*} / \partial t > 0$, $\partial d_r^{A^*} / \partial a > 0$. This suggests that higher t and a are conducive to increasing the demand for the offline channel. When customers face higher privacy concerns cost, their willingness to shop in the online channel decreases, which, in turn, encourages them to shop in the offline channel. Intuitively, one might think that a higher a would decrease the demand for the offline channel. However, we discover that this is not the case. The rationale behind this result is that a higher a intensifies competition between the two channels, which may lead the retailer to set a lower price. Due to the demand increment resulting from the decrease in prices outweighing the reduction caused by the weakening of product matching advantages, the demand for the offline channel also increases with the increase in a . In summary, the demand for offline channels has risen since the adoption of AR technology.

To analyze the optimal strategy for the supplier adopting AR technology, we define the change in the supplier's direct profit from the online channel after adopting AR technology as $\Delta_o = p_m^A d_m^A a l - p_m^N d_m^N l$, and the change in the supplier's wholesale profit from the offline channel after adopting AR technology as $\Delta_r = w^A d_r^A h - w^N d_r^N h$.

Proposition 3. *The supplier has motivation to adopt AR technology if and only if (i) $a_5 < a < 1/l$ or (ii) $1 < a \leq a_5$ and $0 < t \leq t_6$; otherwise, the supplier has no motivation to adopt AR technology.*

Proposition 3 demonstrates that a supplier's decision to adopt AR technology hinges on two key parameters: the improvement rate of product matching a and the privacy concerns cost t (see Figure 2). The supplier's profit is derived from two sources: direct profit from the online channel and wholesale profit from the offline channel. Despite the potential decrease in the retailer's marginal profit, the demand for the offline channel increases significantly. Therefore, the adoption of AR technology consistently boosts the wholesale profit of the offline channel, i.e., $\Delta_r > 0$. There exists a threshold t_s such that if the consumer's privacy cost is relatively low (i.e., $0 < t < t_s$), the direct profit of the online channel increases,

i.e., $\Delta_o > 0$. If the consumer privacy cost is relatively high (i.e., $t_s \leq t \leq \bar{t}$), the direct profit of the online channel decreases, i.e., $\Delta_o < 0$. When the improvement rate of product matching is high (i.e., $a_5 < a < 1/l$), both the direct profit and the wholesale profit increase if the privacy concerns cost is low (i.e., $0 < t \leq t_s$). However, if the privacy concerns cost is high ($t_s \leq t \leq \bar{t}$), the increase in wholesale profit surpasses the decline in direct profit. Thus, the supplier is motivated to adopt AR technology when AR technology significantly improves product matching. When the improvement rate of product matching is low (i.e., $1 < a \leq a_5$), the supplier's motivation to adopt AR technology is influenced by the privacy concerns cost: If the privacy concerns cost is low (i.e., $0 < t \leq t_s$), both the direct profit and wholesale profit increase, motivating the supplier to adopt AR technology. If the privacy concerns cost is moderate (i.e., $t_s < t \leq t_6$), the increase in wholesale profit outweighs the decrease in direct profit, still providing motivation to adopt AR technology. If the privacy concerns cost is extremely high (i.e., $t_6 < t \leq \bar{t}$), the decline in direct profit for the online channel surpasses the increase in wholesale profit for the offline channel, leading to a lack of motivation for the supplier to adopt AR technology. **Figure 2** visually illustrates that the supplier is only suitable for AR technology in the pink area.

Moving forward, we analyze how the adoption of AR technology will affect the retailer's profit, with the results presented in Proposition 4.

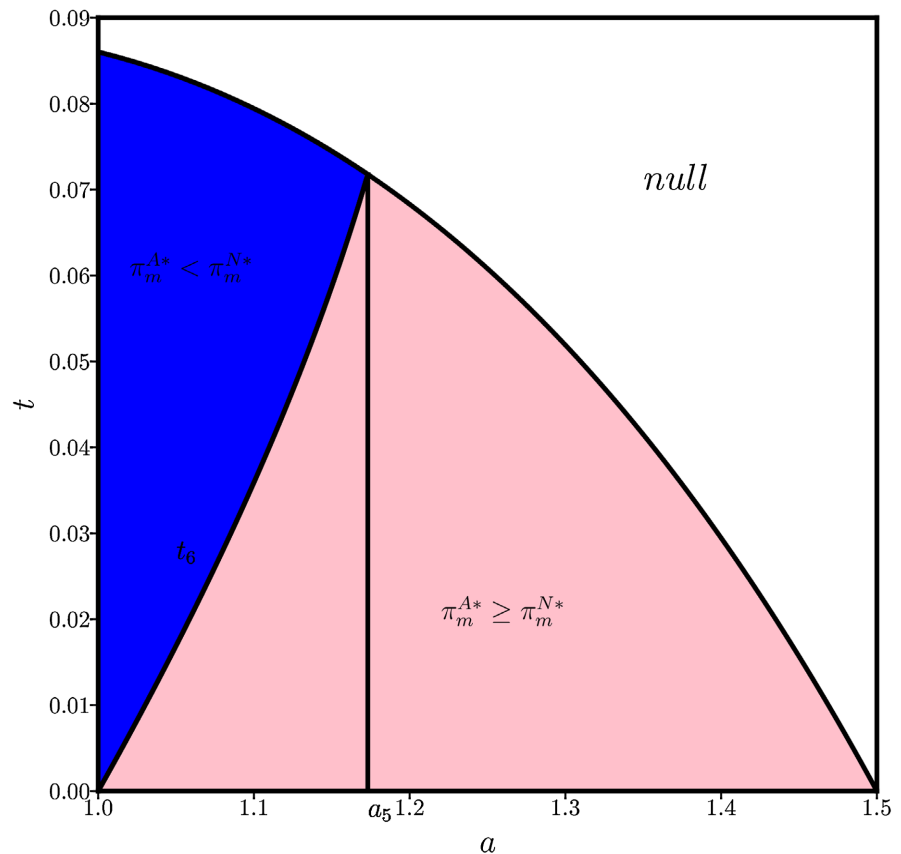


Figure 2. Supplier's optimal adoption strategy of AR technology.

Proposition 4. *The adoption of AR technology will benefit the retailer if and only if $1 < a \leq a_6$ and $t_7 \leq t \leq \bar{t}$; otherwise, the adoption of AR technology will hurt the retailer.*

Proposition 4 reveals an interesting result that the adoption of AR technology in the online channel does not necessarily reduce the retailer's profits (see **Figure 3**). Specifically, when the improvement rate of product matching is low and the customers' privacy concerns cost is high (i.e., $1 < a \leq a_6$ and $t_7 \leq t \leq \bar{t}$), the adoption of AR technology benefits the retailer. The rationale behind this result is that Proposition 2(iii) and Proposition 3(ii) indicate that when the improvement rate of product matching is low and customers' privacy concerns cost is high, the adoption of AR technology increases the marginal profit and demand quantity for the offline channel, thereby enhancing the physical retailer's profit. This suggests that the retailer needs to offer more personalized services to maintain a competitive advantage in product matching and protect consumer privacy effectively when the supplier adopts AR technology in the online channel to offer customers a "try-on" service. By taking these measures, the physical retailer not only avoids harm from the adoption of AR technology but can also benefit from it.

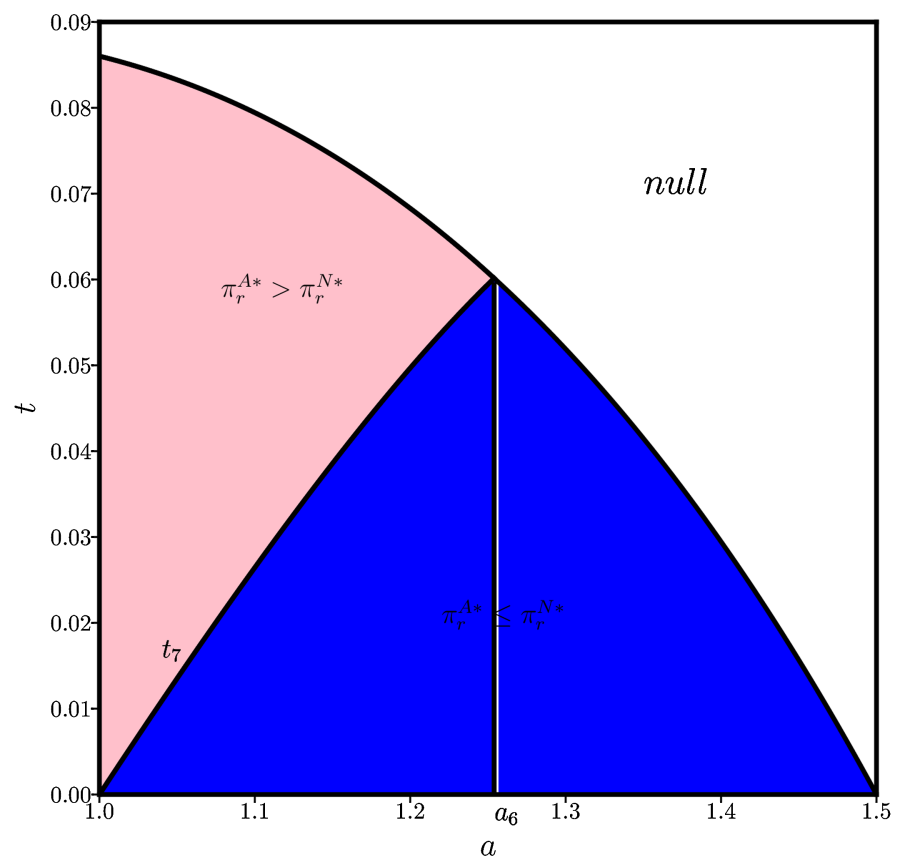


Figure 3. Impact of the adoption of AR technology on the retailer's profit.

Additionally, we find that when the improvement rate of product matching is relatively low and the customers' privacy concerns cost is in the middle (i.e.,

$1 < a \leq a_6$, $t_6 < t < t_7$), the adoption of AR technology enables the supplier and retailer to achieve a win-win situation (see **Figure 4**). If the adoption of AR technology significantly improves product matching in the online channel (i.e., $a_6 < a < 1/l$), it benefits the supplier but harms the retailer. When the adoption of AR technology does not lead to a noticeable improvement in product matching (i.e., $1 < a \leq a_6$), the customers' privacy concerns cost becomes a primary factor influencing the profit allocation after adopting AR technology. When the privacy concerns cost is low, the profit spillover of AR technology adoption is occupied by the physical retailer, and when the privacy concerns cost is high, the profit spillover of AR technology adoption is occupied by the supplier. Thus, it is only when the privacy concerns cost falls within the intermediate range that the adoption of AR technology can lead to a win-win situation for both supplier and physical retailer.

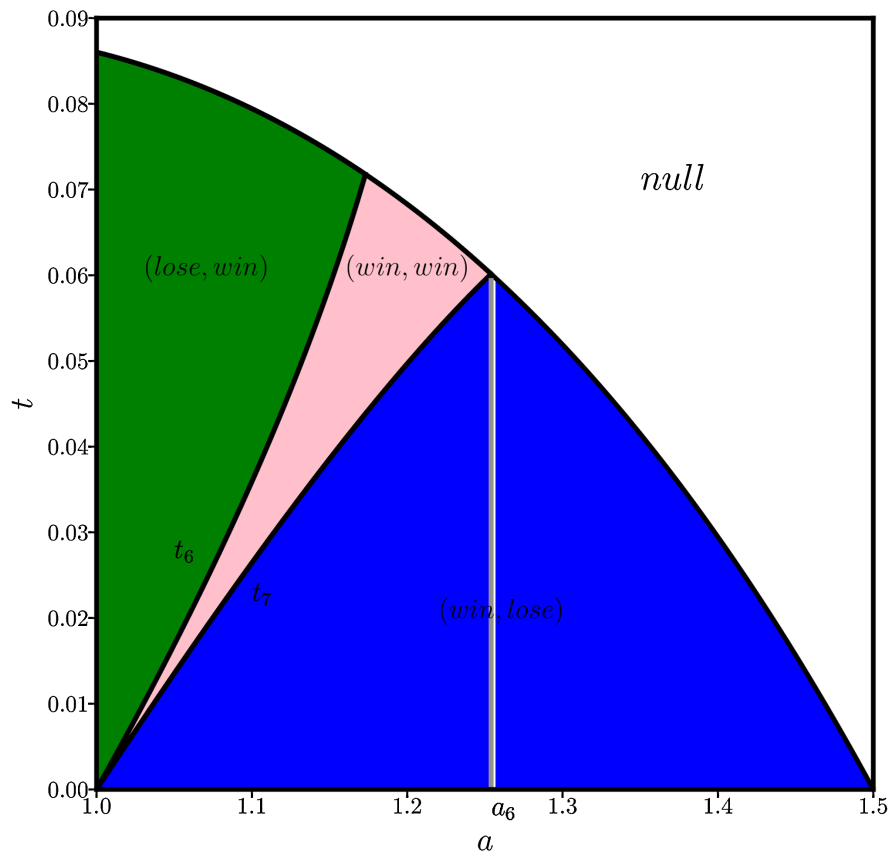


Figure 4. Condition for achieving a win-win situation.

Based on the above analysis, the impact of AR technology on the total profit of the supply chain is summarized in Proposition 5.

Proposition 5. *The adoption of AR technology results in an enhancement of the total profit of the supply chain if and only if (i) $a_7 < a < 1/l$ or (ii) $1 < a \leq a_7$, $0 < t \leq t_8$ or $t_9 \leq t \leq \bar{t}$; otherwise, the adoption of AR technology results in a reduction of the total profit of the supply chain.*

Proposition 5 indicates that, in most cases, the adoption of AR technology can increase the overall profit of the supply chain (see **Figure 5**). However, there are exceptions. When the improvement rate of product matching is limited and the privacy concerns cost is at an intermediate level (i.e., $1 < a \leq a_7$ and $t_8 < t < t_9$), the reduction in the supplier's profit outweighs the increase in the retailer's profit. In this specific scenario, the adoption of AR technology leads to a decrease in the overall profit of the supply chain.

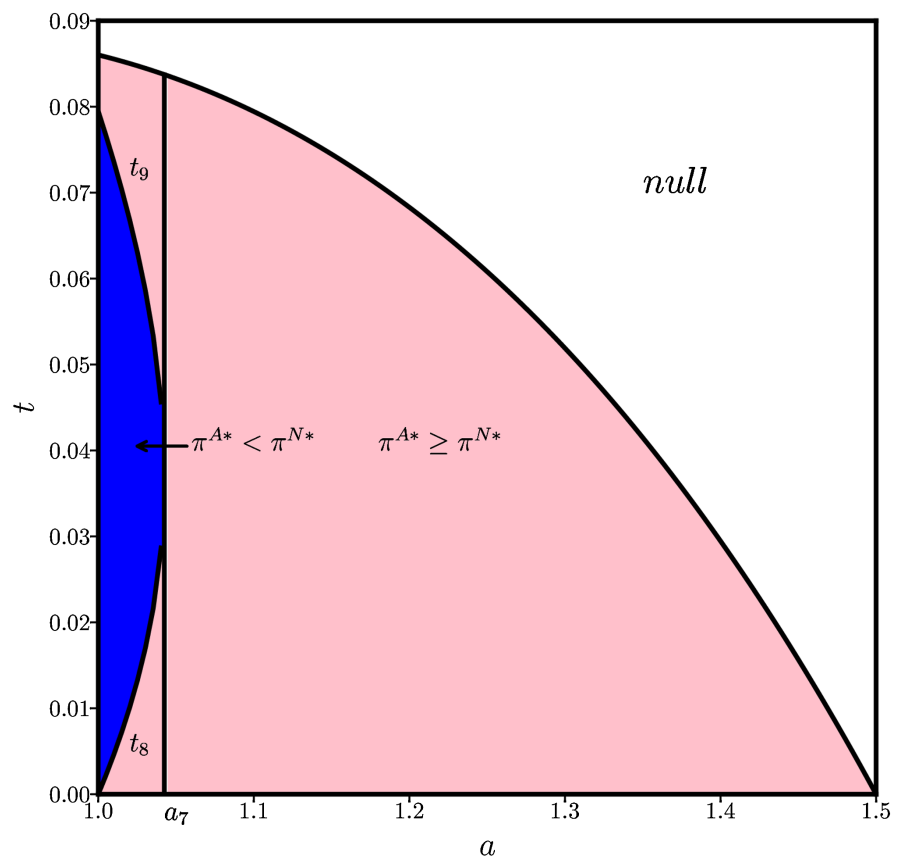


Figure 5. Impact of the adoption of AR technology on the supply chain's profit.

6. Conclusion

In online shopping, completely eliminating product mismatches and reducing consumer returns is challenging. However, technological advancements such as AR technology may become effective tools for addressing these mismatches in online channels. This paper explores whether suppliers should adopt AR technology in dual-channel supply chains, considering consumer returns and privacy concerns. The main conclusions are as follows.

6.1. Summary of Findings

Initially, we observe that the supplier is motivated to adopt AR technology when it significantly enhances the likelihood of product matching in the online channel. This explains why AR technology was first popularized in online channels in the

apparel and makeup space. Additionally, the supplier is incentivized to adopt AR technology even when it has a limited impact on improving product matching in the online channel, especially if consumers face a low risk of privacy disclosure. Secondly, we discover that while the adoption of AR technology may reduce the retailer's profit in many scenarios, there are specific circumstances where it actually enhances profitability. Particularly, when the improvement rate of product matching is low and customers' privacy concerns costs are high, the retailer experiences a positive impact from adopting AR technology due to higher marginal profits and increased demand. This indicates that retailers should not fear the adoption of AR technology as long as they focus on providing better customer support and protecting consumer privacy. Finally, we find that in conditions where the improvement rate of product matching is relatively low and consumers' privacy concerns costs are moderate, the adoption of AR technology results in a mutually beneficial situation for both the supplier and the physical retailer.

6.2. Managerial Implications

Based on the findings presented, we propose the following managerial implications to assist various participants in developing effective action plans.

First, it is essential for suppliers to avoid the indiscriminate adoption of AR technology, as they need to weigh the profits of different channels. AR technology is advantageous to suppliers only when it significantly enhances product matching or minimizes consumer concerns regarding privacy breaches. Specifically, suppliers should focus on improving the performance of AR technology by providing a more realistic and immersive try-on experience. This approach ensures that consumers can accurately perceive the texture, size, and style of products in a virtual environment. Furthermore, suppliers must prioritize consumer privacy protection, ensuring that personal information and usage data are strictly safeguarded during the AR experience. This builds consumer trust and acceptance of the technology. By taking these measures, suppliers can effectively increase consumer satisfaction and purchase intentions, thereby achieving sales growth and enhanced market competitiveness.

Second, for physical retailers, the adoption of AR technology by upstream suppliers, although potentially intensifying market competition, is not necessarily detrimental. Physical retailers can counter this challenge by offering superior services. They should strive to provide personalized shopping experiences, assisting consumers in finding and purchasing desired products more conveniently. This can be achieved through professional advice from staff, comprehensive product displays, and a seamless shopping process. Additionally, physical retailers should place a high priority on consumer privacy protection, ensuring the safety of personal information during in-store shopping to enhance consumer trust in physical stores. By doing so, physical retailers can maintain their competitive edge and benefit from increased consumer demand and higher product prices due to the adoption of AR technology by suppliers, thus improving their market position

and profitability.

In conclusion, both suppliers and physical retailers should strategically utilize and respond to AR technology based on their specific circumstances, enhancing technology performance and service quality to achieve mutual development and a win-win situation.

6.3. Limitation and Future Research

This study has some limitations in model settings and problem assumptions. Firstly, the study only considers the scenario with a single supplier and a single physical retailer. Therefore, it is worthwhile to investigate whether suppliers would adopt AR technology when considering multiple suppliers and physical retailers. Secondly, major online platforms like JD.com and Taobao have introduced AR try-on services in recent years. Therefore, future research could explore the adoption of AR technology by online platforms. Finally, it would be intriguing to investigate how consumer virtual showrooming behavior (i.e., exploring products online and completing purchases offline) influences suppliers' decisions to implement AR technology in a dual-channel supply chain, taking into account both consumer returns and consumer's privacy concerns cost.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Online Appendix

Proof of Lemma 1

In the case without AR technology, we have $\frac{\partial \pi_m^N(w, p_m)}{\partial p_m} = \frac{l(2p_m - p_r - w)}{l-1}$, $\frac{\pi_r^N(p_r)}{\partial p_r} = \frac{-1+l-lp_m+2p_r-w}{l-1}$. Then $\frac{\partial^2 \pi_m^N(w, p_m)}{\partial p_m^2} = -\frac{2l}{1-l} < 0$, $\frac{\partial^2 \pi_r^N(p_r)}{\partial p_r^2} = -\frac{2}{1-l} < 0$. Solving $\frac{\partial \pi_m^N(w, p_m)}{\partial p_m} = 0$ and $\frac{\pi_r^N(p_r)}{\partial p_r} = 0$, we get $p_m(w) = \frac{-1+l-3w}{-4+l}$ and $p_r(w) = \frac{2-2l+2w+lw}{4-l}$. Substituting $p_m(w)$ and $p_r(w)$ into $\pi_m^N(w)$, we have $\frac{\partial \pi_m^N(w)}{\partial w} = \frac{8+l^2-16w-2lw}{(4-l)^2}$ and $\frac{\partial^2 \pi_m^N(w)}{\partial w^2} = -\frac{2(8+l)}{(4-l)^2} < 0$. By solving $\frac{\partial \pi_m^N(w)}{\partial w} = 0$, we get $w^{N*} = \frac{8+l^2}{16+2l}$. Substituting w^{N*} into $p_m(w)$ and $p_r(w)$, we get $p_m^{N*} = \frac{10-l}{2(8+l)}$ and $p_r^{N*} = \frac{12-2l-l^2}{2(8+l)}$. The corresponding equilibrium demand quantity and profits are $d_m^{N*} = \frac{2+l}{2(8+l)}$, $d_r^{N*} = \frac{2+l}{8+l}$, $\pi_m^{N*} = \frac{(2+l)^2}{4(8+l)}$ and $\pi_r^{N*} = \frac{(1-l)(2+l)^2}{(8+l)^2}$.

Proof of Lemma 2

In the case with AR technology, we have $\frac{\partial \pi_m^A(w, p_m)}{\partial p_m} = \frac{t-al(-2p_m+p_r+w)}{-1+al}$, $\frac{\partial \pi_r^A(p_r)}{\partial p_r} = \frac{-1+al-alp_m+2p_r-t-w}{-1+al}$. Then $\frac{\partial^2 \pi_m^A(w, p_m)}{\partial p_m^2} = -\frac{2al}{1-al} < 0$, $\frac{\partial^2 \pi_r^A(p_r)}{\partial p_r^2} = -\frac{2}{1-al} < 0$. By solving $\frac{\partial \pi_m^A(w, p_m)}{\partial p_m} = 0$ and $\frac{\partial \pi_r^A(p_r)}{\partial p_r} = 0$, we get $p_m(w) = \frac{a^2l^2+2t-al(1+t+3w)}{al(-4+al)}$ and $p_r(w) = -\frac{2+t+al(-2+w)+2w}{-4+al}$. Substituting $p_m(w)$ and $p_r(w)$ into $\pi_m^A(w)$, we have $\frac{\partial \pi_m^A(w)}{\partial w} = \frac{8+a^2l^2-16w-al(t+2w)}{(-4+al)^2}$ and $\frac{\partial^2 \pi_m^A(w)}{\partial w^2} = -\frac{2(8+al)}{(-4+al)^2} < 0$. By solving $\frac{\partial \pi_m^A(w)}{\partial w} = 0$, we get $w^{A*} = \frac{8+a^2l^2-alt}{16+2al}$. Substituting w^{A*} into $p_m(w)$ and $p_r(w)$, we get $p_m^{A*} = \frac{10al-a^2l^2-8t+alt}{16al+2a^2l^2}$ and $p_r^{A*} = \frac{4(3+t)+al(-2-al+t)}{2(8+al)}$. The corresponding equilibrium demand quantity and profits are $d_m^{A*} = \frac{-a^3l^3-a^2l^2(1-t)-8t+al(2+t)}{2al(1-al)(8+al)}$, $d_r^{A*} = \frac{(2+al)(1-al+t)}{(1-al)(8+al)}$, $\pi_m^{A*} = \frac{-a^4l^4-a^3l^3(3-2t)+a^2l^2(6-t)t+8t^2+al(4-8t-3t^2)}{4al(1-al)(8+al)}$ and $\pi_r^{A*} = \frac{(2+al)^2(1-al+t)^2}{(1-al)(8+al)^2}$.

Proof of Lemma 3

(i) $\frac{\partial w^{A*}}{\partial a} = \frac{l(16al+a^2l^2-8(1+t))}{2(8+al)^2}$. $\frac{\partial w^{A*}}{\partial a}$ decreases with t . By solving $\frac{\partial w^{A*}}{\partial a} = 0$, we get $t_1 = -1+2al + \frac{a^2l^2}{8}$. $t_1 - \bar{t} = \frac{(8+al)(8+al(-16+al(1+al)))}{8(-8+al+a^2l^2)}$, let $G_1(a) = 8+al(-16+al(1+al))$. $\frac{\partial G_1(a)}{\partial a} = l(-16+2al+3a^2l^2) < 0$,

indicating that $G_1(a)$ decreases with a . When $a = \frac{1}{l}$, $G_1\left(\frac{1}{l}\right) = -6 < 0$. There exists $a_1 \in \left(1, \frac{1}{l}\right]$, for $1 < a < a_1$, we have $G_1(a) \geq 0$, $t_1 \leq \bar{t}$. In this case, if $0 < t \leq t_1$, then $\frac{\partial w^{A*}}{\partial a} \geq 0$; otherwise, $\frac{\partial w^{A*}}{\partial a} < 0$. For $\max(a_1, 1) < a \leq \frac{1}{l}$, we have $G_1(a) < 0$ and $t_1 > \bar{t}$, thus $\frac{\partial w^{A*}}{\partial a} > 0$. $\frac{\partial w^{A*}}{\partial t} = \frac{-al}{2(8+al)} < 0$.

$$(ii) \frac{\partial p_m^{A*}}{\partial a} = -\frac{9l}{(8+al)^2} + \frac{(64+16al-a^2l^2)t}{2a^2l(8+al)^2}. \text{ It is easy to observe that } \frac{\partial p_m^{A*}}{\partial a} \text{ increases with } t. \text{ Setting } \frac{\partial p_m^{A*}}{\partial a} = 0,$$

we obtain $t_2 = \frac{18a^2l^2}{64+16al-a^2l^2}$. $t_2 - \bar{t} = \frac{-(8+al)(16+al(-8+al)(3+al))}{(-64-16al+a^2l^2)(-8+al+a^2l^2)}$, let $G_2(a) = 16+al(-8+al)(3+al)$.

$\frac{\partial G_2(a)}{\partial a} = l(-24-10al+3a^2l^2) < 0$, indicating that decreases with a . When $a = \frac{1}{l}$, $G_2\left(\frac{1}{l}\right) = -12 < 0$. There exists

$a_2 \in \left(1, \frac{1}{l}\right]$, for $1 < a \leq a_2$, we have $G_2(a) \geq 0$, $t_2 \leq \bar{t}$. In this case, if $0 < t \leq t_2$, then $\frac{\partial p_m^{A*}}{\partial a} \leq 0$; otherwise,

$\frac{\partial p_m^{A*}}{\partial a} > 0$. For $\max(a_2, 1) < a \leq \frac{1}{l}$, we have $G_2(a) < 0$ and $t_2 > \bar{t}$, thus $\frac{\partial p_m^{A*}}{\partial a} < 0$. $\frac{\partial p_m^{A*}}{\partial t} = \frac{-8+al}{2al(8+al)} < 0$.

$$(iii) \frac{\partial p_r^{A*}}{\partial a} = -\frac{l(28+16al+a^2l^2-4t)}{2(8+al)^2} < 0, \quad \frac{\partial p_r^{A*}}{\partial t} = \frac{4+al}{2(8+al)} > 0.$$

Proof of Proposition 1

(i) $w^{A*} - w^{N*} = \frac{l(8-8l+a^2l(8+l)-a(8+l^2+(8+l)t))}{2(8+l)(8+al)}$. It is easy to observe that $w^{A*} - w^{N*}$ decreases with t . By

solving $w^{A*} - w^{N*} = 0$, we obtain $t_3 = \frac{(1-a)(8-8(1+a)l-al^2)}{a(8+l)}$.

$t_3 - \bar{t} = \frac{(8+al)(8-8l+a^2l(8+l^2)+a(-8-2l+l^2))}{a(8+l)(8-al-a^2l^2)}$. Let $G_3(a) = 8-8l+a^2l(8+l^2)+a(-8-2l+l^2)$. By solving

$G_3(a) = 0$, the two roots are given by $\frac{8+2l-l^2-\sqrt{64-224l+244l^2-36l^3+33l^4}}{2(8l+l^3)} < 1$ and

$a_3 = \frac{8+2l-l^2+\sqrt{64-224l+244l^2-36l^3+33l^4}}{2(8l+l^3)}$. For $1 < a \leq a_3$, we have $G_3(a) \leq 0$, $t_3 \leq \bar{t}$. In this case, If

$0 < t \leq t_3$, then $w^{A*} \geq w^{N*}$; otherwise, $w^{A*} < w^{N*}$. For $a_3 < a \leq \frac{1}{l}$, we have $G_3(a) > 0$, $t_3 > \bar{t}$, thus $w^{A*} > w^{N*}$.

$$(ii) p_m^{A*} - p_m^{N*} = \frac{9(1-a)l}{(8+l)(8+al)} - \frac{(8-al)t}{2al(8+al)} < 0.$$

(iii) $p_r^{A*} - p_r^{N*} = \frac{28l-28al+8l^2-8a^2l^2+(1-a)al^3}{2(8+l)(8+al)} + \frac{(32+4l+8al+al^2)t}{2(8+l)(8+al)}$. It is easy to observe that $p_r^{A*} - p_r^{N*}$

increases with t . By solving $p_r^{A*} - p_r^{N*} = 0$, we get $t_4 = \frac{l(a^2l(8+l)-4(7+2l)+a(28-l^2))}{(8+l)(4+al)}$. Let

$$G_4(a) = t_4 - \bar{t} = \frac{l(a^3 l^2(2+l)^2 + 20a(8+l) - 32(7+2l) + a^2 l(52 + 38l + 9l^2))}{(8+l)(4+al)(8-al-a^2 l^2)}. \quad \frac{\partial G_4(a)}{\partial a} > 0 \text{ for } 1 < a \leq \frac{1}{l} \text{ and}$$

$$\frac{1}{2} < l < 1, \text{ indicating that } G_4(a) \text{ increases with } a. \quad G_4(1) = -\frac{l(2-l-l^2)}{8-l-l^2} < 0, \quad G_4\left(\frac{1}{l}\right) = \frac{9(4-3l-l^2)}{5(8+l)} > 0. \text{ There}$$

exists $a_4 \in \left(1, \frac{1}{l}\right]$, for $1 < a \leq a_4$, we have $t_4 \leq \bar{t}$. In this case, if $0 < t \leq t_4$, then $p_r^{A*} \leq p_r^{N*}$; otherwise, $p_r^{A*} > p_r^{N*}$.

For $a_4 < a \leq \frac{1}{l}$, we have $t_4 > \bar{t}$, thus, $p_r^{A*} < p_r^{N*}$.

Proof of Proposition 2

$$(i) \quad d_m^{A*} - d_m^{N*} = \frac{-6al^2 + 6a^2 l^2 + 6a^2 l^3 - 6a^3 l^3}{2al(8+l)(1-al)(8+al)} + \frac{(8al + al^2 + 8a^2 l^2 + a^2 l^3 - 8(8+l))t}{2al(8+l)(1-al)(8+al)}. \text{ It is easy to observe that}$$

$$d_m^{A*} - d_m^{N*} \text{ decreases with } t. \text{ By solving } d_m^{A*} - d_m^{N*} = 0, \text{ we get } t_5 = \frac{6(a-1)(1-al)al^2}{(8+l)(8-al-a^2 l^2)}.$$

$$t_5 - \bar{t} = -\frac{al(2+l)(8-7al-a^2 l^2)}{(8+l)(8-al-a^2 l^2)} < 0, \text{ thus } t_5 < \bar{t}. \text{ If } 0 < t \leq t_5, \text{ then } d_m^{A*} \geq d_m^{N*}; \text{ otherwise, } d_m^{A*} < d_m^{N*}.$$

$$(ii) \quad d_r^{A*} - d_r^{N*} = \frac{(2+al)(1-al+t)}{(1-al)(8+al)} - \frac{2+l}{8+l}. \text{ It is easy to observe that } d_r^{A*} - d_r^{N*} \text{ increases with } t. \text{ When } t = 0, \text{ we}$$

$$\text{have } d_r^{A*} - d_r^{N*} = \frac{6(a-1)l}{(8+l)(8+al)} > 0. \text{ Thus, we can prove that } d_r^{A*} > d_r^{N*}.$$

Proof of Proposition 3

$$\pi_m^{A*} - \pi_m^{N*} = \frac{(8-3al-a^2 l^2)t^2}{4al(1-al)(8+al)} - \frac{(4+al)t}{2(8+al)} + \frac{l(a^2 l(8+l) - 4(7+2l) - a(-28+l^2))}{4(8+l)(8+al)}. \text{ It is easy to observe that}$$

$$\pi_m^{A*} - \pi_m^{N*} \text{ is a convex function with respect to } t. \text{ We get } \Delta_1 = \frac{3a(2+l)^2 + a^2 l(2+l)^2 - 4(7+2l)}{4a(8+l)(al-1)(8+al)}. \text{ There exists}$$

$$\tilde{a} = -\frac{3}{2l} + \frac{1}{2} \sqrt{\frac{36+148l+41l^2}{l^2(2+l)^2}}, \text{ such that if } 1 < a \leq \tilde{a}, \text{ then } \Delta_1 \geq 0; \text{ otherwise, } \Delta_1 < 0, \pi_m^{A*} > \pi_m^{N*}. \text{ In the case of}$$

$1 < a \leq \tilde{a}$, by solving $\pi_m^{A*} - \pi_m^{N*} = 0$, This yields two solutions for t , namely \tilde{t}_1 and \tilde{t}_2 , given by:

$$\tilde{t}_1 = \frac{al(1-al) \left(4+al-(8+al) \sqrt{\frac{3a(2+l)^2 + a^2 l(2+l)^2 - 4(7+2l)}{a(8+l)(7al+a^2 l^2 - 8)}} \right)}{8-3al-a^2 l^2} \text{ and}$$

$$\tilde{t}_2 = \frac{al(1-al) \left(4+al+(8+al) \sqrt{\frac{3a(2+l)^2 + a^2 l(2+l)^2 - 4(7+2l)}{a(8+l)(7al+a^2 l^2 - 8)}} \right)}{8-3al-a^2 l^2} > \bar{t}. \text{ In the main text, we set } t_6 = \tilde{t}_1. \text{ There exists}$$

$a_5 \in \left(1, \frac{1}{l}\right]$, For $1 < a \leq a_5$, then $t_6 \leq \bar{t}$. In this case, for $0 < t \leq t_6$, we have $\pi_m^{A*} \geq \pi_m^{N*}$; otherwise, $\pi_m^{A*} < \pi_m^{N*}$. For

$a_5 < a < \tilde{a}$ such that $t_6 > \bar{t}$, then $\pi_m^{A*} > \pi_m^{N*}$. In summary, for $1 < a \leq a_5$, if $0 < t \leq t_6$, then $\pi_m^{A*} \geq \pi_m^{N*}$; otherwise,

$\pi_m^{A*} < \pi_m^{N*}$. For $a_5 < a \leq \frac{1}{l}$, $\pi_m^{A*} > \pi_m^{N*}$.

Proof of Proposition 4

$\pi_r^{A^*} - \pi_r^{N^*} = \frac{(2+al)^2(1-al+t)^2}{(1-al)(8+al)^2} - \frac{(1-l)(2+l)^2}{(8+l)^2}$. It is easy to observe that $\pi_r^{A^*} - \pi_r^{N^*}$ is a convex function with

respect to t . We get $\Delta_2 = \frac{4(1-l)(2+l)^2(2+al)^2}{(8+l)^2(1-al)(8+al)^2} > 0$, by solving $\pi_r^{A^*} - \pi_r^{N^*} = 0$. This yields two solutions for t ,

namely \tilde{t}_3 and \tilde{t}_4 , given by: $\tilde{t}_3 = -1+al - \frac{(1-l)(2+l)(8+al)}{(8+l)(2+al)\sqrt{1-al}} < 0$, $\tilde{t}_4 = -1+al + \frac{(1-l)(2+l)(8+al)}{(8+l)(2+al)\sqrt{1-al}}$. In the

main text, we set $t_7 = \tilde{t}_2$. There exists $a_6 \in \left(1, \frac{1}{l}\right]$, for $1 < a \leq a_6$, then $t_7 \leq \bar{t}$. In this case, if $0 < t \leq t_7$, then

$\pi_r^{A^*} \leq \pi_r^{N^*}$; otherwise, $\pi_r^{A^*} > \pi_r^{N^*}$. For $a_6 < a \leq \frac{1}{l}$ such that $t_7 > \bar{t}$, $\pi_r^{A^*} < \pi_r^{N^*}$.

Proof of Proposition 5

$\pi^{A^*} - \pi^{N^*} = \frac{(2+al)^2(1-al+t)^2}{(1-al)(8+al)^2} + \frac{a^4l^4 + a^3l^3(3-2t) + a^2l^2(-6+t)t - 8t^2 + al(-4+8t+3t^2)}{4al(-1+al)(8+al)}$. It is easy to observe that $\pi^{A^*} - \pi^{N^*}$ is a convex function with respect to t . We get $\Delta_3 = 4al^2(8+l)^2(8+al)^2(9a^4(-4+l)l^3(2+l)^2 - 48(-32+l+4l^2) + a^2l(1264+436l+16l^2-15l^3) + 2a^3l^2(80-4l+2l^2+3l^3) + 4a(-320-464l+7l^2+48l^3))$. There exists

$a_7 = -\frac{3}{2l} + \frac{1}{2}\sqrt{\frac{36+148l+4l^2}{l^2(2+l)^2}}$, such that if $1 < a \leq a_7$ then $\Delta_3 \geq 0$; otherwise, $\Delta_3 < 0$, $\pi^A > \pi^N$. In the case of

$1 < a \leq a_7$, by solving $\pi^A - \pi^N = 0$. This yields two solutions for t , namely t_8 and t_9 , given by:

$t_8 = \frac{al(8+l)^2(16-20al+a^2l^2+3a^3l^3) + \sqrt{\Delta_3}}{(8+l)^2(64+5a^2l^2+3a^3l^3)}$ and $t_9 = \frac{al(8+l)^2(16-20al+a^2l^2+3a^3l^3) - \sqrt{\Delta_3}}{(8+l)^2(64+5a^2l^2+3a^3l^3)}$. In summary, for

$1 < a \leq a_7$, if $0 < t \leq t_8$, or $t_9 \leq t < \bar{t}$, then $\pi^{A^*} \geq \pi^{N^*}$; otherwise, $\pi^{A^*} < \pi^{N^*}$. For $a_7 < a \leq \frac{1}{l}$, $\pi^{A^*} > \pi^{N^*}$.