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ANALYSIS OF GOVERNMENT SUBSIDY STRATEGIES FOR BLOCKCHAIN-ENABLED GREEN SUPPLY CHAINS UNDER COMPETITION

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Abstract. This study uses game-theory to construct a dual-channel green supply chain consisting of a manufacturer, a blockchain-enabled platform, and a non-blockchain-enabled offline retailer, with the aim of comparing two government subsidy strategies: greenness investment cost subsidy and production subsidy, and exploring the impact of blockchain adoption. First, firms without government subsidy should adopt blockchain only when privacy costs are low. Both subsidy strategies can always motivate the manufacturer to increase greenness investment levels and achieve a triple-win situation. Second, when the government controls the greenness investment level, the demand, profits, and subsidy amount under cost subsidy are always lower than those under production subsidy. Third, when the government controls the subsidy amount, the greenness investment level under cost subsidy is always higher than that under production subsidy. The offline demand and retailer's profit are higher under production subsidy, while the online demand and platform's profit are higher under cost subsidy. The manufacturer's profit is higher under cost subsidy only when the subsidy level is low. Additionally, regardless of governmental goals, the platform's profit is always higher than the retailer's profit, indicating that downstream firms under government subsidy should always adopt blockchain.

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1. Introduction

1.1. Background and motivation

With the rapid growth of the platform economy, online platforms have become ubiquitous and have significantly transformed consumers' consumption patterns [38]. According to reports, JD.com, a leading Chinese online retail platform, achieved sales revenue of 461.1 billion RMB in 2018[1] and a net income of 951.6 billion RMB in 2021, reflecting a year-on-year growth rate of 27.6%. The platform boasts an active user base of 569 million, with a net increase of over 100 million users[2]. An increasing number of manufacturers are embracing both offline retailers and online platforms as sales channels. For instance, electronic device manufacturers like Apple and Huawei not only distribute their products through brick-and-mortar stores but also leverage online platforms such as JD.com and Tmall [46]. Online platforms provide consumers with the convenience of purchas-

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Keywords. Blockchain-enabled green supply chain, cost subsidy, production subsidy, competition, privacy costs.

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[1] http://it.people.com.cn/n1/2019/0228/c1009-30921229.html.

[2] https://guba.sina.com.cn/?s=thread&tid=28655&bid=28066.

ing products without limitations of time and space, empowering manufacturers to tap into a wider potential market demand. Generally, online platforms operate under two primary models: the marketplace mode and the reselling mode [39]. This study specifically focuses on the reselling mode, whereby online platforms procure products directly from manufacturers and resell them on their platforms. In practice, platforms like Amazon and JD.com predominantly operate using the reselling mode. Establishing online sales channels enables manufacturers to cater to customer demands that offline channels may not fulfill, while a combination of online and offline sales methods facilitates broader product market coverage [25].

In addition to online and offline sales, product attributes play a crucial role in determining their popularity [46]. Green development has emerged as a consensus response to environmental challenges stemming from industrialization and population growth. Concurrently, consumers' environmental consciousness has fueled an increased demand for green products [45]. To meet this preference, many manufacturers have adopted green technologies to offer eco-friendly products. For instance, Apple incorporates renewable energy sources and bio-based recycled plastics in the production of the iPhone 11 Pro[3], while Huawei reduced carbon emissions by 612 tons in 2018 through the use of recyclable and bio-based materials in its products[4]. Similarly, companies like Gree and Haier continually introduce green products. These sustainability initiatives have garnered consumer interest and boosted product sales. However, despite the growing number of manufacturers producing green products and efforts to communicate the distinctions between green and conventional products, consumers may still face uncertainty in evaluating green products due to information asymmetry, particularly on online platforms [15]. When purchasing green products, consumers consider not only the product's intrinsic value but also its environmental impact. This uncertainty in valuation, compounded by limited information, may reduce consumers' willingness to pay premiums, potentially hampering the sales of green products.

The rise of blockchain technology provides an opportunity to address this issue. Compared to traditional technologies like RFID, blockchain offers characteristics such as immutability, irreversibility, traceability, and trustworthiness as an emerging technology [45]. Consequently, blockchain can offer transparent and authentic information to both supply chain participants and consumers. Numerous platforms have developed scalable protocols utilizing blockchain technology, enabling consumers to access reliable and traceable information about product quality [38]. For instance, the online retail platform Everledger has implemented a blockchain-based system for product verification [4], while Alibaba and JD.com leverage blockchain technology to track product origins and ensure authenticity. In recent years, blockchain technology has found applications in managing green and sustainable supply chains, with companies like Ikea using blockchain to verify that their products are genuinely made from specified materials, such as wood [30]. By applying blockchain technology to the sale of green products, consumers can scan QR codes with their smartphones to obtain verifiable information, thus eliminating uncertainties in product valuation [45]. Consequently, the application of blockchain technology aids consumers in understanding the authenticity of green information, thereby increasing the likelihood of their purchasing green products.

While blockchain holds promise in enhancing information transparency, it is important to consider the associated challenges [52]. One significant concern pertains to customer's privacy when utilizing blockchain technology [9]. Blockchain solutions such as BlockVerify and Everledger often require customers to register their digital identities when accessing related functionalities, necessitating the input of personal information and potentially exposing them to privacy risks[5]. Surveys indicate that over 90.0% of consumers express concerns about online privacy, with nearly 50.0% limiting their activities due to such apprehensions[6]. Additionally, blockchain operates on a pseudonymous basis, meaning users have pseudo identities within the blockchain. If hackers manage to link these pseudo identities to consumers' real identities, it could compromise their previous purchase history [27]. Consequently, if consumers highly value their private information, the perceived benefits of blockchain

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[3] `https://www.apple.com/environment/pdf/products/iphone/iPhone_11_Pro_PER_sept2019.pdf`.

[4] `https://www.huawei.com/cn/about-huawei/sustainability/environment-protect/green_pipeline`.

[5] `https://www.provenance.org/whitepaper`.

[6] `https://www.mckinsey.com/business- functions/marketing- and- sales/our-insights/consumer-data-privacy-and-personalization-at-scale`.

may diminish. Therefore, offline retailers lacking blockchain capabilities do not necessarily face a competitive disadvantage against blockchain-enabled platforms. Similarly, platforms embracing blockchain in a competitive landscape should carefully assess the impact of consumers' privacy costs.

Moreover, green products typically entail higher costs compared to non-green products due to increased investments by manufacturers in raw material sourcing, product design, production, internal operations, and logistics [45]. This can dampen manufacturers' willingness to engage in green production. Consequently, governments have implemented various incentive policies, with fiscal subsidies being the most commonly employed approach [8]. These well-designed subsidy policies not only create profit opportunities for enterprises in the green supply chain (GSC) but also reduce the subsidy expenditure for the government [51]. For instance, the Chinese government has introduced a series of subsidies for green household appliances [20]. In this paper, fiscal subsidies for green products primarily consist of greenness investment cost subsidy and production subsidy. The greenness investment cost subsidy involves the government sharing a portion of the increased investment costs incurred by manufacturers when they invest in enhancing the green or sustainable nature of their products, and the production subsidy entails the government providing fixed subsidies to manufacturers for each unit of green product. In the GSC, online platforms competing with offline retailers may influence product pricing and green investment strategies through the adoption of blockchain, thereby impacting government subsidy strategies. Conversely, government subsidy strategies in a competitive environment may also influence blockchain adoption by downstream retail platforms. Thus, it is crucial to explore the interaction between government subsidy and blockchain adoption in a competitive environment.

1.2. Research issues and contributions

Against this backdrop, we establish a GSC model with a dual-channel structure, encompassing competition between a blockchain-enabled online platform and a non-blockchain-enabled offline retailer. Our model incorporates consumers' trust in product information and privacy costs associated with market demand. By employing the optimization theory and Stackelberg game [34, 45], we analyze optimal pricing decisions and greenness investment decisions for green products across three scenarios: no government subsidy, greenness investment cost subsidy, and production subsidy. We also examine the interplay between blockchain adoption and government subsidy strategies. This research provides a theoretical basis for governments to design green subsidy policies in the context of blockchain adoption and offers insights into the application of blockchain in competitive GSCs. The ultimate goal is to foster the green development of enterprises and promote environmental sustainability. This study addresses the following research questions:

- *Under competition, what are the effects of blockchain adoption and government subsidy strategies on green supply chains?*
- *Considering different government goals, how should supply chain members and government choose subsidy strategies?*
- *How do blockchain adoption and government subsidy strategies influence each other?*

Our work has made significant contributions to the existing studies on GSCs. First, we employ game theory to investigate the impact of blockchain adoption on GSCs from the perspective of dual-channel price competition, which distinguishes our study from previous research that focused on single-channel supply chains. Second, we incorporate factors such as product trust, privacy costs, and green investment cost coefficient within the context of GSCs involving platforms. This novel approach sets our model apart from previous research assumptions. Third, from the perspective of government green subsidy strategies, we design cost subsidy and production subsidy strategy and analyze the optimal subsidy strategy selection with blockchain adoption. This enables effective implementation of government subsidy strategies in blockchain-enabled GSCs. In a word, this is the first study to simultaneously incorporate GSC, blockchain technology, government subsidy, privacy costs, and online and offline channels competition into a Stackelberg game model.

The rest of the paper is structured as follows. In Section 2, a literature review is provided. Section 3 presents the model description. Section 4 calculates and compares the equilibrium results under the basic model and the two types of subsidy strategies. Section 5 compares the effects of subsidy strategies under different governmental goals. Finally, managerial implications and future research suggestions are offered in Section 6. All proofs are provided in Appendix B.

2. Literature review

There are three closely related research areas concerning this paper: government subsidy strategies in green supply chain, dual-channel supply chain management, and the application of blockchain in supply chain management.

2.1. Government subsidy strategies in green supply chain

Our work is related to the research on government green subsidies [24]. Sun *et al.* [34] studied the optimal green investment strategies of manufacturers and material suppliers in a two-tier supply chain to determine the impact of government subsidy policies. Meng *et al.* [26] used game theory to consider three types of green innovation subsidy scenarios and divided consumers into green and non-green categories. Li *et al.* [12] developed two green subsidy models for GSCs under quantity regulation and transaction mechanisms: one based on fixed green technology investment costs, and the other based on emission reductions. Tang *et al.* [36] investigated a GSC composed of risk-neutral manufacturers and risk-averse retailers under different government intervention structures using game theory and preference theory. Song and Wang [32] constructed a model with leading manufacturers and subsequent retailers to explore the impact mechanisms of government subsidies on GSCs under different decision scenarios. Chen *et al.* [5] considered the different objectives of maximizing government social welfare and government utility and established a model based on differential games to explore optimal green production and subsidy rates. Rong and Xu [29] analyzed the influence of manufacturers' altruistic preferences and government subsidies on transnational GSCs under dynamic tariffs using a Stackelberg game analysis framework and designing different scenarios. Long *et al.* [21] incorporated the green sensitivity of enterprises and the green preferences of consumers into a three-tier closed-loop manufacturing supply chain and constructed a Stackelberg game model with manufacturer dominance and retailer dominance under government subsidies. We find that most previous studies on government green subsidies have been conducted in traditional supply chains. This paper introduces the platform reselling channel to analyze the impact of blockchain adoption on government green subsidy strategies under online and offline channels competition.

2.2. Dual-channel supply chain management

There have been numerous studies on dual-channel supply chain management [6,51]. For instance, Tian *et al.* [40] examined the implementation of information sharing strategies in a competitive environment under different platform strategies (reselling or agency) for introducing fresh agricultural products. Liu *et al.* [18] investigated the optimal pricing strategies of manufacturers and retailers in a dual-channel supply chain with overconfident consumers. Wang *et al.* [42] studied the channel selection and logistics strategies of manufacturers, where manufacturers can sell to consumers through e-retailers *via* single/dual channels. However, the most relevant research to this paper is the study of dual-channel management that involves competition between offline and online channels. Lu *et al.* [22] and Wang *et al.* [41] explored the choice between direct selling and reselling by upstream firms to establish online sales channels based on existing physical channels. Yan *et al.* [48] studied the conditions for suppliers to introduce e-commerce agency models under the presence of offline channels in a reselling mode. Tang and Yang [35] investigated a fresh product supply chain consisting of retailers constrained by suppliers and capital, where retailers sell through both online and offline channels. Tao *et al.* [37] compared four channel structures, including a mixed structure of online and offline, in a GSC composed of a dominant manufacturer and a retailer. Some scholars have also studied government green subsidy strategies under online and offline channel competition, such as Meng *et al.* [25] and Barman *et al.* [2]. Unlike the scenarios in these studies where upstream firms act as supply chain leaders, this paper considers the case where downstream e-commerce platforms and retailers act as leaders. Additionally, this paper explores the impact of blockchain adoption on competition between blockchain-enabled online channel and non-blockchain-enabled offline channel in a dual-channel GSC, considering the adoption of blockchain by the platform to eliminate consumers' distrust in products.

2.3. Application of blockchain in supply chain management

This paper also involves research on the application of blockchain technology. In recent years, the application of blockchain technology in supply chain management has received significant attention from scholars [7,31,53]. Some scholars focused on the value of blockchain in platform supply chains, such as Wu and Yu [44] and Xu *et al.* [47]. Some scholars analyzed the value of blockchain in GSCs, such as Li *et al.* [13] and Liao [15]. Some scholars examined the value of blockchain in dual-channel supply chains, such as Ye *et al.* [49] and Liu *et al.* [19]. Some scholars investigated the impact of blockchain adoption on government subsidy strategies, such as Liao *et al.* [16] and Xu and Duan [45]. The most relevant studies are those that consider the application of blockchain technology in a dual-channel GSC with platform involvement. For example, Xu *et al.* [46] analyzed supply chain coordination issues in the context of blockchain's impact on greenness and manufacturers' product sales through both offline retailers and online platforms. Song *et al.* [33] and Li *et al.* [17] examined the application of blockchain between two e-commerce platforms in a duopoly competition in the e-commerce market. Jiang and Liu [10] studied traditional retail dual-channel, manufacturer online direct sales dual-channel, and third-party e-commerce distribution dual-channel based on consumer low-carbon sensitivity and channel preference. We find that previous research only considers the advantages or operational costs of blockchain, while overlooking the privacy costs imposed on consumers by blockchain adoption. Only Pun *et al.* [27], Zhang *et al.* [52] and Liao [15] have upon this aspect. In contrast to these studies, our research not only considers the impact of privacy costs on blockchain adoption and government subsidy strategies in a dual-channel supply chain but also analyzes the mutual influence between blockchain adoption and government green subsidies under different government goals.

2.4. Research gap

This literature review demonstrates that some scholars have explored government subsidy decisions in GSCs but without channel competition under platform involvement. Some scholars have considered GSCs with online and offline channels competition but without considering the impact of blockchain adoption. Some scholars have examined the positive impact of blockchain adoption on dual-channel GSCs but have not taken into account the privacy costs imposed on consumers by blockchain adoption. To the best of our knowledge, no scholars have investigated the mutual influence between government subsidy strategies under channel competition and blockchain adoption in GSCs. Therefore, this paper aims to address this issue and fill the gap in existing research. Additionally, we consider the impact of blockchain adoption on government subsidy strategies under two different government goals. This is also one of our contributions. In conclusion, this study is the first to simultaneously incorporate green products, blockchain technology, government subsidy, privacy costs, and online and offline channels competition into a Stackelberg game model. Table 1 summarizes the research gap and further highlight our contributions.

3. Model description

This study considers a dual-channel green supply chain consisting of a manufacturer, an online platform, and an offline retailer. The manufacturer supplies green products with greenness investment level g to the retailer and the platform at offline wholesale price w_1 and online wholesale price w_2, respectively. Then, the retailer sells the green products to consumers at a retail price p_1 through the offline channel, while the platform resells the green products to consumers at a retail price p_2 through the online channel, with $p_1 > w_1 > 0$ and $p_2 > w_2 > 0$.

Assuming that consumers are heterogeneous and their valuation of the product, represented by v, follows a uniform distribution within the interval $[0, 1]$, the net utility of a consumer purchasing a product is limited to one per consumer based on their individual preferences [43, 52]. Additionally, we assume that consumers

Table 1. Comparisons of our paper and the related literature.

Researches	GSC	Dual-channel supply chain	Blockchain adoption	Government subsidy	Privacy costs
Li *et al.* [12]	✓			✓	
Xu *et al.* [46]	✓	✓	✓		
Meng *et al.* [25]	✓	✓		✓	
Pun *et al.* [27]			✓	✓	✓
Tao *et al.* [37]	✓	✓			
Li *et al.* [13]	✓		✓		
Tang *et al.* [36]	✓			✓	
Ye *et al.* [49]		✓	✓		
Liu *et al.* [19]		✓	✓		
Liao *et al.* [16]			✓	✓	
Jiang and Liu [10]	✓	✓	✓		
Xu and Duan [45]	✓		✓	✓	
Zhang *et al.* [52]		✓	✓		✓
Barman *et al.* [1]	✓	✓		✓	
Liao [15]	✓		✓		✓
Zhang *et al.* [53]		✓	✓		
Lu *et al.* [23]		✓	✓		
Liu [17]				✓	
Choi and Lowry [3]				✓	✓
Arora and Jain [1]					✓
This study	✓	✓	✓	✓	✓

are environmentally conscious, and the product's greenness may increase their willingness to pay and demand [21, 32]. However, due to limited or unreliable information, consumers may be uncertain about the initial value and greenness of the product, which can affect their purchase utility [45]. Thus, the net utility of a consumer purchasing a product from the non-blockchain-enabled retailer is $U_1 = \theta(v + \delta g) - p_1$, where θ represents the consumers' trust in the product, $0 < \theta < 1$, and δ is consumers' greenness sensitivity, $0 < \delta \leq 1$.

To mitigate the impact of information asymmetry on consumer perception and increase their trust in products, many platform companies have adopted blockchain technology to trace product information and eliminate mistrust [43]. Although blockchain technology can ensure the authenticity and reliability of information, it may also pose privacy and security risks to individual consumers [15, 27]. Trust, usefulness, and risk are often critical factors to consider [38]. Therefore, we define η as the privacy costs borne by consumers due to the adoption of blockchain technology. Consequently, the net utility of a consumer purchasing a product from the blockchain-enabled platform can be expressed as $U_2 = v + \delta g - p_2 - \eta$.

Consumers determine their preferred purchasing channel by comparing the utility gained from buying products through different channels [38]. The necessary conditions for consumers to buy a green product are $U_1 > 0$ and $U_2 > 0$. If $v > v_1^* = \frac{p_1 - \theta\delta g}{\theta}$, consumers will purchase a green product without blockchain, while if $v > v_2^* = p_2 + \eta - \delta g$, they will purchase a green product with blockchain. Consequently, consumers will choose the product that provides higher utility. If $U_1 = U_2$, we obtain $v^* = \frac{p_2 - p_1 - (1-\theta)\delta g + \eta}{1-\theta}$. Thus, consumers will opt for a green product with blockchain if $v \geq v^*$ and a green product without blockchain if $v_1^* \leq v < v^*$. This implies that the offline demand for products without blockchain is $D_1 = \frac{p_2 - p_1 - (1-\theta)\delta g + \eta}{1-\theta} - \frac{p_1 - \theta\delta g}{\theta}$, while the online demand for products with blockchain is $D_2 = 1 - \frac{p_2 - p_1 - (1-\theta)\delta g + \eta}{1-\theta}$.

In practice, the government may incentivize manufacturers to invest more in green products through various subsidy strategies [12, 34]. Referring to Meng *et al.* [25] and Liu *et al.* [20], this study focuses on two common approaches: the cost subsidy strategy for green investment and the subsidy strategy for each unit of green product produced. Three GSC models are developed based on these strategies: Model-N without government subsidy, Model-C with a cost subsidy strategy, and Model-Q with a production subsidy strategy. Additionally,

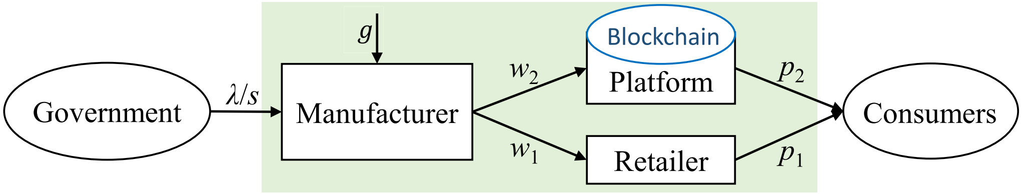


Figure 1. Dual-channel green supply chain structure.

Table 2. Notations and descriptions.

Notations	Descriptions
w_1/w_2	Wholesale price of offline/online channel (decision variable)
p_1/p_2	Retail price of offline/online channel (decision variable)
g	The manufacturer's greenness investment level (decision variable)
θ	Consumer's trust in green products, $0 < \theta < 1$
δ	The consumers' greenness sensitivity, $0 < \delta \leq 1$
v	Consumer's valuation of the product, it follows uniform distribution in $[0, 1]$
η	Consumer's privacy costs caused by the application of blockchain
k	The greenness investment cost coefficient, $k > 0$
λ	Cost subsidy level under the government's cost subsidy strategy
s	Production subsidy level under the government's production subsidy strategy
U_1/U_2	The consumers' utility function of offline/online channel
D_1/D_2	The demand function of offline/online channel
$\Pi_M/\Pi_R/\Pi_T$	Profit function of the manufacturer/offline retailer/platform
Π_G	The government subsidy amount

large retailers or platforms, such as Amazon, JD.com, and Walmart, may have greater influence than upstream manufacturers [45]. The manufacturer has already invested in green research and development before making pricing decisions. Therefore, following [34, 45], a Stackelberg game is considered, where the retailer and the platform dominate. The sequence of events is as follows: first, the government decides on which subsidy strategy to provide to the manufacturer; then, the manufacturer decides on the greenness investment level g; next, the retailer and the platform determine the retail prices (p_1, p_2) of the product; finally, the manufacturer decides on the wholesale prices (w_1, w_2). The supply chain structure is illustrated in Figure 1.

To provide green products to consumers, the manufacturer bears the total greenness investment cost $\frac{1}{2}kg^2$, where k is the greenness investment cost coefficient [1,11,46]. Without loss of generality, we assume that the unit production cost and the application cost of blockchain technology are zero, as is common in previous studies [15,38]. Meanwhile, in order for the model to be valid and for equilibrium results to be meaningful, we assume that the consumers' privacy costs are not infinitely large, *i.e.*, the condition $0 < \eta < \frac{4k(4-\theta)(1-\theta)}{2k(4-\theta)(2-\theta)-3\theta\delta^2}$ is met. Table 2 summarizes the key parameters and decision variables of our models.

4. Model analysis

This section analyzes the optimal decisions, demand, and profits of the GSC under different models. Then, by comparing the model without government subsidy, the government cost subsidy model, and the government production subsidy model, the optimal green subsidy strategy for supply chain members is determined, as well as the impact of these two subsidy strategies on the decisions of the blockchain-enabled dual-channel supply chain.

4.1. Model-N

Under Model-N, the government does not adopt any subsidy strategy. The profit functions of the manufacturer, retailer, and platform are, respectively:

$$\Pi_M^N = w_1^N D_1^N + w_2^N D_2^N - \frac{1}{2}k\left(g^N\right)^2, \tag{1}$$

$$\Pi_R^N = \left(p_1^N - w_1^N\right)D_1^N, \tag{2}$$

$$\Pi_T^N = \left(p_2^N - w_2^N\right)D_2^N. \tag{3}$$

Using the backward method to solve equations (1)–(3), we can obtain the following lemma.

Lemma 1. *Under the Model-N, if $k > \frac{(4+5\theta)\delta^2}{2(4-\theta)^2}$, the equilibrium results are*

$$g^{N^*} = \frac{(4+5\theta)\delta - (4+\theta)\eta\delta}{2k(4-\theta)^2 - (4+5\theta)\delta^2}, \quad w_1^{N^*} = \frac{k\theta(4-\theta)(3-\eta) - \theta\eta\delta^2}{2k(4-\theta)^2 - (4+5\theta)\delta^2}, \quad w_2^{N^*} = \frac{2k(4-\theta)(2+\theta-2\eta) + \theta\eta\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$p_1^{N^*} = \frac{k\theta(4-\theta)(5-2\theta+\eta) - \theta(3+\theta)\eta\delta^2}{2k(4-\theta)^2 - (4+5\theta)\delta^2}, \quad p_2^{N^*} = \frac{2k(4-\theta)[3(2-\theta) - 2(3-\theta)\eta] + 7\theta\eta\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]}.$$

From Lemma 1, the optimal demand and profits are, respectively:

$$D_1^{N^*} = \frac{2k(4-\theta)(1-\theta+\eta) - (2+\theta)\eta\delta^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]}, \quad D_2^{N^*} = \frac{2k(4-\theta)[2(1-\theta) - (2-\theta)\eta] + 3\theta\eta\delta^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$\Pi_R^{N^*} = \frac{\theta[2k(4-\theta)(1-\theta+\eta) - (2+\theta)\eta\delta^2]^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2},$$

$$\Pi_M^{N^*} = w_1^{N^*} D_1^{N^*} + w_2^{N^*} D_2^{N^*} - \frac{1}{2}k(g^{N^*})^2, \quad \Pi_T^{N^*} = \frac{[2k(4-\theta)(2(1-\theta) - (2-\theta)\eta) + 3\theta\eta\delta^2]^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2}.$$

Corollary 1. (1) $w_2^{N^*} > w_1^{N^*}$.

(2) *If* $0 < \eta < \frac{4k(4-\theta)(3-\theta)(1-\theta)}{2k(4-\theta)(6-\theta)-(13+2\theta)\theta\delta^2}$, $p_2^{N^*} > p_1^{N^*}$, *otherwise* $p_2^{N^*} \leq p_1^{N^*}$.

(3) *If* $0 < \eta < \frac{k(4-\theta)(1-\theta)}{k(4-\theta)(3-\theta)-(1+2\theta)\delta^2}$, $D_2^{N^*} > D_1^{N^*}$, *otherwise* $D_2^{N^*} \leq D_1^{N^*}$.

(4) *If* $0 < \eta < \frac{2k(4-\theta)(1-\theta)(2-\sqrt{\theta})}{2k(4-\theta)(2-\theta+\sqrt{\theta})-[(2+\theta)\sqrt{\theta}+3\theta]\delta^2}$, $\Pi_T^{N^*} > \Pi_R^{N^*}$, *otherwise* $\Pi_T^{N^*} \leq \Pi_R^{N^*}$.

Corollary 1 compares prices, demand, and profits of channels with and without blockchain. We find that after adopting blockchain, the wholesale price will always increase, while the retail price, demand, and profit will only increase when consumers' privacy costs are low. This suggests that competition among downstream enterprises is affected by privacy costs, and only when privacy costs are low should enterprises adopt blockchain, at which point consumers will pay a high price for the benefits brought by blockchain.

Corollary 2. (1) $\frac{\partial g^{N^*}}{\partial \eta} < 0$.

(2) $\frac{\partial w_2^{N^*}}{\partial \eta} < 0$, $\frac{\partial p_2^{N^*}}{\partial \eta} < 0$, $\frac{\partial D_2^{N^*}}{\partial \eta} < 0$, $\frac{\partial \Pi_T^{N^*}}{\partial \eta} < 0$.

(3) $\frac{\partial w_1^{N^*}}{\partial \eta} < 0$. *If* $k > \frac{(3+\theta)\delta^2}{4-\theta}$, $\frac{\partial p_1^{N^*}}{\partial \eta} > 0$, *otherwise* $\frac{\partial p_1^{N^*}}{\partial \eta} \leq 0$. *If* $k > \frac{(2+\theta)\delta^2}{2(4-\theta)}$, $\frac{\partial D_1^{N^*}}{\partial \eta} > 0$ *and* $\frac{\partial \Pi_R^{N^*}}{\partial \eta} > 0$, *otherwise* $\frac{\partial D_1^{N^*}}{\partial \eta} \leq 0$ *and* $\frac{\partial \Pi_R^{N^*}}{\partial \eta} \leq 0$.

Corollary 2 indicates that higher privacy costs for consumers lead to lower prices, demand, profits, and greenness investment levels in the online channel. This is because high privacy costs resulting from blockchain adoption make it less likely for the platform to implement blockchain. Without blockchain, the value of greenness for consumers is low, which reduces the manufacturer's enthusiasm for green investment. To encourage downstream enterprises to increase product orders, the manufacturer will reduce wholesale prices, including both online and offline. The effect of privacy costs on the retail price, demand, and profit of the offline channel is influenced by the greenness investment cost coefficient k. Specifically, when k is large, the retail price, demand, and profit of the retailer all increase with increasing privacy costs. This is because both a large k value and privacy costs result in a significant decrease in greenness, reducing the effectiveness of blockchain adoption. The reduction in the platform's competitiveness allows the retailer to increase offline retail price while maintaining high demand to gain more profits. Conversely, when k is small, the retail price, demand, and profit of the retailer all decrease with increasing privacy costs.

4.2. Model-*C*

Under Model-C, the government provides a subsidy for the manufacturer's greenness investment costs [45], and the cost subsidy level is λ. The profit functions of the retailer and the platform are the same as in equations (2) and (3), while the manufacturer's profit function and the government subsidy amount are, respectively:

$$\Pi_M^C = w_1^C D_1^C + w_2^C D_2^C - \frac{1}{2}(1-\lambda)k\big(g^C\big)^2, \tag{4}$$

$$\Pi_G^C = \frac{1}{2}\lambda k (g^C)^2. \tag{5}$$

Similarly, we can obtain the following lemma by using the backward method.

Lemma 2. *Under the Model-C, if* $k > \frac{(4+5\theta)\delta^2}{2(1-\lambda)(4-\theta)^2}$, *the equilibrium results are*

$$g^{C*} = \frac{(4+5\theta)\delta - (4+\theta)\eta\delta}{2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2}, \quad w_1^{C*} = \frac{k\theta(1-\lambda)(4-\theta)(3-\eta) - \theta\eta\delta^2}{2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2},$$

$$w_2^{C*} = \frac{2k(1-\lambda)(4-\theta)(2+\theta-2\eta) + \theta\eta\delta^2}{2[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]}, \quad p_1^{C*} = \frac{k\theta(1-\lambda)(4-\theta)(5-2\theta+\eta) - \theta(3+\theta)\eta\delta^2}{2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2},$$

$$p_2^{C*} = \frac{2k(1-\lambda)(4-\theta)[3(2-\theta) - 2(3-\theta)\eta] + 7\theta\eta\delta^2}{2[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]}.$$

According to Lemma 2, the optimal demand, profits and government subsidy amount are, respectively:

$$D_1^{C*} = \frac{2k(1-\lambda)(4-\theta)(1-\theta+\eta) - (2+\theta)\eta\delta^2}{2(1-\theta)[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]}, \quad D_2^{C*} = \frac{2k(1-\lambda)(4-\theta)[2(1-\theta) - (2-\theta)\eta] + 3\theta\eta\delta^2}{2(1-\theta)[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$\Pi_M^{C*} = w_1^{C*}D_1^{C*} + w_2^{C*}D_2^{C*} - \frac{1}{2}k(1-\lambda)(g^{C*})^2, \quad \Pi_R^{C*} = \frac{\theta[2k(1-\lambda)(4-\theta)(1-\theta+\eta) - (2+\theta)\eta\delta^2]^2}{2(1-\theta)[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]^2},$$

$$\Pi_T^{C*} = \frac{[2k(1-\lambda)(4-\theta)(2(1-\theta) - (2-\theta)\eta) + 3\theta\eta\delta^2]^2}{2(1-\theta)[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]^2}, \quad \Pi_G^{C*} = \frac{\lambda k[(4+5\theta)\delta - (4+\theta)\eta\delta]^2}{2[2k(1-\lambda)(4-\theta)^2 - (4+5\theta)\delta^2]^2 0}.$$

Proposition 1. *Comparing the equilibrium results and demand of Model-C and Model-N, there are:* $g^{C*} > g^{N^*}$, $w_1^{C*} > w_1^{N^*}$, $w_2^{C*} > w_2^{N^*}$, $p_1^{C*} > p_1^{N^*}$, $p_2^{C*} > p_2^{N^*}$, $D_1^{C*} > D_1^{N^*}$, $D_2^{C*} > D_2^{N^*}$.

Proposition 1 shows that the government's cost subsidy strategy can always incentivize the manufacturer to improve greenness investment level, which will increase demand for both online and offline channels. Meanwhile, the manufacturer will raise wholesale prices to gain more profits. Correspondingly, the platform and the retailer will also raise retail prices.

Proposition 2. *Comparing the profits of Model-C and Model-N, there are:*

(1) $\Pi_R^{C*} > \Pi_R^{N^*}$, $\Pi_T^{C*} >_T^{N^*}$.

(2) *If* $\lambda_1 < \lambda < 1$, $\Pi_R^{C*} - \Pi_R^{N^*} > \Pi_T^{C*} - \Pi_T^{N^*}$, *otherwise* $\Pi_R^{C*} - \Pi_R^{N^*} \leq \Pi_T^{C*} - \Pi_T^{N^*}$, *where* $\lambda_1 = 1 - \frac{\delta^2\{k(4-\theta)(4+5\theta)[3(1-\theta)-(5-2\theta)\eta]-(2+7\theta)\eta[k(4-\theta)^2-(4+5\theta)\delta^2]\}}{k(4-\theta)\{(4-\theta)(2+7\theta)\eta\delta^2+[4k(4-\theta)^2-(4+5\theta)\delta^2][3(1-\theta)-(5-2\theta)\eta]\}}$.

Proposition 2 demonstrates that the government's cost subsidy strategy can increase profits for both the platform and the retailer, due to the simultaneous increase in retail price and demand. Moreover, we observe that when the cost subsidy level is high, this strategy is more advantageous for the retailer than for the platform. In other words, when the cost subsidy level is high, retailers without blockchain adoption are more likely to prefer the government's cost subsidy strategy over platforms with blockchain adoption.

4.3. Model-*Q*

Under Model-Q, the government provides a subsidy for the manufacturer's production of each unit of green product [25], and the production subsidy level is s. The profit functions of the retailer and the platform are the same as in equations (2) and (3), while the manufacturer's profit function and the government subsidy amount are, respectively:

$$\Pi_M^Q = \left(w_1^Q + s\right)D_1^Q + \left(w_2^Q + s\right)D_2^Q - \frac{1}{2}k\left(g^Q\right)^2, \tag{6}$$

$$\Pi_G^Q = s\left(D_1^Q + D_2^Q\right). \tag{7}$$

We can obtain the following lemma by using the backward method.

Lemma 3. *Under Model-Q, if* $k > \frac{(4+5\theta)\delta^2}{2(4-\theta)^2}$, *the equilibrium results are*

$$g^{Q^*} = \frac{(4+5\theta)\delta + (8+\theta)s\delta - (4+\theta)\eta\delta}{2k(4-\theta)^2 - (4+5\theta)\delta^2}, \quad w_1^{Q^*} = \frac{k(4-\theta)[3\theta - 3s(2-\theta) - \theta\eta] + [3s(1+2\theta) - \theta\eta]\delta^2}{2k(4-\theta)^2 - (4+5\theta)\delta^2},$$

$$w_2^{Q^*} = \frac{2k(4-\theta)[2+\theta - s(5-2\theta) - 2\eta] + [9s(1+\theta) + \theta\eta]\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$p_1^{Q^*} = \frac{k(4-\theta)[\theta(5-2\theta) - s(2+\theta) + \theta\eta] - [\theta(3+\theta)\eta - s(1+7\theta+\theta^2)]\delta^2}{2k(4-\theta)^2 - (4+5\theta)\delta^2},$$

$$p_2^{Q^*} = \frac{2k(4-\theta)[3(2-\theta) - 3s - 2(3-\theta)\eta] + [7\theta\eta + 3s(5+\theta)]\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]}.$$

According to Lemma 3, the optimal demand, profits and government subsidy amount are, respectively:

$$D_1^{Q^*} = \frac{2k(4-\theta)[(\theta+2s)(1-\theta) + \theta\eta] - (2+\theta)[s(1-\theta) + \theta\eta]\delta^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$D_2^{Q^*} = \frac{2k(4-\theta)[(2+s)(1-\theta) - (2-\theta)\eta] + 3[s(1-\theta) + \theta\eta]\delta^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]},$$

$$\Pi_M^{Q^*} = (w_1^{Q^*} + s)D_1^{Q^*} + (w_2^{Q^*} + s)D_2^{Q^*} - \frac{1}{2}k(g^{Q^*})^2,$$

$$\Pi_R^{Q^*} = \frac{[2k(4-\theta)((\theta+2s)(1-\theta) + \theta\eta) - (2+\theta)(s(1-\theta) + \theta\eta)\delta^2]^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2},$$

$$\Pi_T^{Q^*} = \frac{[2k(4-\theta)((2+s)(1-\theta) - (2-\theta)\eta) + 3(s(1-\theta) + \theta\eta)\delta^2]^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2},$$

$$\Pi_G^{Q^*} = \frac{ks(4-\theta)[3\theta + s(2+\theta) - \theta\eta] - s[s(1-\theta) + \theta\eta]\delta^2}{\theta[2k(4-\theta)^2 - (4+5\theta)\delta^2]}.$$

Corollary 3. (1) $\frac{\partial g^{Q^*}}{\partial s} > 0$.

(2) $\frac{\partial D_1^{Q^*}}{\partial s} > 0$, $\frac{\partial D_2^{Q^*}}{\partial s} > 0$.

(3) $\frac{\partial \Pi_R^{Q^*}}{\partial s} > 0$, $\frac{\partial \Pi_T^{Q^*}}{\partial s} > 0$, $\frac{\partial \Pi_G^{Q^*}}{\partial s} > 0$.

(4) *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+2\theta)\delta^2}{(2-\theta)(4-\theta)}$, $\frac{\partial w_1^{Q^*}}{\partial s} > 0$, *otherwise* $\frac{\partial w_1^{Q^*}}{\partial s} \leq 0$. *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{9(1+\theta)\delta^2}{2(4-\theta)(5-2\theta)}$, $\frac{\partial w_2^{Q^*}}{\partial s} > 0$, *otherwise* $\frac{\partial w_2^{Q^*}}{\partial s} \leq 0$.

(5) *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+7\theta+\theta^2)\delta^2}{(2+\theta)(4-\theta)}$, $\frac{\partial p_1^{Q^*}}{\partial s} > 0$, *otherwise* $\frac{\partial p_1^{Q^*}}{\partial s} \leq 0$. *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(5+\theta)\delta^2}{2(4-\theta)}$, $\frac{\partial p_2^{Q^*}}{\partial s} > 0$, *otherwise* $\frac{\partial p_2^{Q^*}}{\partial s} \leq 0$.

Corollary 3 indicates that the greenness investment level, market demand, and the profits of the platform and the retailer will increase with increasing production subsidy level s, while changes in prices are influenced by the greenness investment cost coefficient k. Specifically, only when k is low, both online and offline wholesale and retail prices will increase with increasing production subsidy level. This is because when k is low, the manufacturer will increase greenness investment, which will result in more demand from downstream enterprises. To gain more profits, the manufacturer will raise wholesale prices, and correspondingly, downstream enterprises will raise retail prices. However, when k is high, the manufacturer will decrease greenness investment, leading to a decrease in demand. In order to encourage downstream enterprises to reduce retail prices and increase product orders, the manufacturer will transfer the government subsidy amount to downstream enterprises by reducing wholesale prices.

Proposition 3. *Comparing the equilibrium results and demand of Model-Q and Model-N, there are:*

(1) $g^{Q^*} > g^{N^*}$, $D_1^{Q^*} > D_1^{N^*}$, $D_2^{Q^*} > D_2^{N^*}$.

(2) *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+2\theta)\delta^2}{(2-\theta)(4-\theta)}$, $w_1^{Q^*} > w_1^{N^*}$, *otherwise* $w_1^{Q^*} \leq w_1^{N^*}$. *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{9(1+\theta)\delta^2}{2(4-\theta)(5-2\theta)}$, $w_2^{Q^*} > w_2^{N^*}$, *otherwise* $w_2^{Q^*} \leq w_2^{N^*}$.

(3) *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+7\theta+\theta^2)\delta^2}{(2+\theta)(4-\theta)}$, $p_1^{Q^*} > p_1^{N^*}$, *otherwise* $p_1^{Q^*} \leq p_1^{N^*}$. *If* $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(5+\theta)\delta^2}{2(4-\theta)}$, $p_2^{Q^*} > p_2^{N^*}$, *otherwise* $p_2^{Q^*} \leq p_2^{N^*}$.

Proposition 3 indicates that the government's production subsidy strategy can always incentivize the manufacturer to improve the greenness investment level, which will increase market demand. This is similar to Proposition 1. However, the impact of the production subsidy strategy on product prices is not fixed and depends on the greenness investment cost coefficient k. Specifically, only when k is low, the production subsidy strategy will increase both online and offline wholesale and retail prices for both channels, corresponding to Corollary 3.

Proposition 4. *Comparing the profits of Model-Q and Model-N, there are:* $\Pi_R^{Q^*} > \Pi_R^{N^*}$, $\Pi_T^{Q^*} > \Pi_T^{N^*}$.

Proposition 4 demonstrates that the government's production subsidy strategy can increase the profits of the platform and the retailer. Although retail prices may decrease, the reduction in wholesale prices may lead to an increase in marginal profits for the platform and the retailer, while demand always increases. Therefore, the final profits for the platform and the retailer will increase.

Proposition 5. *Comparing the greenness investment levels of Model-C and Model-Q, if* $\eta > \eta_1$, $g^{Q^*} > g^{C*}$, *otherwise* $g^{Q^*} \leq g^{C*}$, *where* $\eta_1 = \frac{4+5\theta}{4+\theta} - \frac{s(8+\theta)\left[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2\right]}{2\lambda k(4+\theta)(4-\theta)^2}$.

Proposition 5 compares the greenness investment levels under the government's cost subsidy strategy and production subsidy strategy, which are related to consumers' privacy costs η. We find that when privacy costs are high, the greenness investment level under the production subsidy strategy is higher than that under the cost subsidy strategy. This is because when privacy costs are high, demand decreases. The manufacturer needs to increase greenness investment to boost demand. The increase in demand results in more funds received by the manufacturer from the production subsidy, making him more willing to increase greenness investment. This ultimately leads to a higher greenness investment level under the production subsidy strategy compared to the cost subsidy strategy. This further indicates that when consumers are more concerned about their privacy, the government should adopt the production subsidy strategy to achieve higher greenness investment level and protect the environment.

Proposition 6. *Comparing the pricing of Model-C and Model-Q, there are:* $w_1^{Q^*} < w_1^{C*}$, $w_2^{Q^*} < w_2^{C*}$, $p_1^{Q^*} < p_1^{C*}$, $p_2^{Q^*} < p_2^{C*}$.

Proposition 6 compares the wholesale and retail prices under the government's cost subsidy strategy and production subsidy strategy. We find that both the wholesale and retail prices under the production subsidy strategy are always lower than those under the cost subsidy strategy. This is because the improvement in greenness investment level allows supply chain members to offset the high greenness investment costs and gain more profits by increasing prices.

Proposition 7. *Comparing the demand of Model-C and Model-Q, there are:*

(1) $D_1^{Q^*} > D_1^{C*}$ *if and only if* $\eta > \eta_2$, *where* $\eta_2 = \frac{4+5\theta}{4+\theta} - \frac{s\left[4k(4-\theta)-(2+\theta)\delta^2\right]\left[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2\right]}{2\lambda k\theta\delta^2(4-\theta)(4+\theta)}$.
(2) $D_2^{Q^*} > D_2^{C*}$ *if and only if* $\eta > \eta_3$, *where* $\eta_3 = \frac{4+5\theta}{4+\theta} - \frac{s\left[2k(4-\theta)+3\delta^2\right]\left[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2\right]}{4\lambda k\delta^2(4-\theta)(4+\theta)}$.

Proposition 7 compares the demand under the government's cost subsidy strategy and production subsidy strategy, which are related to consumers' privacy costs η. We find that when privacy costs are high, the demand under the production subsidy strategy is higher than that under the cost subsidy strategy. This is because the positive effects brought by the improvement in greenness investment level are greater than the negative effects caused by the increase in retail prices, ultimately leading to an increase in online and offline demand.

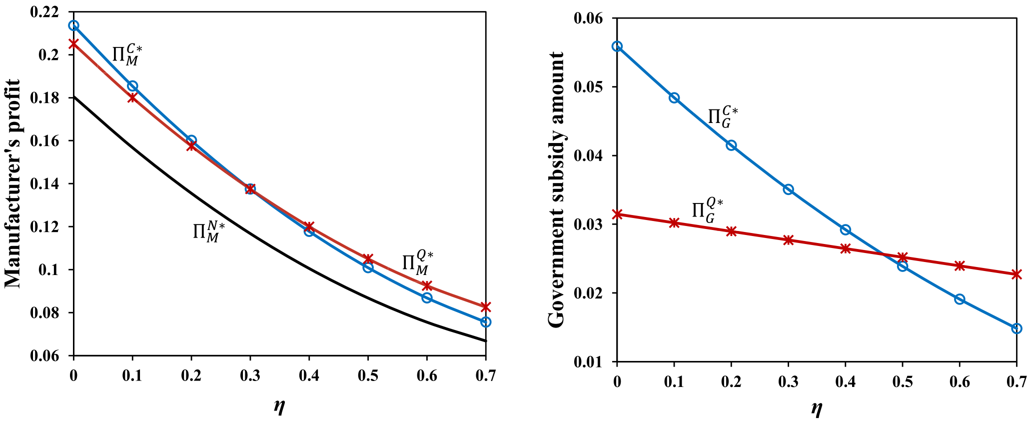
Proposition 8. *Comparing the profits of Model-C and Model-Q, there are:*

(1) *If* $\eta > \eta_2$, $\Pi_R^{Q^*} > \Pi_R^{C*}$, *otherwise* $\Pi_R^{Q^*} \le \Pi_R^{C*}$.
(2) *If* $\eta > \eta_3$, $\Pi_T^{Q^*} > \Pi_T^{C*}$, *otherwise* $\Pi_T^{Q^*} \le \Pi_T^{C*}$.

Proposition 8 compares the optimal profits under the government's cost subsidy strategy and production subsidy strategy, which are related to consumers' privacy costs η. We find that when privacy costs are high, the profits of the platform and the retailer under the production subsidy strategy are higher than those under the cost subsidy strategy. This is mainly due to the increase in market demand. This further indicates that downstream enterprises, whether blockchain-enabled online channel or non-blockchain-based offline channel, will prefer the government to adopt the production subsidy strategy when consumers are more concerned about their privacy. Conversely, when the privacy costs brought by blockchain application are low, downstream enterprises prefer the cost subsidy strategy.

As comparing the manufacturer's profits and the government subsidy amounts under different models is complex, we will use numerical examples to observe their size relationships. Referring to Xu and Duan [45] and Liao [15], we set $\theta = 0.5$, $k = 1$, $\delta = 1$, $\lambda = 0.3$, and $s = 0.05$.

From Figure 2a, we find that both the government's cost subsidy strategy and production subsidy strategy are beneficial to the manufacturer, and when consumers' privacy costs η are high, the production subsidy strategy is most favorable to the manufacturer. Combining Propositions 1–4, regardless of which subsidy strategy the government adopts, consumers can purchase greener products, while the manufacturer, platform, and retailer can all gain more profits, which is not affected by blockchain adoption. In addition, when privacy costs are high, the manufacturer, platform, and retailer will all choose the production subsidy strategy. Conversely, when privacy costs are low, they will all choose the cost subsidy strategy.



(a) (b)

Figure 2. Comparison of the manufacturer's profit and government subsidy amount. (a) Manufacturer's profit. (b) Government subsidy amount.

From Figure 2b, we find that when privacy costs are high, the government subsidy amount under the production subsidy strategy is higher, while when privacy costs are low, the government subsidy amount under the cost subsidy strategy is higher. Additionally, as the privacy costs caused by blockchain application increase, the manufacturer's profit decrease, and the government subsidy amount under two strategies also decrease, with the profit and subsidy amounts under the cost subsidy strategy being most affected. In summary, both the government and supply chain enterprises need to pay attention to the privacy costs brought by blockchain application when implementing blockchain in a GSC, as this will change traditional green subsidy schemes.

5. Comparison of subsidy strategies under different governmental goals

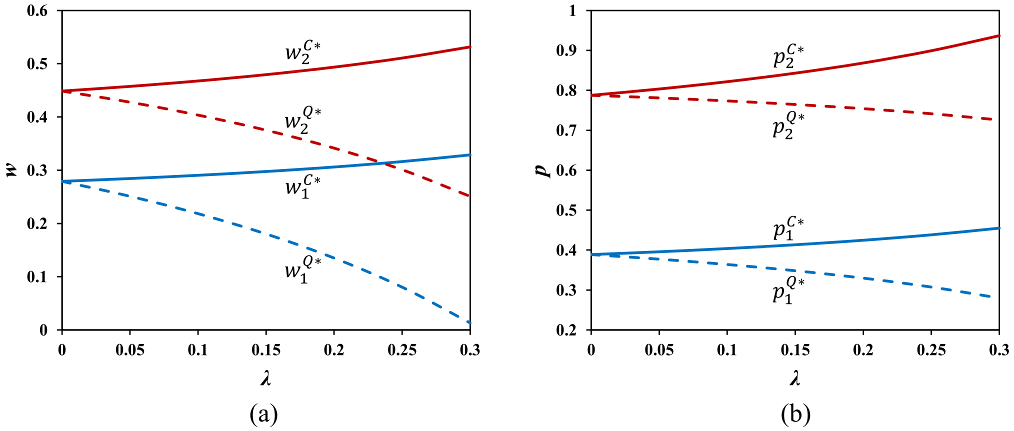
In practical applications, the government often sets targets for green subsidies or limits the amount of subsidies provided [2]. Specifically, the government focuses on two issues: First, using different subsidy strategies to achieve the same level of greenness investment; Second, providing the same subsidy amount to supply chain enterprises under different subsidy strategies. Therefore, we will analyze the effects of the government's cost subsidy strategy and production subsidy strategy on supply chain decisions under different governmental goals.

5.1. Controlling greenness investment level

In this section, we compare the prices, demand, profits, and government subsidy amount under two subsidy strategies in the context of the same greenness investment level to determine the optimal subsidy strategy.

Proposition 9. *When the greenness investment levels under two subsidy strategies are the same, i.e.,* $g^{Q^*} = g^{C*}$*, the subsidy levels satisfy the relationship:* $s_g(\lambda) = \frac{2\lambda k(4-\theta)^2[4+5\theta-(4+\theta)\eta]}{(8+\theta)[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]}$.

According to Proposition 9, when the government's subsidy level satisfies a certain relationship, the greenness investment levels under the government's cost subsidy strategy and production subsidy strategy are the same, indicating the government's focus on greenness investment level. We find that when the greenness investment level is the same, there exists a one-to-one correspondence between the subsidy levels of the two subsidy strategies. Additionally, the production subsidy level increases with the cost subsidy level, while decreasing with the privacy costs.



(a) (b)

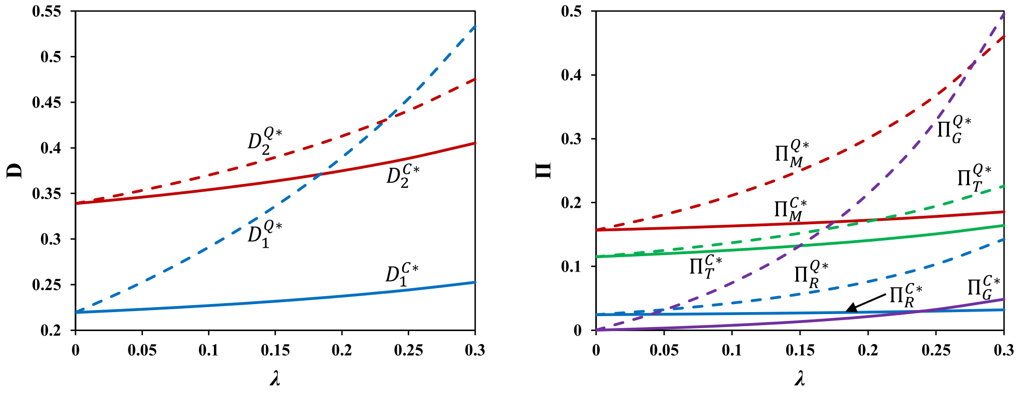
Figure 3. Comparison of pricing with controlling greenness investment level. (a) Wholesale price. (b) Retail price.

Next, we will explore the changes and size relationships in prices, demand, and profits under the two subsidy strategies when the greenness investment level is the same. Except for $\eta = 0.1$, the parameter settings are consistent with Figure 2.

Figure 3 shows that as the subsidy level λ increases, the wholesale and retail prices under the government's cost subsidy strategy increase, while those under the production subsidy strategy decrease. Additionally, the wholesale and retail prices under the cost subsidy strategy are always higher than those under the production subsidy strategy. Therefore, although consumers purchase products with the same greenness investment level, they can only buy affordable products under the production subsidy strategy. From this perspective, the government's production subsidy strategy is more beneficial to consumers. In addition, we find that whether under the cost subsidy strategy or the production subsidy strategy, both the wholesale and retail prices of blockchain-based online channel are higher than those of non-blockchain-based offline channel. This is mainly because when the greenness investment level reaches a certain value, the positive effects of blockchain application outweigh its negative effects, and supply chain enterprises raise prices to gain more profits.

Figure 4 shows that as the subsidy level λ increases, the demand, profits, and government subsidy amount under two subsidy strategies increase. Specifically, Figure 4a shows that the demand under the government's cost subsidy strategy is always lower than that under the production subsidy strategy, and this demand gap is more pronounced in non-blockchain-based offline channel. Additionally, under the cost subsidy strategy, the demand of blockchain-based online channel is higher than that of non-blockchain-based offline channel, while under the production subsidy strategy, this only holds true when the subsidy level is low. Therefore, to achieve higher demand, the platform should always adopt blockchain technology under the government's cost subsidy strategy, while under the production subsidy strategy, the platform should only adopt blockchain technology when the subsidy level is low.

Figure 4b shows that the profits and government subsidy amount under the government's cost subsidy strategy are always lower than those under the production subsidy strategy, and this gap increases with the subsidy level λ. Therefore, both the manufacturer and the platform/retailer prefer the government to adopt the production subsidy strategy. In order to ensure that the greenness investment level under the production subsidy strategy is the same as that under the cost subsidy strategy, the government should increase the subsidy level under the production subsidy strategy. From this perspective, the cost subsidy strategy is more beneficial to the government. Additionally, under two subsidy strategies, the platform's profit is higher than the retailer's profit, mainly due to increased demand and marginal profits brought about by blockchain application. Therefore,



(a) (b)

FIGURE 4. Comparison of demand and profits with controlling greenness investment level. (a) Demand. (b) Profits and subsidy amount.

downstream enterprises should adopt blockchain technology as much as possible to enhance consumers' trust in products, regardless of which subsidy strategy the government adopts.

5.2. Controlling subsidy amount

In this section, we compare the greenness investment levels, prices, demand, and profits under two subsidy strategies in the context of the same government subsidy amount to determine the optimal subsidy strategy in this scenario.

Proposition 10. *When the government subsidy amounts under two subsidy strategies are the same, i.e.,* $\Pi_G^{Q^*} = \Pi_G^{C*}$*, the subsidy levels satisfy the relationship:* $s_G(\lambda) = \frac{\sqrt{B^2+4\theta HA[2k(4-\theta)^2-(4+5\theta)\delta^2]}-B}{2A}$*, where* $A = k(4-\theta)(2+\theta) - (1-\theta)\delta^2$*,* $B = \theta[k(4-\theta)(3-\eta) - \eta\delta^2]$*,* $H = \frac{\lambda k[(4+5\theta)\delta-(4+\theta)\eta\delta]^2}{2[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]^2}$.

According to Proposition 10, when the government's subsidy level satisfies a certain relationship, the subsidy amounts under the government's cost subsidy strategy and production subsidy strategy are the same, indicating the government's focus on the subsidy amount. This is similar to Proposition 9.

Next, we will explore the changes and size relationships in prices, demand, and profits under the two subsidy strategies when the government subsidy amount is the same. The parameter settings are consistent with Section 5.1.

Figure 5 compares the subsidy levels corresponding to the government's focus on greenness investment level and subsidy amount under different privacy costs η. We find that regardless of the government's focus, the production subsidy level increases with the cost subsidy level λ, and they have a one-to-one correspondence, which is not affected by privacy costs. As privacy costs increase, a lower production subsidy level can satisfy the government's focus on greenness investment level and subsidy amount. Additionally, achieving the government's goal of controlling greenness investment level requires a higher production subsidy level than achieving the government's goal of controlling subsidy amount (*i.e.*, $s_g > s_G$). Therefore, whether the government focuses on greenness investment level or subsidy amount, it can find a corresponding subsidy level to achieve the same greenness investment level or subsidy amount.

Figure 6 shows that as the subsidy level λ increases, the greenness investment levels of two subsidy strategies and the wholesale and retail prices of the cost subsidy strategy increase, while the wholesale and retail prices of the production subsidy strategy decrease. Moreover, the greenness investment level, wholesale and retail prices

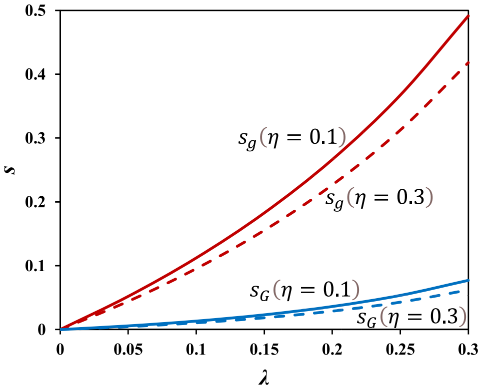


FIGURE 5. Comparison of subsidy level under different governmental goals.

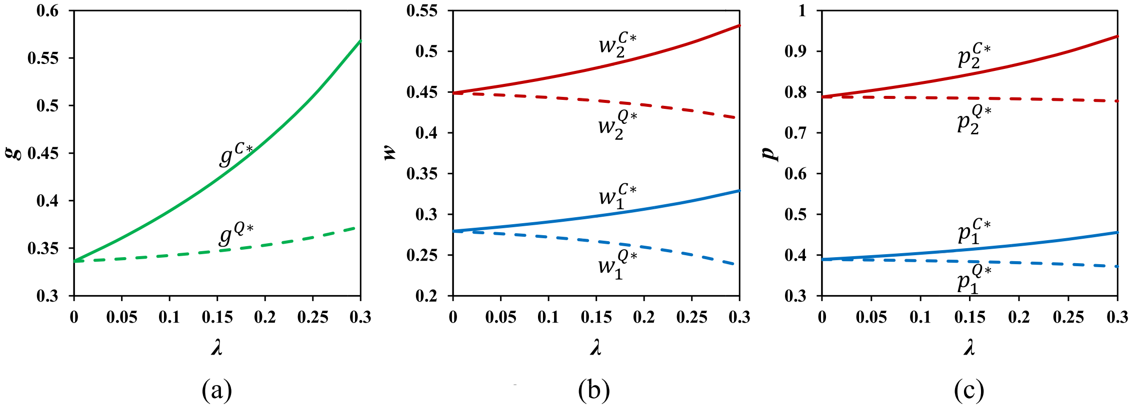


FIGURE 6. Comparison of pricing and greenness investment level with controlling subsidy amount. (a) Greenness investment level. (b) Wholesale price. (c) Retail price.

under the cost subsidy strategy are always higher than those under the production subsidy strategy. Further, when the government focuses on the subsidy amount, consumers can purchase products with higher greenness investment level and lower prices under the production subsidy strategy. Therefore, the government's production subsidy strategy is more beneficial to consumers, while the government should adopt the cost subsidy strategy if it wants to achieve higher greenness investment level. Additionally, we find that whether under the cost subsidy strategy or the production subsidy strategy, both the wholesale and retail prices of blockchain-based online channel are higher than those of non-blockchain-based offline channel. This is similar to when the government focuses on the greenness investment level.

Figure 7 shows that as the subsidy level λ increases, the demand and profits of two subsidy strategies increase. Specifically, Figure 7a shows that the offline demand under the cost subsidy strategy is always lower than that under the production subsidy strategy, while the online demand under the cost subsidy strategy is always higher than that under the production subsidy strategy, and the online demand gap is more pronounced. Additionally, under both subsidy strategies, the demand of blockchain-based online channel is always higher than that of non-blockchain-based offline channel. Therefore, from the perspective of demand, the supply chain should always adopt blockchain technology. This is different from the scenario where the government focuses on the greenness investment level.

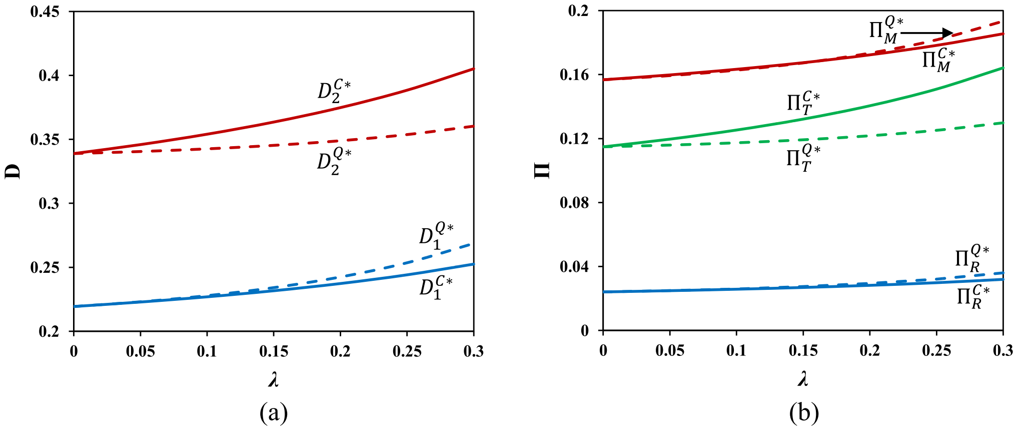


FIGURE 7. Comparison of demand and profits with controlling subsidy amount. (a) Demand. (b) Profits.

Figure 7b shows that under the cost subsidy strategy, the profit of the retailer is always lower than those under the production subsidy strategy, while the platform's profit is greater under the cost subsidy strategy. Therefore, when the government subsidy amount is the same, the retailer prefers the government to adopt the production subsidy strategy, while the platform is more inclined to the government adopting the cost subsidy strategy. When the subsidy level is low, the manufacturer chooses the cost subsidy strategy, and when the subsidy level is high, the manufacturer chooses the production subsidy strategy. This is different from the government's focus on the greenness investment level. However, it is similar in that under both subsidy strategies, the platform's profit is higher than the retailer's profit. This indicates that regardless of whether the government focuses on the greenness investment level or subsidy amount, downstream enterprises should adopt blockchain technology as much as possible to obtain higher profits.

6. CONCLUSION

6.1. Concluding remarks and managerial implications

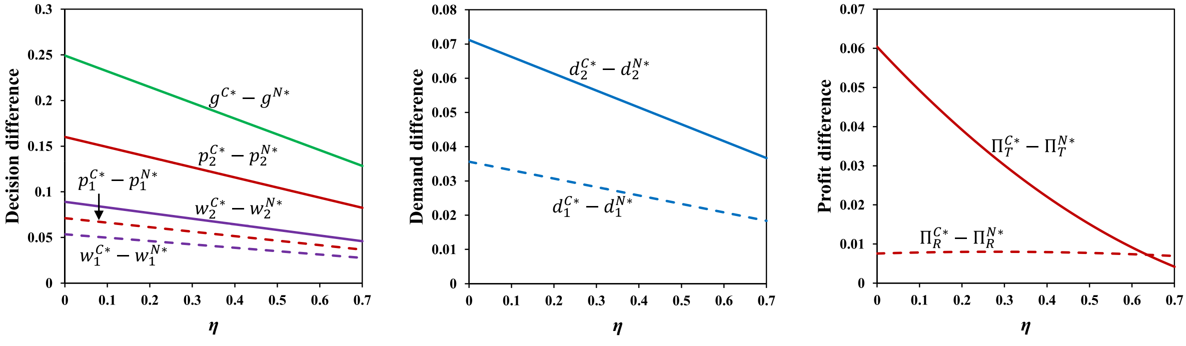
With the growing awareness of environmental protection among consumers, more and more of them tend to purchase green products. However, due to the lack of product information, consumers have uncertainties about the value and greenness level of the purchased products, which reduces their purchasing intentions. Recently, numerous platform enterprises have adopted blockchain to eliminate this uncertainty, but it comes with privacy costs for consumers. Therefore, this paper considers the impact of consumers' privacy costs and constructs a dual-channel GSC consisting of a manufacturer, a blockchain-enabled platform, and an offline retailer without blockchain. Additionally, in conjunction with the government's focus on green development in practice, the study analyzes the impact of two government green subsidy strategies on blockchain-enabled GSC and the preferences of supply chain members towards subsidy strategies. Furthermore, we explore the effects and choices of government subsidy strategies under different governmental goals. Our research yields interesting observations and managerial insights in the context of dual-channel GSC practices.

- First, after adopting blockchain, wholesale prices will always increase, while retail prices, demand, and profits will increase only when consumers' privacy costs are low. Additionally, as privacy costs increase, online prices, demand, profits, and greenness investment level decrease. However, only when the greenness investment cost coefficient is relatively high, offline retail prices, demand, and profits increase with increasing privacy costs. Thus, companies should only consider adopting blockchain technology when privacy costs are relatively low.

- Second, both cost subsidy and production subsidy strategies implemented by the government consistently incentivize the manufacturer to enhance their greenness investment level and result in higher profits for the manufacturer, platform, and retailer. The production subsidy strategy is always more beneficial for the offline retailer without blockchain compared to the blockchain-enabled platform, while this holds true for the cost subsidy strategy only when the subsidy level is relatively high. Therefore, both cost subsidy and production subsidy strategies are feasible measures for government-led green development. Additionally, under the production subsidy strategy, the greenness investment level, demand, profits of supply chain members, and government subsidy amount are higher than under the cost subsidy strategy only when privacy costs are relatively high. The wholesale prices and retail prices are always higher under the cost subsidy strategy. Thus, both the government and supply chain enterprises need to consider the privacy costs associated with blockchain application when a GSC adopts blockchain technology, as it will modify traditional green subsidy schemes in the supply chain.
- Third, when the greenness investment levels are the same, wholesale prices and retail prices under the cost subsidy strategy are consistently higher than those under the production subsidy strategy, while demand, profits, and government subsidy amount under the cost subsidy strategy are consistently lower than those under the production subsidy strategy. Therefore, supply chain enterprises prefer the government to adopt the production subsidy strategy. Influenced by blockchain application, wholesale prices and retail prices in the online channel are always higher than those in the offline channel. Additionally, under the cost subsidy strategy, demand in the online channel is higher than that in the offline channel, whereas under the production subsidy strategy, this holds true only when the subsidy level is relatively low. Furthermore, in both subsidy strategies, the platform's profit is higher than the retailer's profit. Thus, regardless of which subsidy strategy the government adopts, downstream enterprises should consider adopting blockchain technology as much as possible to enhance consumers' trust in green products.
- Fourth, when the government subsidy amount is the same, the change of prices is similar to the scenario when the greenness investment levels are equal. The greenness investment level under the cost subsidy strategy is consistently higher than that under the production subsidy strategy. Therefore, if the government aims to achieve higher product greenness, it should adopt the cost subsidy strategy. Influenced by the blockchain application, demand in the online channel is higher than that in the offline channel. The offline demand and the retailer's profit under the cost subsidy strategy are consistently lower than those under the production subsidy strategy, while the online demand and the platform's profit are lower under the production subsidy strategy. Hence, the retailer prefers the government to implement the production subsidy strategy, while the platform is more inclined towards the cost subsidy strategy. Moreover, the manufacturer opt for the cost subsidy strategy only when the subsidy level is relatively low. Similar to the scenario when the greenness investment levels are equal, the platform's profit is consistently higher than the retailer's profit. Therefore, downstream enterprises should always consider adopting blockchain under different governmental goals.

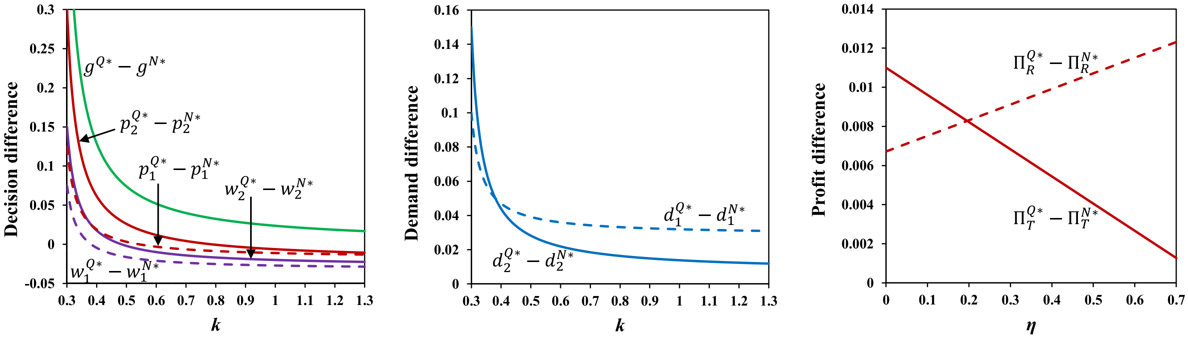
6.2. Future studies

Despite making significant contributions, this study has some limitations, which provide opportunities for future research. For example, this paper assumes that a manufacturer simultaneously supplies products with the same level of greenness investment to both the platform and the retailer. However, in reality, platforms and retailers may have their own private manufacturers, leading to chain-to-chain competition. Additionally, in reality, different downstream enterprises may order green products with different greenness investment levels, which can affect the competition between online and offline channels. Therefore, establishing a game-theoretic model for a dual-channel GSC that considers chain-to-chain competition and varying levels of greenness is a worthwhile direction for future research. Furthermore, in practice, governments may provide subsidies not only to manufacturers producing green products but also to downstream enterprises and consumers. Additionally, blockchain application may be supported by the government. These issues related to government subsidies present important avenues for further investigation.



(a) (b) (c)

FIGURE A.1. Comparison of Model-C and Model-N. (a) Decisions. (b) Demand. (c) Profits.



(a) (b) (c)

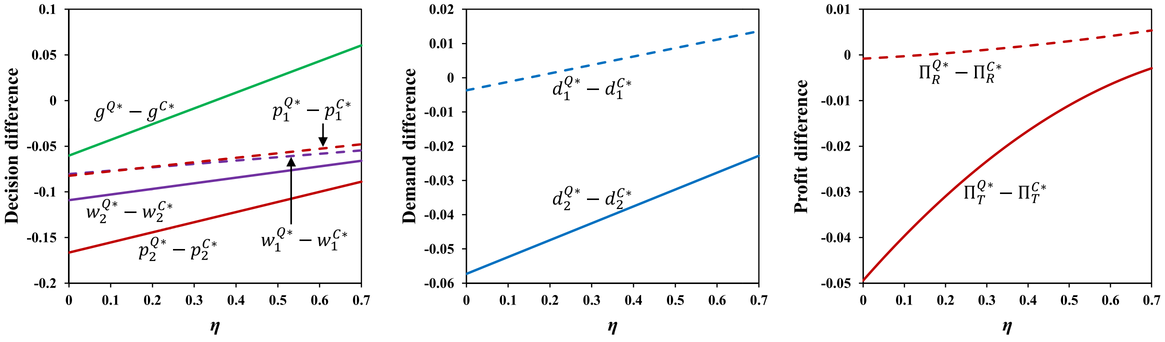
FIGURE A.2. Comparison of Model-Q and Model-N. (a) Decisions. (b) Demand. (c) Profits.

APPENDIX A. NUMERICAL EXPERIMENT

In Section 4, we compare Model-N, Model-C, and Model-Q to explore the value and strategies of government subsidy. In this section, we will use numerical experiments to validate these conclusions and deepen the understanding of these propositions. In addition, we will explore the impact of privacy costs on these conclusions. The parameter settings are similar to Figure 2.

Figure A.1 compares the equilibrium results of Model-C and Model-N. We find that the government's cost subsidy strategy always leads to an increase in greenness investment levels, prices, demand, and profits. This is consistent with Propositions 1 and 2. In addition, with the increase in privacy costs, the cost subsidy strategy is less likely to make them increase. Therefore, the privacy costs caused by blockchain will weaken the benefits of cost subsidy strategy. Especially for the platform, when privacy costs are high, cost subsidy brings lower benefits to the platform than to the retailer. Therefore, under cost subsidy strategy, the platform adopting blockchain may be more disadvantageous.

Figure A.2 compares the equilibrium results of Model-Q and Model-N. Due to privacy costs have no effect on price comparisons, we explore the impact of the greenness investment cost coefficient on price comparisons. We find that the government's production subsidy strategy always leads to an increase in greenness investment levels, demand, and profits, while only lower the greenness investment cost coefficient can increase prices. This is consistent with Propositions 3 and 4. In addition, as the cost coefficient of greenness investment increases, production subsidy strategy is less likely to increase them, and production subsidy strategy is more likely to



(a) (b) (c)

Figure A.3. Comparison of Model-C and Model-Q. (a) Decisions. (b) Demand. (c) Profits.

increase the demand for non-blockchain-enabled products. Unlike cost subsidy strategy, as privacy costs increase, production subsidy strategy can increase the retailer's profit even more. Therefore, under the production subsidy strategy, the platform adopting blockchain may be beneficial for competing retailer.

Figure A.3 compares the equilibrium results of Model-Q and Model-C. We find that the retail and wholesale prices under the production subsidy strategy are always lower than those under the cost subsidy strategy. When the privacy costs are high, the greenness investment levels, demand, and profits under the production subsidy strategy are higher than those under the cost subsidy strategy. These are consistent with Propositions 5–8. In addition, as the privacy costs increase, the greenness investment levels, prices, demand, and profits under the production subsidy strategy are more likely to be higher than under the cost subsidy strategy. Therefore, when the privacy costs caused by blockchain are low, the platform and the retailer prefer the government to adopt a cost subsidy strategy, while when the privacy costs caused by blockchain are high, the platform and the retailer prefer the government to adopt a production subsidy strategy.

Appendix B. Proofs

Proof of Lemma 1. Let $m_i = p_i^N - w_i^N$, $i \in \{1,2\}$, m_1 and m_2 represent the marginal profits of the retailer and the platform, respectively, and are the actual decision variables at this time.

According to the backward method, first, we take the partial derivative and second partial derivative of equation (1) with respect to w_1^N and w_2^N, respectively, and we get:

$$\frac{\partial \Pi_M^N}{\partial w_1^N} = \frac{\theta m_2 + 2\theta w_2^N + \theta\eta - m_1 - 2w_1^N}{\theta(1-\theta)}, \frac{\partial \Pi_M^N}{\partial w_2^N} = \frac{1-\theta-m_2-2w_2^N+m_1+2w_1^N+(1-\theta)\delta g^N-\eta}{1-\theta};$$
$$\frac{\partial^2 \Pi_M^N}{\partial (w_1^N)^2} = \frac{-2}{\theta(1-\theta)}, \frac{\partial^2 \Pi_M^N}{\partial (w_2^N)^2} = \frac{-2}{1-\theta}; \frac{\partial^2 \Pi_M^N}{\partial w_1^N \partial w_2^N} = \frac{\partial^2 \Pi_M^N}{\partial w_2^N \partial w_1^N} = \frac{2}{1-\theta}.$$

The Hessian matrix of Π_M^N about $\left(w_1^N, w_2^N\right)$ is

$$H\left(w_1^N, w_2^N\right) = \begin{bmatrix} \dfrac{-2}{\theta(1-\theta)} & \dfrac{2}{1-\theta} \\ \dfrac{2}{1-\theta} & \dfrac{-2}{1-\theta} \end{bmatrix}.$$

From $\frac{\partial^2 \Pi_M^N}{\partial \left(w_1^N\right)^2} < 0$, $\frac{\partial^2 \Pi_M^N}{\partial \left(w_2^N\right)^2} < 0$, and $\left|H(w_1^N, w_2^N)\right| = \frac{\partial^2 \Pi_M^N}{\partial \left(w_1^N\right)^2}\frac{\partial^2 \Pi_M^N}{\partial (w_2^N)^2} - \frac{\partial^2 \Pi_M^N}{\partial w_1^N \partial w_2^N}\frac{\partial^2 \Pi_M^N}{\partial w_2^N \partial w_1^N} = \frac{4}{\theta(1-\theta)} > 0$, we can deduce that the Hessian matrix is negative definite. Therefore, Π_M^N is jointly concave in w_1^N and w_2^N. Let

$\frac{\partial \Pi_M^N}{\partial w_1^N} = 0$ and $\frac{\partial \Pi_M^N}{\partial w_2^N} = 0$, we get:

$$w_1^N = \frac{\theta - m_1 + \theta\delta g^N}{2} \quad \text{and} \quad w_2^N = \frac{1 - m_2 + \delta g^N - \eta}{2}.$$

Then, substituting the above wholesale prices into equations (2) and (3), respectively. We take the partial derivative and second partial derivative of equation (2) with respect to m_1 and equation (3) with respect to m_2, respectively, we get:

$$\frac{\partial \Pi_R^N}{\partial m_1} = \frac{\theta m_2 - 2m_1 + \theta\eta}{2\theta(1-\theta)}, \frac{\partial^2 \Pi_R^N}{\partial m_1^2} = \frac{-1}{\theta(1-\theta)} < 0;$$
$$\frac{\partial \Pi_T^N}{\partial m_2} = \frac{1 - \theta + m_1 - 2m_2 + (1-\theta)\delta g^N - \eta}{2(1-\theta)}, \frac{\partial^2 \Pi_T^N}{\partial m_2^2} = \frac{-1}{1-\theta} < 0.$$

Let $\frac{\partial \Pi_R^N}{\partial m_1} = 0$ and $\frac{\partial \Pi_T^N}{\partial m_2} = 0$, we get:

$$m_1 = \frac{\theta(1-\theta) + \theta\delta(1-\theta)g^N + \theta\eta}{4-\theta} \text{and} m_2 = \frac{2(1-\theta) + 2\delta(1-\theta)g^N - (2-\theta)\eta}{4-\theta}.$$

Next, substituting the marginal profits m_1 and m_2 into equations (1), we further take the partial derivative and second partial derivative of equation (1) with respect to g^N, we get:

$$\frac{\partial \Pi_M^N}{\partial g^N} = \frac{\delta[(4+5\theta)(1+\delta g^N) - (4+\theta)\eta]}{2(4-\theta)^2} - kg^N, \frac{\partial^2 \Pi_M^N}{\partial (g^N)^2} = \frac{\delta^2(4+5\theta)}{2(4-\theta)^2} - k.$$

Solving the above equations, we find that when $\frac{\partial^2 \Pi_M^N}{\partial (g^N)^2} < 0$, *i.e.* $k > \frac{\delta^2(4+5\theta)}{2(4-\theta)^2}$, Π_M^N is concave in g^N. Let $\frac{\partial \Pi_M^N}{\partial g^N} = 0$, we get $g^{N^*} = \frac{(4+5\theta)\delta - (4+\theta)\eta\delta}{2k(4-\theta)^2 - (4+5\theta)\delta^2}$.

Finally, substituting the greenness investment level g^{N^*} into the marginal profits, wholesale prices, retail prices, demand, and profits. Hence, we get Lemma 1. □

Proof of Corollary 1. (1) $w_2^{N^*} - w_1^{N^*} = \frac{4k(4-\theta)(1-\theta) - \left[2k(4-\theta)(2-\theta) - 3\theta\delta^2\right]\eta}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]} > 0.$

(2) $p_2^{N^*} - p_1^{N^*} = \frac{4k(4-\theta)(3-\theta)(1-\theta) - \left[2k(4-\theta)(6-\theta) - (13+2\theta)\theta\delta^2\right]\eta}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]}$. From $k > \frac{\delta^2(4+5\theta)}{2(4-\theta)^2}$ in Lemma 1, we find that $2k(4-\theta)(6-\theta) - (13+2\theta)\theta\delta^2 > 0$. Thus, we have that when $0 < \eta < \frac{4k(4-\theta)(3-\theta)(1-\theta)}{2k(4-\theta)(6-\theta) - (13+2\theta)\theta\delta^2}$, $p_2^{N^*} > p_1^{N^*}$, otherwise $p_2^{N^*} \leq p_1^{N^*}$.

(3) $D_2^{N^*} - D_1^{N^*} = \frac{k(4-\theta)(1-\theta) - [k(4-\theta)(3-\theta) - (1+2\theta)\delta^2]\eta}{(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]}$. From this, we obtain that when $0 < \eta < \frac{k(4-\theta)(1-\theta)}{k(4-\theta)(3-\theta) - (1+2\theta)\delta^2}$, $D_2^{N^*} > D_1^{N^*}$, otherwise $D_2^{N^*} \leq D_1^{N^*}$.

(4) $\Pi_T^{N^*} - \Pi_R^{N^*} = \frac{\left\{2k(4-\theta)[2(1-\theta) - (2-\theta)\eta] + 3\theta\eta\delta^2\right\}^2 - \theta\left[2k(4-\theta)(1-\theta+\eta) - (2+\theta)\eta\delta^2\right]^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2}$. From this, we obtain that when $0 < \eta < \frac{2k(4-\theta)(1-\theta)(2-\sqrt{\theta})}{2k(4-\theta)(2-\theta+\sqrt{\theta}) - \left[(2+\theta)\sqrt{\theta} + 3\theta\right]\delta^2}$, $\Pi_T^{N^*} > \Pi_R^{N^*}$, otherwise $\Pi_T^{N^*} \leq \Pi_R^{N^*}$.

□

Proof of Corollary 2. (1) $\frac{\partial g^{N^*}}{\partial \eta} = \frac{-(4+\theta)\delta}{2k(4-\theta)^2 - (4+5\theta)\delta^2} < 0.$

(2) $\frac{\partial w_2^{N^*}}{\partial \eta} = \frac{-4k(4-\theta) + \theta\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]} < 0$; $\frac{\partial p_2^{N^*}}{\partial \eta} = \frac{-4k(4-\theta)(3-\theta) + 7\theta\delta^2}{2[2k(4-\theta)^2 - (4+5\theta)\delta^2]} < 0$; $\frac{\partial D_2^{N^*}}{\partial \eta} = \frac{-2k(2-\theta)(4-\theta) + 3\theta\delta^2}{2(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]} < 0$; $\frac{\partial \Pi_T^{N^*}}{\partial \eta} = \frac{\left[-2k(2-\theta)(4-\theta) + 3\theta\delta^2\right]\left\{2k(4-\theta)[2(1-\theta) - (2-\theta)\eta] + 3\theta\eta\delta^2\right\}}{(1-\theta)[2k(4-\theta)^2 - (4+5\theta)\delta^2]^2} < 0.$

(3) $\frac{\partial w_1^{N^*}}{\partial \eta} = \frac{-k\theta(4-\theta)-\theta\delta^2}{2k(4-\theta)^2-(4+5\theta)\delta^2} < 0.$
$\frac{\partial p_1^{N^*}}{\partial \eta} = \frac{\theta\left[k(4-\theta)-(3+\theta)\delta^2\right]}{2k(4-\theta)^2-(4+5\theta)\delta^2}$, from this, we obtain that when $k > \frac{(3+\theta)\delta^2}{4-\theta}$, $\frac{\partial p_1^{N^*}}{\partial \eta} > 0$, otherwise $\frac{\partial p_1^{N^*}}{\partial \eta} \leq 0$.
$\frac{\partial D_1^{N^*}}{\partial \eta} = \frac{2k(4-\theta)-(2+\theta)\delta^2}{2(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]}$ and $\frac{\partial \Pi_R^{N^*}}{\partial \eta} = \frac{\theta\left[2k(4-\theta)(1-\theta+\eta)-(2+\theta)\eta\delta^2\right]\left[2k(4-\theta)-(2+\theta)\delta^2\right]}{(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]^2}$, from them, we obtain that when $k > \frac{(2+\theta)\delta^2}{2(4-\theta)}$, $\frac{\partial D_1^{N^*}}{\partial \eta} > 0$ and $\frac{\partial \Pi_R^{N^*}}{\partial \eta} > 0$, otherwise $\frac{\partial D_1^{N^*}}{\partial \eta} \leq 0$ and $\frac{\partial \Pi_R^{N^*}}{\partial \eta} \leq 0$.
□

Proof of Lemma 2. The proof process is similar to Lemma 1, so it is omitted. □

Proof of Proposition 1. The proofs can be directly obtained from the optimal strategies, so they are omitted. □

Proof of Proposition 2. (1) $\Pi_R^{C*} - \Pi_R^{N^*} = \frac{\theta\left[2k(4-\theta)^2-(4+5\theta)\delta^2\right]^2\left[2k(1-\lambda)(4-\theta)(1-\theta+\eta)-(2+\theta)\eta\delta^2\right]^2}{2(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]^2[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]^2}$
$-\frac{\theta\left[2k(4-\theta)(1-\theta+\eta)-(2+\theta)\eta\delta^2\right]^2\left[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2\right]^2}{2(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]^2[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]^2} > 0.$
Similarly, we have that $\Pi_T^{C*} > \Pi_T^{N^*}$.

(2) From (1), we can obtain that when $\lambda_1 < \lambda < 1$, $\Pi_R^{C*} - \Pi_R^{N^*} > \Pi_T^{C*} - \Pi_T^{N^*}$, otherwise $\Pi_R^{C*} - \Pi_R^{N^*} \leq \Pi_T^{C*} - \Pi_T^{N^*}$.

□

Proof of Lemma 3. The proof process is similar to Lemma 1, so it is omitted. □

Proof of Corollary 3. The proof process is similar to Corollary 2, so it is omitted. □

Proof of Proposition 3. (1) It is obvious, $g^{Q^*} > g^{N^*}$.
$D_1^{Q^*} - D_1^{N^*} = \frac{s(1-\theta)\left[4k(4-\theta)-(2+\theta)\delta^2\right]}{2\theta(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]}$, $D_2^{Q^*} - D_2^{N^*} = \frac{s(1-\theta)\left[2k(4-\theta)+3\delta^2\right]}{2(1-\theta)[2k(4-\theta)^2-(4+5\theta)\delta^2]}$, from $k > \frac{(4+5\theta)\delta^2}{2(4-\theta)^2}$, we can know that $D_1^{Q^*} > D_1^{N^*}$, $D_2^{Q^*} > D_2^{N^*}$.

(2) $w_1^{Q^*} - w_1^{N^*} = \frac{3s\left[(1+2\theta)\delta^2-k(2-\theta)(4-\theta)\right]}{2k(4-\theta)^2-(4+5\theta)\delta^2}$, from this, we obtain that when $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+2\theta)\delta^2}{(2-\theta)(4-\theta)}$, $w_1^{Q^*} > w_1^{N^*}$, otherwise $w_1^{Q^*} \leq w_1^{N^*}$. $w_2^{Q^*} - w_2^{N^*} = \frac{s[9(1+\theta)\delta^2-2k(4-\theta)(5-2\theta)]}{2[2k(4-\theta)^2-(4+5\theta)\delta^2]}$, from this, we obtain that when $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{9(1+\theta)\delta^2}{2(4-\theta)(5-2\theta)}$, $w_2^{Q^*} > w_2^{N^*}$, otherwise $w_2^{Q^*} \leq w_2^{N^*}$.
(3) $p_1^{Q^*} - p_1^{N^*} = \frac{s\left[(1+7\theta+\theta^2)\delta^2-k(2+\theta)(4-\theta)\right]}{2k(4-\theta)^2-(4+5\theta)\delta^2}$, from this, we obtain that when $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(1+7\theta+\theta^2)\delta^2}{(2+\theta)(4-\theta)}$, $p_1^{Q^*} > p_1^{N^*}$, otherwise $p_1^{Q^*} \leq p_1^{N^*}$. $p_2^{Q^*} - p_2^{N^*} = \frac{3s\left[(5+\theta)\delta^2-2k(4-\theta)\right]}{2[2k(4-\theta)^2-(4+5\theta)\delta^2]}$, from this, we obtain that when $\frac{(4+5\theta)\delta^2}{2(4-\theta)^2} < k < \frac{(5+\theta)\delta^2}{2(4-\theta)}$, $p_2^{Q^*} > p_2^{N^*}$, otherwise $p_2^{Q^*} \leq p_2^{N^*}$.

□

Proof of Proposition 4–8. The proofs are similar to the proofs of Proposition 2 and 3, so they are omitted. □

Proof of Proposition 9. From $g^{Q^*} = g^{C*}$, *i.e.*, $\frac{(4+5\theta)\delta+(8+\theta)s\delta-(4+\theta)\eta\delta}{2k(4-\theta)^2-(4+5\theta)\delta^2} = \frac{(4+5\theta)\delta-(4+\theta)\eta\delta}{2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2}$, we have that $s_g(\lambda) = \frac{2\lambda k(4-\theta)^2[4+5\theta-(4+\theta)\eta]}{(8+\theta)[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]}$. □

Proof of Proposition 10. First, $\Pi_G^{Q^*} = \Pi_G^{C*}$, *i.e.*, $\frac{ks(4-\theta)[3\theta+s(2+\theta)-\theta\eta]-s[s(1-\theta)+\theta\eta]\delta^2}{\theta[2k(4-\theta)^2-(4+5\theta)\delta^2]} = \frac{\lambda k[(4+5\theta)\delta-(4+\theta)\eta\delta]^2}{2[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]^2}$.
Then, let $H = \Pi_G^{C*} = \frac{\lambda k[(4+5\theta)\delta-(4+\theta)\eta\delta]^2}{2[2k(1-\lambda)(4-\theta)^2-(4+5\theta)\delta^2]^2}$, we have that $ks(4-\theta)[3\theta + s(2+\theta) - \theta\eta] - s[s(1-\theta) + \theta\eta]\delta^2 - H\theta\left[2k(4-\theta)^2 - (4+5\theta)\delta^2\right] = 0$. From this, we obtain that $As^2 + Bs - H\theta\left[2k(4-\theta)^2 - (4+5\theta)\delta^2\right] = 0$, where $A = k(4-\theta)(2+\theta) - (1-\theta)\delta^2$ and $B = \theta\left[k(4-\theta)(3-\eta) - \eta\delta^2\right]\cdot$

Next, let $f(s) = As^2 + Bs - H\theta\big[2k(4-\theta)^2 - (4+5\theta)\delta^2\big]$. According to the discriminant $\varDelta_s = B^2 + 4\theta HA[2k(4-\theta)^2 - (4+5\theta)\delta^2] > 0$ of the roots of $f(s)$, we can know that $f(s)$ has two roots. From $f(s) = 0$, the two roots of the equation can be obtained as follows:

$$\widehat{s}(\lambda) = \frac{-\sqrt{B^2 + 4\theta HA[2k(4-\theta)^2 - (4+5\theta)\delta^2]} - B}{2A} < 0 \ \text{ and}$$
$$\overline{s}(\lambda) = \frac{\sqrt{B^2 + 4\theta HA[2k(4-\theta)^2 - (4+5\theta)\delta^2]} - B}{2A}.$$

Finally, from $s > 0$, we obtain that when $s_G(\lambda) = \overline{s}(\lambda)$, $\Pi_G^{Q^*} = \Pi_G^{C*}$. ☐

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