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论文题目： What value does blockchain bring to the food supply chain safety and traceability? A game-theoretic analysis

What value does blockchain bring to the food supply chain safety and traceability? A game-theoretic analysis

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Abstract

Food safety is a vital issue for people’s health and well-being, and also one of the most difficult social problems that the government has been facing for a long time. Meanwhile, blockchain technology has been recently adopted to improve safety and traceability in food supply chains (FSC). However, whether through outsourcing or self-implementation of a blockchain-based food traceability system (BTS), there are significant costs involved, as well as concerns regarding consumer privacy. Motivated by observations of real-world practice, we explore the value of blockchain in enhancing traceability and safety in FSC through a Stackelberg game-theoretical analysis. By comparing the equilibrium solutions of the scenarios with and without blockchain, we uncover the value of blockchain in tracing food products. Our findings show that blockchain adoption can increase FSC prices under certain conditions. We derive the third-party BTS service fee threshold that determines blockchain adoption for tracing food products and reveal the moderating effect of consumer traceability preferences and privacy concerns. Furthermore, the investigation of who should lead the implementation of BTS finds that equal cost-sharing between the manufacturer and the retailer results in no difference in BTS implementation leadership. Otherwise, the manufacturer always benefits from leading, and the retailer should lead the BTS implementation if they need to bear higher costs. Finally, based on the derived operational conclusions for the FSC enterprises, we also propose some policy implications for the government to support and regulate the adoption of BTS.

Keywords Blockchain · Traceability · Food supply chain · Operations management

Catalogue:

1. Introduction

Food safety is a vital issue for society and a primary goal for governments in food supply chain (FSC) management. To achieve this goal, one of the key aspects is improving traceability in the FSC, which is essential to safeguard food quality and safety while to satisfy growing consumer concerns about food provenance. Besides, ensuring food quality and improving food traceability have long been management challenges in the FSC.

Despite the importance of food safety and traceability, foodborne diseases and contamination incidents still occur frequently around the world, posing serious threats to public health and economic development. According to the World Health Organization, an estimated 600 million people fall ill after eating contaminated food each year, resulting in 420 000 deaths and the loss of 33 million healthy life years[1]. The economic impact of food safety outbreaks on food businesses and supply chains is also significant, with a loss of US$ 110 billion each year in productivity and medical expenses in low- and middle-income countries[1]. Some examples of recent food safety incidents are shown in Table 1.

This indicates that the current methods of ensuring food safety and traceability in the FSC are not sufficient or reliable. At present, a common way to ensure food safety and traceability is to use Internet of things (IoT) and Radio frequency identification (RFID) technology to record and encode information on production, transportation, packaging, etc. of food products. Consumers can scan the QR code or barcode of the food package, verify the unique packaging, or check the authentication certificates come with the food to assess the food quality and trace the provenance. However, these methods involve a few problems. First, testing agencies for product quality and safety may not be credible. The deceptive retailer may conspire with the testing agency or simply fabricate a certificate to prove their products' effectiveness. Second, even if the testing agency is credible, the packaging or certificates of foods can be falsified or replaced at any time along the supply chain. Third, all the historical product information can be manually amended and deleted in the central database. As a result, although there are multiple methods to maintain product quality and provenance in the current FSC, none of them enables truly credible traceability. Thus, this explains why food safety issues are repeated. Therefore, there is a need for a more secure and transparent solution to improve food safety

[1] https://www.who.int/news-room/fact-sheets/detail/food-safety(accessed 14 Sep 2023)

and traceability in the FSC.

Table 1. Examples of recent food safety incidents around the world.

Time	Food Type	Description
2022	Melons	A Salmonella Braenderup outbreak was linked to the consumption of Galia melons from Honduras, affecting 12 countries and over 300 people[2].
2021	Shrimp	A Vibrio parahaemolyticus outbreak was associated with the consumption of frozen cooked shrimp products from India, involving 9 countries and 34 cases[3].
2020	Onions	A multistate outbreak of Salmonella Newport infections linked to onions imported from Mexico and distributed by Thomson International Inc. in the United States and Canada. The outbreak sickened 1,127 people and hospitalized 1671[4].
2019	Chicken nuggets	A recall of certain batches of chicken nuggets produced by Tyson Foods Inc. due to possible contamination with rubber pieces. The recall affected 36,420 pounds of chicken nuggets sold nationwide[5]

Besides, consumers' preference for food traceability is also becoming increasingly important (Behnke & Janssen, 2020; Casino et al., 2021; Dasaklis et al., 2022). Several factors drive consumers' preference for traceability, including concerns about food safety, environmental sustainability, ethical production practices, etc. For example, Nestlé has been accused of using child labour and forced labour in its cocoa supply chain in West Africa[6]. Despite its commitments to end these practices, Nestlé has failed to eradicate them and has faced lawsuits and boycotts from human rights groups and consumers[7]. Additionally, in the Philippines, where the country loses P62 billion ($1.2 billion) annually to illegal, unreported, and unregulated (IUU) fishing activities, the government has launched a campaign to combat IUU fishing and protect the marine environment, but the situation remains

[2] https://thebarbecuelab.com/food-safety-statistics/(accessed 14 Sep 2023)
[3] https://www.fao.org/state-of-food-security-nutrition/2021/en/(accessed 14 Sep 2023)
[4] https://www.cdc.gov/salmonella/newport-07-20/index.html(accessed 14 Sep 2023)
[5] https://www.cnn.com/2019/01/30/health/panko-chicken-nugget-recall/index.html#:~:text=Tyson%20Foods%20is%20recalling%2036%2C420%20pounds%20of%20chicken,Panko%20Chicken%20Nuggets%2C%E2%80%9D%20produced%20on%20November%2026%2C%202018. (accessed 14 Sep 2023)
[6] https://www.theguardian.com/global-development/2021/feb/12/mars-nestle-and-hershey-to-face-landmark-child-slavery-lawsuit-in-us(accessed 14 Sep 2023)
[7] https://www.independent.co.uk/world/nestle-mars-hersey-cocoa-child-slaves-b1948199.html(accessed 14 Sep 2023)

unresolved[8]. Hence, consumers want to know where their purchased food comes from, how it was produced, and whether it was produced in an environmentally friendly way. They also want to know whether the wine was produced using ethical labour practices and whether the workers involved in the production process were treated fairly.

Figure 1. Some potential results of the FSC lack of reliable traceability.

However, the adoption of blockchain technology in the FSC provides new solutions to the above problems. Blockchain technology is considered to be one of the most disruptive technologies in the food industry and the cornerstone of future food industry (Kamilaris et al., 2019). This is because the emergence of blockchain technology has brought a tremendous improvement in food safety assurance and traceability (Charles et al., 2023; Yadav et al., 2021; Yavaprabhas et al., 2022). The blockchain-based tracing system (BTS) provides an immutable ledger that allows for secure and transparent tracking of foods from farm to table. This ensures that all stakeholders in the food industry, from manufacturers to consumers, can have confidence in the provenance and quality of the food products, and this also facilitates the digital governance of the food industry by the government. With the support of the Yunnan Provincial Government, E-Visible, a company that sells tea bricks, launched a blockchain-based "Tea Texture Chain" project. The project aims to provide quality assurance and traceability service for the sale of Pu'er tea bricks, a type of fermented herbal tea produced in the Yunnan province of China. Pu'er tea is highly valued for its unique flavor and health benefits, but also faces the problem of counterfeiting and adulteration. The "Tea Texture Chain" project leverages the natural texture of each tea brick, which is formed by randomly pressing over 10,000 tea leaves, as a unique identifier that links to all the details of the tea recorded in the blockchain (i.e., growth, harvesting, processing, packaging, delivery, etc.). The blockchain technology ensures that the data is

[8] https://www.rappler.com/environment/numbers-illegal-unreported-unregulated-fishing-philippines/(accessed 14 Sep 2023)

immutable, transparent, and verifiable by all stakeholders in the tea industry, from producers to consumers. By scanning the surface texture of a tea brick using a smartphone app, consumers can access all the production and distribution information, as well as verify the authenticity and quality of the product. The government can also benefit from the "Tea Texture Chain" project by having access to reliable and real-time data on the tea industry, which can help them monitor and regulate the market, protect the reputation and brand value of Yunnan tea, and promote its export and consumption[9].

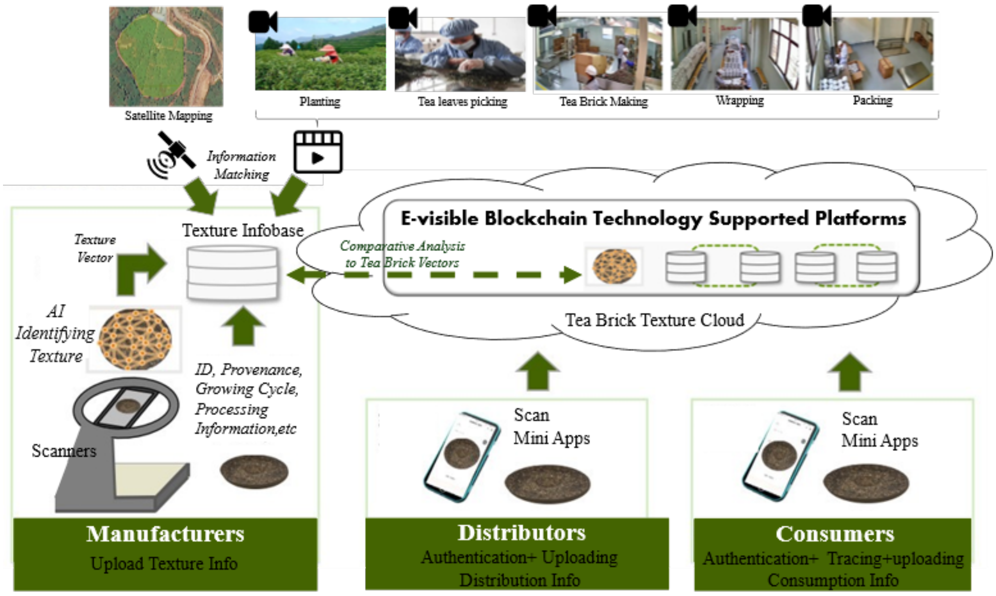

Figure 2. Example of tea texture chain enabled authentic tea bricks selling.

With the increasing awareness of the benefits that blockchain can offer for food quality assurance and traceability, the global blockchain in FSC market size is expected to grow from USD 133 million in 2020 to USD 948 million by 2025[10]. Several food enterprises, such as AgriChain[11], AgriLedger[12,] AgriDigital[13,], etc. have pioneered the use of blockchain technology to manage activities in the FSC. Moreover, instead of FSC agents implementing their own BTS, many tech giants have taken advantage of their blockchain expertise to provide blockchain-as-a-service (BaaS) for the FSC, like Alibaba and IBM (detailed in Table 2). The global BaaS market size stood at USD 1.90 billion in

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[9] http://www.easy-visible.com/qkl/t8.html (accessed 14 Sep 2023)
[10] https://www.prnewswire.com/news-releases/global-blockchain-in-agriculture-and-food-supply-chain-market-2020-to-2025---increase-in-funding-and-investments-in-agri-food-blockchain-presents-opportunities-301188322.html (accessed 14 Sep 2023)
[11] https://agrichain.com/ (accessed 14 Sep 2023)
[12] http://www.agriledger.io/home/ (accessed 14 Sep 2023)
[13] https://www.agridigital.io/us (accessed 14 Sep 2023)

2019 and is projected to reach USD 24.94 billion by 2027[14].

Table 2. Some examples of BaaS for the FSC.

Company	Description
Alibaba	● Alibaba Cloud provides a BaaS platform called Ant Blockchain, which enables food producers and distributors to track the provenance of food and reduce the risk of fraud in the supply chain[15].Take the Hyperledger Fabric version as an example, it can charge monthly and yearly subscriptions, or charges $0.000472 per GB per hour for storage space beyond 6TB per node[16].
IBM	● IBM's blockchain-based platform is used by major players in the food industry, such as foodries and retailers, to track the journey of food from the vineyard to the store shelf[17]. It has introduced a new hourly pricing model that is based on virtual processor core (VPC) allocation. The nodes are allocated on an hourly basis, at a flat rate of $0.29 /VPC-hour12[18].
Amazon	● Amazon Managed Blockchain enables food producers to track the quality and authenticity of their products, as well as improve supply chain efficiency. The price factors including region, framework, node type, data transfer, storage, request, and encryption key19.
Microsoft	● Microsoft Azure Blockchain Service helps food producers to improve traceability and transparency in the supply chain, as well as reduce the risk of food quality problems [20] . Basic BaaS charging $0.0996/hour for transaction node price, $0.0996/hour for validator node price, and $0.05/hour for blockchain storage price GB. Standard BaaS charging $0.318/hour for transaction node price, $0.318/hour for validator node price, and $0.05/hour for blockchain storage price GB[21].

However, the adoption of blockchain in FSC has faced several obstacles. One of the biggest hurdles is the cost of purchasing BaaS solutions or implementing a BTS by FSC members. The pricing of different third-party BTS providers is illustrated in Table 2. The price may not seem much at first

[14] https://www.fortunebusinessinsights.com/blockchain-as-a-service-baas-market-102721(accessed 14 Sep 2023)
[15] https://chuangxin.chinadaily.com.cn/a/202107/07/WS60e64fe6a3101e7ce9758a13.html(accessed 14 Sep 2023)
[16] https://www.alibabacloud.com/help/zh/blockchain-as-a-service/latest/specifications-and-pricing(accessed 14 Sep 2023)
[17] https://newsroom.ibm.com/2020-12-10-eProvenance-Uncorks-VinAssure-TM-an-IBM-Blockchain-Powered-Platform-to-Strengthen-Collaboration-and-Optimize-the-Food-Supply-Chain(accessed 14 Sep 2023)
[18] https://www.ibm.com/cloud/blockchain-platform/pricing(accessed 14 Sep 2023)
[19] https://aws.amazon.com/cn/blockchain/blockchain-for-supply-chain-track-and-trace/(accessed 14 Sep 2023)
[20] https://azure.microsoft.com/en-us/blog/ethereum-blockchain-as-a-service-now-on-azure/(accessed 14 Sep 2023)
[21] https://101blockchains.com/azure-blockchain/(accessed 14 Sep 2023)

glance, but it can add up quickly over time and across multiple nodes in FSC. Plus, implementing BTS by FSC members themselves also requires investing in hardware, software, maintenance, and security. The exact cost of implementing a BTS varies depending on the complexity and scale of the system, with an estimate of around $40K to $300K[22]. Therefore, both options pose significant financial challenges for FSC members who want to adopt blockchain in the food industry.

In addition, consumer privacy is another concern for blockchain technologies, which also applies to the FSC. A KPMG report shows 56% of customers distrust companies' privacy policies[23]. Even though blockchain is pseudonymous[24], hackers can link pseudo-identities to real ones and infer 80% of transactions. Ironically, they can reveal all their past purchases whenever they want due to blockchain's immutability. It can be a more serious issue in FSC as the target customers of high-valued foods (like caviar, foie gras, truffles) are normally with high social status and wealth[25], and therefore are sensitive to the leak of personal information. At the same time, as one popular choice of luxury gifts, some consumers want to conceal the food's former ownership and regifting history. Obviously, blockchain's transparency and immutability increase their privacy concerns. Hence, ensuring data security while utilizing the benefits of blockchain technology presents a significant challenge in the food industry.

Motivated by the observations of real-world practices, and to help the government gain deeper insights into the challenges of FSC members adopting blockchain technology to ensure food safety and traceability, this study addresses the following questions:

(i) What are the optimal wholesale and retail prices, and level of traceability effort for the FSC members, with blockchain adoption for FSC traceability and safety?

(ii) How does the adoption of BTS affect the FSC performance? Is it possible that adopting blockchain does more harm than good?

(iii) How does the adoption of the third-party's BTS or self-implementation affect the FSC members' operational decisions and performances?

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[22] https://appinventiv.com/guide/blockchain-app-development-cost/(accessed 14 Sep 2023)
[23] https://advisory.kpmg.us/articles/2021/bridging-the-trust-chasm.html(accessed 14 Sep 2023)
[24] Emerging Technology. 2017. Bitcoin transactions aren't as anonymous as everyone hoped. MIT technology Review, August 23.(accessed 14 Sep 2023)
[25] https://www.fortunebusinessinsights.com/food-market-102836(accessed 14 Sep 2023)

To address the above research questions, we develop a consumer utility-based analytical model and conduct a Stackelberg game-theoretic analysis. To better understand the value of blockchain to the FSC, we compare the two scenarios with and without blockchain, and derive the condition for adopting blockchain. Our analysis uncovers the value of blockchain in tracing food products within the FSC and includes extended modelling to discuss the preferable choice of using blockchain technology. Meanwhile, our analysis will also provide valuable insights for the government on how to encourage FSC members to adopt blockchain technology in different forms, and how to facilitate the digital transformation of government governance.

This paper makes some contributions to the literature on blockchain applications in the FSC. First, this paper is one of the earliest studies that use a game-theoretic analysis to explore the value of blockchain in the FSC. We propose a feasible method to quantify and characterize the value of blockchain technology in the FSC, which has been a challenge for previous studies. Second, this paper explores blockchain-based traceability in the FSC with the consideration of different ways to adopt BTS (e.g., outsourcing or self-implementation). We derive optimal operational decisions for FSC members under different scenarios and provide managerial implications for using blockchain strategies in the FSC. Third, this paper is highly relevant to the government's plan to build a traceable system for the entire food industry chain, and to support the digitalization of government administration. Our research can help the government understand the difficulties and challenges faced by food enterprises in applying blockchain technology, and clarify the steps and logic of deploying blockchain traceability systems by enterprises, so as to formulate more reasonable guidance and subsidy policies.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 describes the basic analytical models for the FSC without BTS adoption (Model N) and with third-party BTS adoption (Model B). In Section 4, the two basic models are compared and the values of blockchain in FSC are examined. Section 5 presents an extended analysis of the various approaches to implementing blockchain in FSC, and Section 6 concludes the study. We give proof of all the results in the Appendix B.

2. Literature review

2.1 The adoption of Blockchain technology in the FSC

With the prevalent adoption of blockchain technology in supply chains, the cases of blockchain application in the FSC are often cited as compelling evidence of how blockchain technology can be used to improve supply chain traceability, visibility, trust, etc. (Rogerson & Parry, 2020; Sunny et al., 2020; Tiscini et al., 2020). Meanwhile, some scholars undertake detailed case studies of implementing blockchain technology within the FSC. Danese et al. (2021) conduct a multiple-case study of five Italian wine companies using blockchain and found that the key factor in designing blockchain systems is the desired level of counterfeiting protection that a brand owner wants to provide to customers through blockchain. Brookbanks and Parry (2022) present a case study of two beverage supply chains through semi-structured interviews to determine how trust and trustworthiness develop in buyer-supplier relationships and the impact of a blockchain-based technology proof of concept on supply chain trust.

Moreover, considering the uniqueness of the FSC, several researchers employ other methodologies to investigate the application of blockchain technology in the FSC. Saurabh and Dey, (2021) examine the determinants of technology adoption in the grape wine supply chain by proposing a blockchain architecture. They find that disintermediation, traceability, price, trust, compliance, and coordination and control are the most significant factors in the given order for actors in the grape wine supply chain to adopt blockchain technology. Tokkozhina et al. (2021) propose an architecture for a blockchain-based system to track FSC transactions from produce harvesting to product sales. This system demonstrates the potential of blockchain technology to reduce counterfeiting, assure food origin, avoid health risks, and increase brand reputation. Adamashvili et al. (2021) design an agent-based model and a GAMA program simulation to investigate whether a blockchain-based FSC could be more effective than a traditional one in terms of information sharing, and time and costs of tracking back products. Luzzani et al. (2021) conduct an exploratory study on the use of blockchain technology in the FSC for improving sustainability. It shows that blockchain allows for the collection of relevant data and information, but food companies have little familiarity with its applications.

A review of existing studies on blockchain technology reveals several key trade-offs in its application to the FSC, including enhanced traceability and food safety, concerns over consumer privacy, and high costs. Our research addresses the issue of blockchain adoption in the FSC, we extend the current literature by utilizing a game theory-based analytical model, and our model examines the effects of blockchain technology on challenging OM problems.

2.2 Supply chain traceability management

Constructing a robust and reliable tracing system is vital for supply chains. Previous research has shown that consumers have a sufficient preference for product traceability(Qian et al., 2020; Lu et al., 2016; Ubilava and Foster, 2009). Besides, earlier studies have also explored how traditional food tracing technologies, such as wireless sensor networks (WSN) or radio frequency identification (RFID), can enhance FSC traceability (Cimino & Marcelloni, 2012; Expósito et al., 2013). These methods can help identify and control food quality, and satisfy consumer's traceability preferences to some extent. However, they are not fully trustworthy tracing systems.

Nowadays, supply chain traceability management has entered a new era with the development of blockchain technology in recent years. For instance, Yiu (2021) discusses blockchain technology's potential to develop decentralized product anti-counterfeiting and traceability ecosystems in the supply chain. The paper identifies key areas of decentralization, fundamental system requirements, and feasible mechanisms for developing secure and immutable scientific data provenance tracking and management platforms utilizing blockchain technology. Hastig and Sodhi (2020) conduct a thematic analysis of the implementation of blockchain for supply chain traceability. Their findings indicate that the critical success factors for successful implementation include companies' capabilities, collaboration, technology maturity, supply chain practices, leadership, and governance of traceability efforts. Cui et al., (2023) provide a theoretical investigation into the value and design of traceability-driven blockchains under different supply chain structures. They find that firms operating in various supply chains may encounter unique challenges when they adopt blockchain technology. It may be easier to gain traction in a serial supply chain, whereas it would be more critical for the buyer in a parallel supply chain to influence data governance and compensate suppliers for their efforts to improve data quality. Wu et al. (2021) analytically explore the strategies for adopting a blockchain technology system in the fresh product supply chain (FPSC) by comparing the scenarios of non-blockchain technology with three different FPSC members leading the construction of the blockchain system respectively. They derive the optimal conditions for blockchain system deployment in FPSC and design a two-part tariff contract for FPSC coordination. Fan et al. (2022) discuss the adoption of blockchain in supply chains and provides a trade-off condition regarding consumers' traceability awareness, production costs, and the cost of blockchain adoption. They also find that revenue-sharing contracts can promote the use of blockchain.

Existing research indicates that supply chain traceability management is a persistent topic of interest, particularly with the advancement of tracing technology. While early studies have focused on the adoption of previous generation tracing technology in the FSC, the adoption of blockchain has primarily been examined through qualitative methods. Our research considers the unique characteristics of the FSC and extends the current literature on traceability management.

2.3 Blockchain-based supply chain operations management

Finally, our work is also related to the growing body of literature that tackles the OM problems in the blockchain-based supply chain. Currently, many types of supply chains have scholars conducting Blockchain-based OM research, such as medicine supply chains, E-commerce supply chains, green product supply chains, and so on (Choi, 2022; Luo & Choi, 2022; Niu & Dong, et al., 2021; Xu & Duan, 2022). To be specific, Liu et al. (2022) develop an analytical model to examine the value of blockchain technology in the imported fresh food supply chain during the COVID-19 pandemic. By considering the risk attitudes of supply chain members, they find that blockchain technology does not necessarily bring substantial benefits to the supply chain. However, it can help manufacturers and retailers increase their profits in certain conditions. Choi (2019) examines various consumer utility-driven operational models and emphasizes the importance of blockchain technology-supported platforms for diamond authentication and certification. The paper reveals that the shopping convenience and the cost of blockchain-technology-based diamond authentication and certification are critical factors in determining whether to adopt blockchain or not.

Furthermore, other related studies also reveal some interesting insights in general supply chain content. Pun et al. (2021) employ a model based on signalling game theory to investigate the potential use of blockchain technology by firms and governments in combating counterfeiting. Their analysis considers the impact of customers' post-purchase regret and concerns about leaving a digital footprint on the adoption of blockchain technology. Additionally, the authors consider the effectiveness of different government strategies in promoting the use of blockchain technology. Shen et al. (2022) examine the use of Permissioned Blockchain Technology (PBT) to combat copycats in the supply chain. They find that PBT benefits Brand Name Companies (BNCs) by helping customers identify product authenticity and quality, increasing BNC profitability, consumer surplus, and social welfare, and reducing copycat earnings. However, BNCs may decrease product quality when using PBT if consumers can distinguish between genuine and imitation products.

Our research contributes to this research area by identifying two key characteristics of blockchain-based traceability in the FSC: its ability to guaranteeing the food quality and its potential impact on consumer privacy. Additionally, we examine the optimal mode of BTS adoption, whether through outsourcing or self-implementation, which enriches the existing research.

3. Optimal strategies of the FSC

As a high-value-added product with a complex production process, the traceability of food products is an important issue in the food industry. The more detailed the traceability, like raw material origin, brewing year, storage method, etc., the more the consumers' expectations such as the quality, collection value, or eco-production preference can be guaranteed. Plus, as one of the most obvious exogenous benefits of food traceability, the level of traceability is positively correlated with the ability of consumers to identify the safe and well-qualitied food, which means the more effort manufacturers spend on food traceability, the higher possibility that customers can inspect food safety issues.

While blockchain technology has significantly improved food traceability in the supply chain. Its decentralized and transparent ledger system guarantees traceability information cannot be tampered with. This means that the BTS can not only transmit basic production and processing information, but also eliminate food fraud and contamination. Same as Non-blockchain-based tracing systems, the higher the level of traceability efforts in the BTS, the better the traceability preferences of consumers can be satisfied.

In our study, we consider whether the manufacturer and the retailer decide to use blockchain to enhance traceability in the FSC. Each agent in the FSC makes its own pricing decision. The definitions of different models and some important variables are described in Table 3 to enhance readability

Table 3. Abbreviation and definitions of variables.

Notation/Acronym	Meaning
FSC	Food Supply Chain
BTS	Blockchain-based Tracing Systems
BaaS	Blockchain-as-a-Service
NBT	Non-blockchain-based Traceability
BBT	Basic Blockchain-based Traceability
SBT	Self-implemented Blockchain-based Traceability
$\boldsymbol{i}$	Abbreviation of the different Model $i = N, B, SM, SR$
$\boldsymbol{U_i}$	Consumers' utility of purchasing the food
$\boldsymbol{v}$	Consumers' valuation of the food
$\boldsymbol{D_i}$	The demand of the retailer
$\boldsymbol{\alpha}$	Probability that a food may have a quality and safety problem
$\boldsymbol{g}$	Consumers' concern about personal traceability information
$\boldsymbol{\theta}$	Consumers' sensitivity to the food traceability
$\boldsymbol{t_i}$	The traceability effort of the food (NBT, BBT and SBT)
$\boldsymbol{k_i}$	The cost coefficient of traceability effort
$\boldsymbol{K_i(t)}$	The traceability cost
$\boldsymbol{p_i}$	The retail price of food products
$\boldsymbol{w_i}$	The wholesale price of the manufacturer
$\boldsymbol{c_b}$	The unit service fee c_b from BTS
$\boldsymbol{\pi_{mi}}$	The profit of the manufacturer
$\boldsymbol{\pi_{ri}}$	The profit of the retailer

3.1 Model N: Non-blockchain-based tracing systems

In Model N, we assume the food traceability sensitive consumer θ has the possibility α to encountering food safety problems. Following (Pun et al., 2021; Shen et al., 2022), we investigate the situation where all the supply chain members have a perception that food safety issues might occur. Plus, to describe the manufacturer's traceability efforts for food without using blockchain, we denote t_n as the non-blockchain-based traceability (NBT) effort. Meanwhile, considering the increased NBT efforts can enhance consumer ability to distinguish foods quality and safety. Thus, αt_n indicates the positive utility of consumers successfully detecting a food safety problem, and $\alpha(1 - t_n)$ represents the negative utility of buying a product with quality or safety issues. This assumption is in line with previous studies (Luo & Choi, 2022).

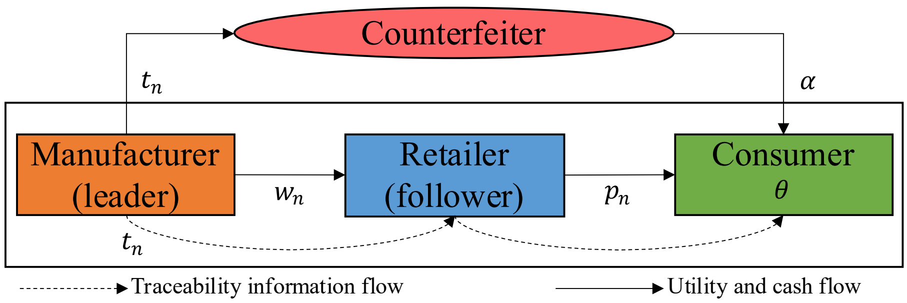


Figure 3. The structure of the FSC in Model N.

We consider a single consumer market in which consumers have a heterogeneous valuation v of the food. We assume v follows a distribution $f(\cdot)$, which is a uniform distribution with a lower bound of 0 and an upper bound of 1. When the consumer decides whether to buy the food, they will consider factors including (i) the retail price p_n; (ii) the level of traceability, which we denote by θt_n; and (iii) the risks of consumers suffering from food safety issues $\alpha(1 - t_n)$. Noting that consumers choose to buy the food when the consumers' utility $U_n = v - p_n - \alpha(1 - t_n) + \theta t_n > 0$. Then, the demand function is given as follows:

$$D_n = 1 - p_n - \alpha(1 - t_n) + \theta t_n \tag{1}$$

The structure of the FSC in the Model N is shown in Fig. 3 and the sequence of events is as follows. The manufacturer determines the wholesale price w_n and NBT effort t_n as the FSC leader. Then, the retailer determines the retail price p_n as the follower. To focus on our main research problem and avoid trivial cases, we assume that the manufacturer's production cost and the retailer's selling cost are zero (Liu et al., 2022; Pun et al., 2021; Wu & Wang, 2023). However, we consider the NBT cost $K_n(t_n)$ incurred by the manufacturer in implementing non-blockchain-based measures, which is given by $k_n {t_n}^2/2$, where $k_n > 0$ and represents the NBT cost coefficient (Chen et al., 2017; He & Ma, 2022; Zhao et al., 2022). Intuitively, improving the traceability level indicates more information sharing among FSC members, like stricter food distribution monitoring, and more advanced security measures, etc. Those lead to a non-trivial cost when the desirable NBT level is higher. It is therefore reasonable to apply a quadratic cost structure, which reflects the fact that the marginal NBT cost increases for achieving a higher traceability level.

Figure 4. Sequence of events for Model N.

Thus, the profit functions of the manufacturer (π_m) and the retailer (π_r) are given as follows:

$$\pi_{mn}(w_n, t_n) = w_n D_n - K_n(t) \tag{2}$$

$$\pi_{rn}(p_n) = (p_n - w_n)D_n \tag{3}$$

Using backward induction, we derive the optimal decisions of the FSC without blockchain. For a given w_n, checking the second-order condition of (3.3), we find that $\frac{\partial^2 \pi_{rn}}{\partial {p_n}^2} = -2 < 0$, which implies that (3.3) is a concave function. Then by solving the first-order condition of (3.3), we derive the optimal retail price for given w_n and t_n. Putting ${p_n}^*(w_n, t_n)$ into the demand function (3.1), we derive the optimal demand for given w_n and t_n, i.e., ${D_n}^*(w_n, t_n)$. Then putting it into (3.2), we find that π_{mn} is jointly concave in w_n and t_n when $k_n > \frac{(\theta+\alpha)^2}{4}$, so we derive the analytical closed-form expressions of the equilibrium wholesale price ${w_n}^* = 2k_n A$, the traceability effort ${t_n}^* = (\alpha + \theta)A$, and the retail price ${p_n}^* = 3k_n A$, where, $A = \frac{(1-\alpha)}{4k_n - (\alpha+\theta)^2}$. Note that it is reasonable to set $k_n > \frac{(\theta+\alpha)^2}{4}$, which indicates that exerting effort to raising improving the identifiability of genuine food is expensive. Hence, we yield the optimal profit of both manufacturer and retailer as follows: ${\pi_{mn}}^* = \frac{k_n(1-\alpha)}{2}A$, ${\pi_{rn}}^* = {k_n}^2 A^2$. Next, we perform sensitivity analyses on key parameters of Model N, and summarize the sensitivity analyses results in Table 4. From the results, we generate the following insights.

Choi, (2019) finds that the increase in fake certification leads to a monotonic decrease in market price and supply chain profit. Different from their findings, we find that food safety risk (α) increases FSC prices when $k_n < (2 - \alpha + \theta)(\alpha + \theta)/4$, and FSC profits rise with α when $k_n < (1 + \theta)(\alpha + \theta)/4$. This is counterintuitive and depends on the value of the NBT cost coefficient (k_n). When k_n is small, it allows food manufacturers to improve traceability more efficiently, helping consumers better identify genuine foods. The prevalence of unsafe food may lead consumers to be more willing to pay a higher price for the increase of NBT levels, resulting in increased profits for safety assured foods. Moreover, we also find that food safety risk induces traceability improvement when k_n lower than a certain threshold, or (α, θ) are low; FSC prices, profits and NBT effort increase with traceability sensitivity θ but decrease with NBT cost coefficient k_n monotonically. All the sensitivity analyses results of Model N are summarized in Appendix.

Table 4. The results of the sensitivity analyses in Model N.

	$\boldsymbol{\alpha}\uparrow$	$\boldsymbol{\theta}\uparrow$	$\boldsymbol{k_n}\uparrow$
$\boldsymbol{p_n}^*$	$\downarrow$: $k_n > (\alpha+\theta)(2-\alpha+\theta)/4$ $\uparrow$: $(\theta+\alpha)^2/4 < k_n < (\alpha+\theta)(2-\alpha+\theta)/4$	$\uparrow$	$\downarrow$
$\boldsymbol{w_n}^*$	$\downarrow$: $k_n > (\alpha+\theta)(2-\alpha+\theta)/4$ $\uparrow$: $(\theta+\alpha)^2/4 < k_n < (\alpha+\theta)(2-\alpha+\theta)/4$	$\uparrow$	$\downarrow$
$\boldsymbol{t_n}^*$	$\downarrow$: $(0 < \alpha \le \frac{1}{2} \&\& 1-2\alpha < \theta < 1 \&\& k_n > E) \| \| (\frac{1}{2} < \alpha < 1 \&\& 0 < \theta < 1 \&\& k_n > E)$ $\uparrow$: $(0 < \alpha \le \frac{1}{2} \&\& 0 < \theta \le 1-2\alpha) \| \| (1-2\alpha < \theta < 1 \&\& k_n < E))) \| \| (\frac{1}{2} < \alpha < 1 \&\& 0 < \theta < 1 \&\& k_n < E)$	$\uparrow$	$\downarrow$
$\boldsymbol{\pi_{rn}}^*$	$\downarrow$: $k_n > (2-\alpha+\theta)(\alpha+\theta)/4$ $\uparrow$: $(\theta+\alpha)^2/4 < k_n < (2-\alpha+\theta)(\alpha+\theta)/4$	$\uparrow$	$\downarrow$
$\boldsymbol{\pi_{mn}}^*$	$\downarrow$: $k_n > (1+\theta)(\alpha+\theta)/4$ $\uparrow$: $(\theta+\alpha)^2/4 < k_n < (1+\theta)(\alpha+\theta)/4$	$\uparrow$	$\downarrow$

$where\ E = (1+\theta)(\alpha+\theta)^2/4(2\alpha+\theta-1)$

3.2 Model B: Adopting third-party BTS

We now consider the case that the FSC members purchase a third-party BTS from a technology company (i.e., IMB, Alibaba) to enhance food traceability. In the FSC practice, the cost of BaaS varies depending on the type and number of blockchain nodes, the amount of storage space used, the network bandwidth consumed, etc. Besides, the FSC members may have different needs and preferences for using the BaaS. For example, a manufacturer may need more storage space and security features than a retailer, while a retailer may need more transaction speed and scalability than a manufacturer. The structure of the FSC in Model B has shown in Fig. 5.

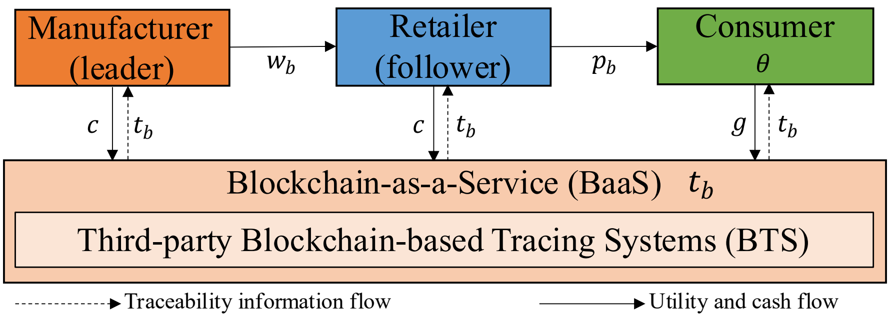


Figure 5. The structure of the FSC in Model B

First, in Model B, technology giants provide third-party BTS as BaaS to FSC, offering a basic blockchain-based traceability (BBT) level t_b, and charging a unit service fee c to each FSC member. t_b can be considered as a basic level of food traceability effort in the context of blockchain adoption, and is an exogenous variable. The case of endogenous traceability efforts will be discussed in the extended analysis. It should be noted that $t_n < t_b \leq 1$ due to the real-time visibility and data access provided by BTS to all FSC participants, facilitating enhanced collaboration and trust compared to non-blockchain-based tracing systems. Second, the BTS ensures that data is stored and verified by multiple nodes in a network, which makes it impossible to tamper with or manipulate, so the possibility of consumers experiencing food safety problems is set to zero (Choi, 2019). Third, when consumers buy food products endorsed by the BTS, there may be concern about their personal information being collected and misused[26], or exposing unwanted details of the food's previous exchanges when regifting it. Following (Liu et al., 2022; Pun et al., 2021), we denote the dis-utilities associated with the consumer privacy concern as g. We summarized the impact of blockchain on model setups in Table 5, and the decision sequence of Model B is shown in Fig. 6.

Figure 6. Sequence of events for Model B.

[26] https://identitymanagementinstitute.org/blockchain-data-privacy-concerns/

Table 5. Features of using blockchain for the FSC.

Features of FSC	Without BTS	With BTS	Features of blockchain technology
Food traceability level	t_n (NBT)	t_b (BBT)	Real-time data acquisition and greater visibility
Food safety concerns	$\alpha(1 - t_n)$	None	Asymmetric cryptography and permanent data record
Privacy concerns	None	g	Public blockchain and distributed ledgers

As discussed above, we have the consumers' utility function $U_b = v - p_b - g + \theta t_b$. Following Niu et al. (2021) and Wu et al. (2021), and the same market assumptions in Model N, the demand for food at a given price p_b and BBT effort t_b is expressed as the following:

$$D_b = 1 - p_b - g + \theta t_b \tag{4}$$

We set the constant parameter c as the unit service fee for using third-party BTS, which means the manufacturer and the retailer should pay for using the third-party BTS service respectively (Liu et al., 2022). This is also consistent with industrial practice. For instance, the Microsoft Azure Blockchain Service charges $0.10 per transaction unit per hour for their standard version of BaaS services[27]. Following the same approach in Model N, we present the profit functions of the manufacturer and the retailer below:

$$\pi_{mb}(w_b) = (w_b - c)D_b \tag{5}$$

$$\pi_{rb}(p_b) = (p_b - w_b - c)D_b \tag{6}$$

Since the proofs of the optimal solutions for Model B are similar to Model N, we omit them and similarly for the extended model. Using backward induction, we derive the optimal decisions under Model B. First, the equilibrium wholesale price and retail price are: ${w_b}^* = \frac{1}{2}B, {p_b}^* = \frac{1}{4}(3B + 2c)$, where $B = 1 - g + \theta t_b$, the abbreviation also captures the non-economic effect of adopting third-party BTS. Substituting ${w_b}^*$ and ${p_b}^*$ into (3.5) and (3.6), respectively, we derive the optimal profits

[27] https://azure.microsoft.com/zh-cn/pricing/details/app-service/windows/

at the optimal prices under Model B as follows: $\pi_{rb}{}^* = \frac{1}{16}(B-2c)^2, \pi_{mb}{}^* = \frac{1}{8}(B-2c)^2$. Next, we perform sensitivity analyses on key parameters of Model B, and summarize the sensitivity analyses results in Table 6.

Table 6. The results of the sensitivity analyses in Model B.

	$c\uparrow$	$\theta\uparrow$	$\beta\uparrow$	$t_b\uparrow$
$p_b{}^*$	↑	↑	↓	↑
$w_b{}^*$	–	↑	↓	↑
$\pi_{rb}{}^*$	↓	↑	↓	↑
$\pi_{mb}{}^*$	↓	↑	↓	↑

From the derived optimal decisions of the retailer and the manufacturer when blockchain technology is adopted, we find that higher consumer privacy concern yields lower prices and profits for the FSC. (Liu et al., 2022) derived similar results but in a different supply chain context. In addition, we extend the conclusions of (Fan et al., 2022) to show that a higher level of BBT and consumer traceability sensitivity can also result in higher prices and profits for the FSC. Moreover, we find that an increase in BTS service fees only increases the retail price but reduces the profits of the whole FSC. Although this conclusion seems intuitive, it is novel compared to existing blockchain-based OM studies, which find that the optimal wholesale price is independent of BTS service fees (Choi, 2019; Fan et al., 2022; Liu et al., 2022; Shen et al., 2022; Wu & Wang, 2023). While, it also means that the third-party BTS providers can influence the food's retail price. Therefore, compared to outsourcing food traceability to a third-party BTS, is it wise and beneficial to self-implement BTS and endogenously determine traceability efforts? We will explore this in Section 5.

4. The value of blockchain in the FSC

Now, we examine the value of adopting blockchain technologies in FSC. We need to understand when blockchain is beneficial to supply chain agents. The comparison of optimal decision between Model B and Model N are summarized in Table 7.

4.1 Effects of using blockchain on FSC prices

By comparing the optimal solutions under Model N and Model B (i.e., $\Delta w = w_b{}^* - w_n{}^*$, $\Delta p = p_b{}^* - p_n{}^*$), we derive the following proposition.

Proposition 1. *The prices in the FSC with blockchain are higher than those without blockchain if and only if any of the following conditions hold: (i) when* $4k_nA < B$*,* $\Delta w > 0$*; (ii) when* $12k_nA < 3B + 2c$*,* $\Delta p > 0$.

Proposition 4.1 shows the effect of blockchain adoption on the pricing decision of the manufacturer and retailer. Noting that the parameter B is a critical factor, which captures the non-economic effect of adopting third-party BTS. Specifically, if consumers are less concerned about their personal information, or the third-party BTS provides a higher level of traceability effort, then the manufacturer and retailer can increase their prices by using blockchain. The results are reasonable because if most consumers are keen to find ways to buy food with more traceability information, they could be food traceability-sensitive rather than price-sensitive. Thus, a higher price is acceptable with blockchain adoption, particularly for high-valued food products. Moreover, if the third-party BTS can provide more reassuring consumer information protection, it will further encourage people to buy blockchain certified foods. In addition, from Proposition 1, we can see that although the third-party BTS provider charges a unit service fee to each member of the FSC, all the costs in the equilibrium result act on the retail price. Hence, there has an increase in the retail price when $c > \frac{3[4k_nA-B]}{2}$.

Table 7**.** Comparison of optimal decision between Model B and Model N.

Parameter	Condition
$\boldsymbol{\Delta D} = \boldsymbol{D_b}^* - \boldsymbol{D_n}^* > \mathbf{0}$	$c < \frac{B-4k_nA}{2}$
$\boldsymbol{\Delta w} = \boldsymbol{w_b}^* - \boldsymbol{w_n}^* > \mathbf{0}$	$4k_nA < B$ (i.e., $g < 1 + \theta t_b - 4k_nA \; or \; t_b > \frac{4k_nA-1+g}{\theta}$)
$\boldsymbol{\Delta p} = \boldsymbol{p_b}^* - \boldsymbol{p_n}^* > \mathbf{0}$	$12k_nA < 3B + 2c$ (i.e., $t_b > \frac{12k_nA+g-2c-3}{3\theta} \; or \; g < \frac{1+\theta t_b-12k_nA+2c}{3} \; or \; c > \frac{3[4k_nA-B]}{2}$)
$\boldsymbol{\Delta \pi_r} = \boldsymbol{\pi_{rb}}^* - \boldsymbol{\pi_{rn}}^* > \mathbf{0}$	$c < \frac{B-4k_nA}{2} \; or \; c < \frac{4(1-\alpha)+B[(\alpha+\theta)^2-4]}{2[(\alpha+\theta)^2-4]} \&\& k_n > \frac{(B-2c)(\alpha+\theta)^2}{4((B-2c)-(1-\alpha))}$
$\boldsymbol{\Delta \pi_m} = \boldsymbol{\pi_{mb}}^* - \boldsymbol{\pi_{mn}}^* > \mathbf{0}$	$c < \frac{1}{2}B - \sqrt{k_n(1-\alpha)A} \; or \; c < \frac{1}{2}(\alpha - g + t\theta) \&\& k_n > \frac{(B-2c)^2(\alpha+\theta)^2}{4((B-2c)^2-(1-\alpha)^2)}$

$A = (1-\alpha)/4k_n - (\alpha+\theta)^2$; $B = 1 - g + \theta t_b$

4.2 Effects of using blockchain on FSC profits

Comparing the optimal expected profits under Model N and Model B (i.e., $\Delta\pi_m = \pi_{mb}{}^* - \pi_{mn}{}^*$, $\Delta\pi_r = \pi_{rb}{}^* - \pi_{rn}{}^*$). we derive the following proposition:

Proposition 2. *Using blockchain to improve the traceability and food safety of the FSC has a positive impact on the profits of the manufacturer and retailer, only if any of the following conditions hold: (i) When* $c < \frac{B}{2} - \sqrt{k_n(1-\alpha)A}$, *we have* $\Delta\pi_m > 0$; *(ii) When* $c < \frac{B-4k_nA}{2}$, *we have* $\Delta\pi_r > 0$.

The most critical factor in determining whether supply chain firms should use blockchain is its cost. Proposition 2 gives the necessary conditions on costs to determine whether the manufacturer and the retailer can benefit from blockchain. When c is small enough, using blockchain becomes beneficial to both manufacturer and retailer. Meanwhile, we find that the manufacturer is more likely to benefit from the adoption of blockchain than the retailer, as the manufacturer can reach the conditions for profitable blockchain adoption earlier than the retailer when service fees charged by third-party BTS decline. Additionally, we notice that the non-economic impact of adopting BTS can also influence the decision on blockchain adoption. For example, lowering the upper bound of g can further increase the threshold of c that makes using blockchain more profitable (i.e., when $0 < g < \frac{1+\theta t_b-4kA}{2} - 2c < 1$ *and* $c < \frac{B-4k_nA}{2} < \frac{1+\theta t_b-4kA}{2}$, we still have $\pi_{rb}{}^* > \pi_{rn}{}^*$). That means it is necessary to reduce consumer concerns about personal privacy or ensure that the third-party BTS provides a higher level of food's traceability.

Proposition 2 indicates that using blockchain may not be necessary for FSC. For FSC members who have not adopted blockchain, the NBT cost coefficient can also affect the value of $\Delta\pi_m$ and. $\Delta\pi_r$. Based on Proposition 2, we derive the following corollary:

Corollary 1. *When* $k_n < \frac{(B-2c)(\alpha+\theta)^2}{4((B-2c)-(1-\alpha))}$, *we have* $\Delta\pi_m < 0$, $\Delta\pi_r < 0$.

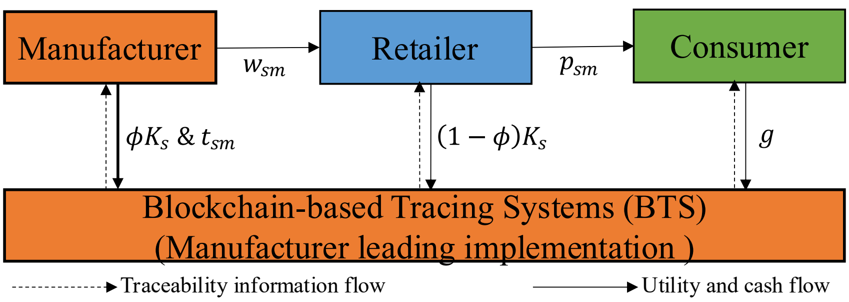
It is clear from Corollary 1 that there exists a threshold for k_n that abandoning blockchain is more profitable. This highlights the fact that if the NBT level can be efficiently improved, FSC members should not blindly vote for using blockchain. (Choi & Ouyang, 2021; Li et al., 2021; Liu et al., 2022; Niu et al., 2021; Shen et al., 2022; Wu et al., 2022) have used similar methods to demonstrate the value of blockchain by comparing the equilibrium results of whether the BTS is used or not. Enriching existing research, we show that FSC members who do not adopt blockchain can achieve comparable outcomes by efficiently improving their NBT levels. Additionally, (Biswas et al., 2023; Choi, 2022; Niu et al., 2021) also analyze the value of blockchain from a cost-benefit perspective. We differ from them by emphasizing the cost coefficient of NBT effort and advocating for judicious consideration of the value of blockchain in food traceability

5. Extension: Self-implements the BTS

Now we examine the scenario in which FSC members self-implement their own BTS. Although some well-known food manufacturers and retailers like Diageo or JD have already implemented their own BTS, FSC members may have conflicting interests or incentives that hinder their willingness to participate in the self-implementation of BTS due to the high investment and uncertain benefits. In the following analysis, we will discuss the cases where manufacturers and retailers lead the implementation of BTS, and explore the optimal strategy for using blockchain (i.e., outsourcing or self-implement). In the FSC, we assume that whoever leads the implementation of the BTS will have the right to determine the Self-implemented Blockchain-based Traceability (SBT) efforts. Other FSC agents may need to bear a certain share of the SBT cost, which is consistent with industry practice.

5.1 Model SM: Manufacturer leading the implementation of the BTS

First, we explore the situation of the manufacturer leading the BTS implementation. For example, the Spirits maker Diageo announced to launch a blockchain-based track-and-trace system for its bottles to combat counterfeiting and boost the company's sustainability practices, and ensure the food traceability is self-controlled and more flexible[28].



[28] https://timesofindia.indiatimes.com/business/india-business/diageo-eyes-blockchain-tech-to-check-pilferage/articleshow/92026777.cms

Figure 7. The structure of the FSC in Model SM.

In Model SM, the manufacturer takes the lead to implement BTS across the entire FSC and determines the level of SBT effort t_{sm} and the wholesale price w_{sm} first. Then, the retailer decides on the retail price p_{sm}. Consumer privacy concerns g are consistent with the settings in Model B. The decision structure of the FSC in Model SM is shown in Fig. 3. Following the same market assumptions in the basic model, we have the demand and profit function in Model SM:

$$D_{sm} = 1 - p_{sm} - g + \theta t_{sm} \tag{7}$$

$$\pi_{m-sm}(w_{sm}, t_{sm}) = w_{sm} D_{sm} - \phi K_{sm}(t_{sm}) \tag{8}$$

$$\pi_{r-sm}(p_{sm}) = (p_{sm} - w_{sm}) D_{sm} - (1 - \phi) K_{sm}(t_{sm}) \tag{9}$$

Specifically, k_s indicates the cost coefficient of food traceability when the manufacturer or the retailer self-implements the BTS; ϕ $(0 \leq \phi \leq 1)$ refers to the proportion of the SBT cost paid by the manufacturer; K_{sm} represents the SBT cost of the FSC, where $K_{sm} = [k_s {t_b}^2 + k_s (t_{sm} - t_b)^2]/2$. Considering a higher traceability level means more data needs to be recorded and verified on the blockchain, which increases the complexity and resource consumption of the system, it is reasonable to apply a quadratic cost structure. This has also been validated by previous studies (Liu et al., 2022; Wu et al., 2022). However, this study further considers the cost structure of endogenous traceability efforts when adopting the BTS. For the manufacturer or the retailer who wants to self-implement BTS, they should reference existing third-party BTS in the market when designing their own BTS, and their requirement for the SBT level should be higher than that of BBT ($t_{sm} > t_b$). Otherwise, they will have no incentive to implement blockchain technology themselves. Hence, the SBT cost structure consists of the sum of the BBT effort level part $k_s {t_b}^2/2$ and the enhancement part $k_s (t_{sm} - t_b)^2/2$. (Song et al., 2022) considered a similar cost structure for blockchain-based information disclosure, but with a binary constant cost.

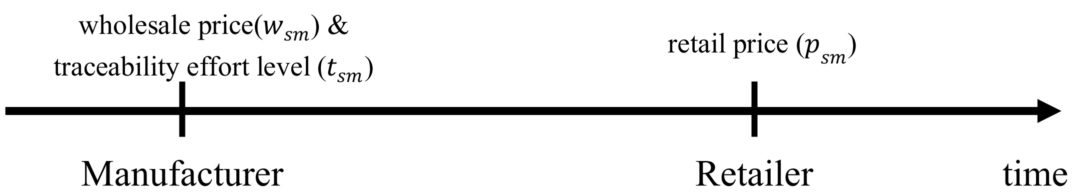


Figure 8. Sequence of events for Model SM.

Table 8. The equilibrium decisions in Model SM.

Parameter	Equilibrium results in Model SM
$\boldsymbol{D_{sm}}^*$	$k_s\varphi B/E$
$\boldsymbol{w_{sm}}^*$	$2k_s\varphi B/E$
$\boldsymbol{p_{sm}}^*$	$3k_s\varphi B/E$
$\boldsymbol{t_{sm}}^*$	$\theta - \theta g + 4k_s\varphi t_b/E$
$\boldsymbol{\pi_{m-sm}}^*$	$(B^2 - t_b{}^2E)k_s\varphi/2E$
$\boldsymbol{\pi_{r-sm}}^*$	$k_sB^2[E - E\varphi + 2k_s\varphi(3\varphi - 2)]/2E^2 - k_st_b{}^2(1-\varphi)/2$

$B = 1 - g + \theta t_b$; $E = 4k_s\varphi - \theta^2$

Following the same approach above, we have the equilibrium decisions given in Table 8. Next, we conduct sensitivity analyses of the above extended models with respect to the key parameters to gain more insights. We report the results of the sensitivity analyses derived from checking the corresponding first-order derivatives of the optimal solutions. The results of the sensitivity analyses in Model SM are summarized in Appendix A, Table A1.

For the retailer: (i) π_{r-sm} decreases with g when $0 < \varphi \leq \frac{2}{3}$ and $k_s > \frac{\theta^2 - \theta^2\varphi}{2\varphi^2}$ or $\frac{2}{3} < \varphi < 1$ and $k_s > \frac{\theta^2}{4\varphi}$. When the retailer needs to afford less than $1/3$ of the SBT cost, the increasing consumer privacy concerns make the retailer's profit decrease, which is similar to the case in Model B. While the difference is that when the retailer needs to afford more than $1/3$ of the cost, it is the higher cost coefficient ($k_s > \frac{\theta^2 - \theta^2\varphi}{2\varphi^2}$) that causes the negative utility β to affect the retailer's profit. (ii) π_{r-sm} decreases with t_b when $\varphi < \frac{2}{3}$ and $\frac{\theta^2}{4\varphi} < k_s < \frac{\theta^2 - \theta^2\varphi}{2\varphi^2}$. When the retailer needs to afford a higher SBT cost ($1 - \varphi > \frac{1}{3}$), retailer's profit decreases with the level of BBT effort t_b. This is reasonable, because with a relatively low cost coefficient ($k_s < \frac{\theta^2 - \theta^2\varphi}{2\varphi^2}$), the rational retailer will call for increasing the SBT level t_s to obtain profit growth. Recall that endogenous SBT effort t_s is referred to BBT effort t_b. An increase in t_b is equivalent to narrowing the improvement margin of t_s, which in turn leads to a decrease in retailer profit. (iii) An increase in φ can result in a decrease in retail prices while simultaneously increasing retailer profit under specific conditions, that is, $\varphi \leq \frac{2}{3}$

or $\varphi > \frac{2}{3}$ and $k_s > \frac{\theta^2}{8(1-\varphi)}$. Noting that the cost coefficient will increase when the manufacturer covers at least 2/3 of the cost. This is because if k_s is low, it is difficult for the retailer to gain a profit advantage from further expansion of φ.

For the manufacturer, we find that (i) an increase in the manufacturer's SBT cost share $\varphi \uparrow$ results in a decrease in the wholesale price $w_{sm} \downarrow$, while simultaneously reducing the manufacturer's profitability $\pi_{m-sm} \downarrow$ and input of SBT efforts $t_{sm} \downarrow$. (ii) π_{m-sm} decreases with t_b when $k_s > \frac{B\theta+b\theta^2}{4b\varphi}$, and increase with t_b when $\frac{\theta^2}{4\varphi} < k_s < \frac{B\theta+b\theta^2}{4b\varphi}$. Similar to the analysis of retailer profit, the SBT cost coefficient k_{sm} plays a key role in these effects. If the k_{sm} is too high, the increasing level of BBT efforts will conversely make manufacturers less profitable. In this case, the manufacturer should give up self-implementing the BTS. (iii) In the SM model, it is the manufacturer determines the level of SBT effort t_{sm}, so in the setting where endogenous t_{sm} are considered, we find that t_{sm} increase with the t_b, but decrease with the g. As our assumption, the endogenous SBT effort t_{sm} is an enhancement to the level of BBT effort t_b, therefore the level of BBT provided by the third-party BTS can be considered as a benchmark in Model SM, whereby t_{sm} is monotonically increasing with t_b. However, the increasing privacy concerns $g \uparrow$ implies that consumers do not trust blockchain technology and under such a condition the manufacturer will reduce the level of SBT effort $t_{sm} \downarrow$, which means reducing the investment in blockchain technology.

5.2 Model SR: Retailer leading the implementation of the BTS

Now we explore the situation that the retailer leads the BTS implementation. JD, one of the largest online food retailers in China, uses its self-implemented blockchain platform to provide the highest level of traceability for partner food brands such as Lafite, Torres, and Penfolds, ensuring the authenticity of the food sold on its platform[29]. All partner brand products sold on JD have exclusive blockchain traceability codes for consumers to track the product's supply chain journey[30].

[29] http://finance.ce.cn/gsxw/201805/10/t20180510_29088726.shtml
[30] https://www.ecommercestrategychina.com/column/jd-launches-the-worlds-first-commodities-traceability-mini-program-using-blockchain-technology

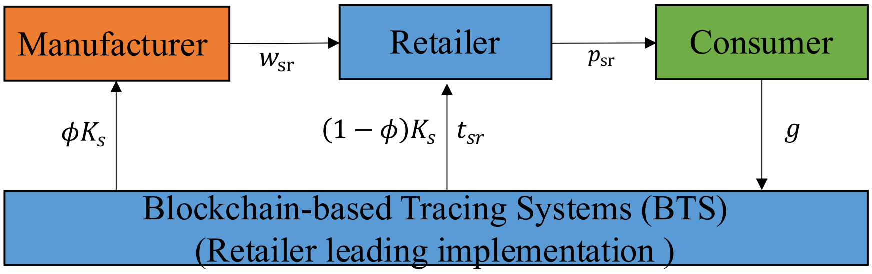


Figure 9. Sequence of events for Model SM.

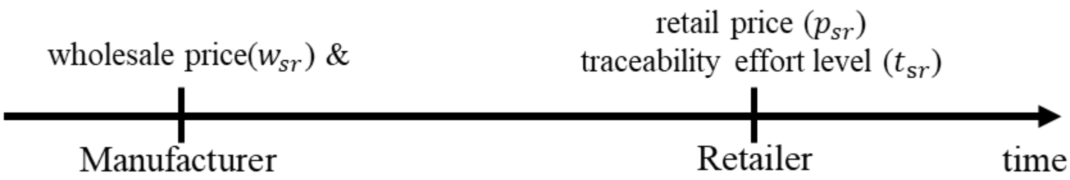


Figure 10. Sequence of events for Model SR.

In Model SR, we consider the retailer leading the implementation of the BTS, the demand and the profit functions are as followed:

$$D_{sr} = 1 - p_{sr} - g + \theta t_{sr} \tag{10}$$

$$\pi_{m-sr}(w_{sr}, t_{sr}) = w_{sr} D_{sr} - \phi K_{sr}(t_{sr}) \tag{11}$$

$$\pi_{r-sr}(p_{sr}) = (p_{sr} - w_{sr}) D_{sr} - (1-\phi) K_{sr}(t_{sr}) \tag{12}$$

Where t_{sr} refers to the SBT level set by the retailer, and the cost function of SBT can be rewritten as:$K_{sr}(t_{sr}) = [k_s {t_b}^2 + k_s(t_{sr} - t_b)^2]/2$. Like the derivations and analyses conducted for Model SM, we can derive the respective equilibrium decisions for Model SR. The equilibrium decisions under Model SR are similar to those for Model SM and summarized in Table 8.

Then, by comparing the findings under Model B, Model SM and Model SR, we have some insights into the way of using the BTS.

Table 8. The equilibrium decisions in Model SR.

Parameter	Equilibrium results in Model SR
$\boldsymbol{D_{sr}}^*$	$Bk_s(1-\varphi)^2/F$

$\boldsymbol{w_{sr}}^*$	$B(2F + \theta^2 - 2k_s(1-\varphi)^2)/3F$
$\boldsymbol{p_{sr}}^*$	$B(2F + \theta^2 + k_s(1-\varphi)^2)/3F$
$\boldsymbol{t_{sr}}^*$	$t_b + \theta(1-\varphi)B/F$
$\boldsymbol{\pi_{m-sr}}^*$	$k_s(B^2(1-\varphi)^2 - t_b{}^2\varphi F)/2F$
$\boldsymbol{\pi_{r-sr}}^*$	$k_s(1-\varphi)(9t_b{}^2F^2 + B^2(\theta^2 + F(-4+3\varphi) + 2k(-1+\varphi)^2(-1+3\varphi)))/18F^2$

$Where\ B = 1 - g + \theta t_{sr};\ F = 4k_s(1-\varphi)^2 + \theta^2(3\varphi - 2)$

5.3 Explore the optimal strategy for implementing blockchain

To figure out which way of using blockchain technology is more beneficial to the FSC members, first, we compare Model SM to Model SR, and derive the following proposition. The comparison results of optimal decision between Model SM and Model SR are summarized in Appendix A, Table A2.

Proposition 3 *For given* $\theta, g, t_b,$ *and* k_s*, we have: (i)* $D_{sm} > D_{sr}$*,* $\pi_{m-sm}{}^* > \pi_{m-sr}{}^*$ *when* $\varphi \neq \frac{1}{2}$*; (ii)* $w_{sm}{}^* > w_{sr}{}^*$*,* $p_{sm}{}^* > p_{sr}{}^*$*,* $t_{sm}{}^* > t_{sr}{}^*$*, and* $\pi_{r-sm}{}^* < \pi_{r-sr}{}^*$ *when* $0 < \varphi < \frac{1}{2}$.

From Proposition 3, we find that the different cost sharing arrangements will yield the following outcomes. When the manufacturer and the retailer share the SBT cost equally, there is no difference in who leads the implementation of the BTS. Otherwise, under any cost sharing arrangement, the demand and manufacturer's profit are strictly larger in Model SM. So, the manufacturer always benefits from leading the implementation of the BTS When the manufacturer shares less than 50% of the cost, there are higher wholesale and retail prices, as well as a higher level of SBT in Model SM. However, the retailer profit is smaller in Model SM. When the manufacturer shares more than 50% of the cost, the comparison results of the retail price, wholesale price, SBT effort and retailer profit will be reversed. It means that the wholesale and retail prices and SBT levels are higher when the BTS lead covers fewer costs. For the retailer, once they need to afford higher costs, they should choose to take the lead in implementing the tracing system themselves.

By comparing Model SM to Model B, we derive the following proposition:

Proposition 4 *For given* θ, g, t_b, φ *and* k_s*, we have:* $D_{sm}{}^* > D_b{}^*$*;* $w_{sm}{}^* > w_b{}^*$*;* $p_{sm}{}^* > p_b{}^*$*, when* $c < min\left[\frac{3B\theta^2}{2E}, \frac{B}{2}\right]$*;* $\pi_{r-sm}{}^* > \pi_{rb}{}^*$*, when*

$min\left[0, \frac{BE-2\sqrt{2k_s({t_b}^2E^2(\varphi-1)+B^2(E-E\varphi+2k_s\varphi(3\varphi-2)))}}{2E}\right] < c < \frac{B}{2};\ {\pi_{m-sm}}^* > {\pi_{mb}}^*,\ when\ min\ [0, \frac{B}{2} - \sqrt{\frac{B^2k\varphi-b^2Ek\varphi}{E}}] < c < \frac{B}{2}.$

The comparison results of optimal decision between Model SM and Model B are summarized in Appendix A, Table A3. In Model SM, manufacturer-led implementation of the BTS can increase demand and wholesale price directly, while it is conditional to raising the retail price, as well as manufacturer and retailer profits. A decrease in service fee c leads to a decrease in the retail price p_b in Model B. Thus, if c is smaller than the certain thresholds, the retail price in Model SM is higher. Meanwhile, it is worth noting that ${p_{sm}}^*$ is strictly larger than ${p_b}^*$when $\frac{\theta^2}{4\varphi} < k_s < \frac{\theta^2}{\varphi}$. That means if the cost coefficient k_s can be controlled within a certain range, Manufacturer-led BTS implementation can achieve a price advantage compared with Model B. For the manufacturer and the retailer, there is a threshold of c that determines which is profitable for the manufacturer to self-implement the BTS or outsourcing, respectively.

Similar to the above analysis, we compared Model SR to Model B and obtained the following findings like Proposition 4. The comparison results of optimal decision between Model SR and Model B are summarized in Appendix A, Table A4. For given θ, g, t_b, φ and k_s, we have: ${D_{\mathrm{sr}}}^* > {D_b}^*$ when $c > \max[0, \frac{B\theta^2(3\varphi-2)}{2F}]$; ${w_{sr}}^* > {w_b}^*$; ${p_{sr}}^* > {p_b}^*$, when $c < \min\ [\frac{B\theta^2(2-\varphi)}{2F}, \frac{B}{2}]$; ${\pi_{r-sr}}^* > {\pi_{rb}}^*$, when $\min\left[0, \frac{3BF+2\sqrt{2k_s(1-\varphi)(9b^2F^2+B^2(\theta^2+F(3\varphi-4)+2k_s(1-\varphi)^2(3\varphi-1)))}}{6F}\right] < c < \frac{B}{2}$; ${\pi_{m-sr}}^* > {\pi_{mb}}^*$, when $\min\ [0, \frac{B}{2} - \sqrt{\frac{B^2k_s-2B^2k_s\varphi-b^2Fk_s\varphi+B^2k_s\varphi^2}{F}}] < c < \frac{B}{2}$. Different from the comparison results between Model SM and Model B, some special cases make the demand higher in Model B compared with Model SR. When the manufacturer has to cover more than 2/3 of the cost of SBT effort ($\varphi > 2/3$), it is a better option for the whole supply chain to seek outsourced Third-party BTS. Besides, the retailer-led implementation of the BTS can increase the retail price directly. The other findings are similar to those in Proposition 4.

6. Conclusions

6.1 Concluding remarks

Food safety is a major issue of people's livelihood, and also a key issue that governments around the world have been committed to safeguard and maintain for a long time. Motivated by the real-world practices of using blockchain to ensure food safety and enhance traceability, this study explores the value of blockchain-based traceability in the FSC. Considering the existing food safety risk and consumers' attitude towards food traceability and information privacy, we develop consumer utility-based analytical models to study the cases without and with blockchain in the basic models. We derive the optimal solutions and uncover the value of blockchain in tracing food products for the FSC by comparing the two scenarios. Furthermore, we extend our analyses to discuss the situation where FSC members endogenously determine the level of BTS traceability effort. By comparing the optimal solutions, we explore an optimal strategy for implementing BTS and provide managerial insights on whether to use blockchain in FSC and how to use it. This also provides some guidance for the government to better facilitate the large-scale adoption of BTS by FSC enterprises. The main findings are summarized as follows:

(i) The existing food safety risk can increase prices and decrease profitability for the FSC members, as well as reduce NBT effort when NBT costs are high. Besides, higher consumer sensitivity and a lower NBT cost coefficient can increase FSC profits. However, there exist thresholds for k_n that make the FSC prices and profits increase with the food safety risk. This differs from (Choi, 2019) but is consistent with industrial practice. This is mainly due to our consideration of NBT's role in enhancing consumers' ability to detect food safety issues. This finding indicates that FSC may not need to adopt blockchain to eliminate food safety issues. The increase in food safety risks can somehow increase consumers' traceability sensitivity. If FSC can efficiently improve the NBT level, consumers will accept the price increase and FSC's profits will also increase.

(ii) When blockchain is adopted, we find the FSC prices and profits increase with higher traceability sensitivity and BBT effort but decrease with higher consumer privacy concerns. This finding extends the results of Liu et al., (2022) to the FSC and adds to the work of Fan et al., (2022) by considering the impact of the BBT effort. Additionally, we found that the optimal wholesale price is independent of BTS service fees.

(iii) The adoption of blockchain can increase the FSC prices with certain conditions. We have derived the threshold for third-party BTS service fees, which will determine whether to trace food products through blockchain. Meanwhile, the moderating effect of consumer traceability preferences and privacy concerns should be considered when paying BTS service fees. Additionally, compared to studies investigating the value of blockchain from a cost-benefit perspective (Biswas et al., 2023; Choi, 2022; Niu et al., 2021), we find that if the NBT effort can effectively work on improving FSC traceability, it may not be necessary for FSC to adopt blockchain. Eliminating food safety issues through BTS may not align with the interests of FSC members.

(iv) Different from Shen et al., (2022) who considered endogenous quality decisions when using blockchain, we consider the traceability effort as the endogenous decision variable, and our analysis focuses more on the cost-sharing of SBT, leading to some new conclusions. We find that increasing the manufacturer's SBT cost share lowers FSC prices and manufacturer profitability, but can increase the retailer's profit under certain conditions. Endogenous SBT effort increases with BBT effort but decreases with consumer privacy concerns. The impact of other key parameters on FSC prices and profits remains consistent with the basic model, with added threshold conditions.

(v) Self-implementing the BTS can increase the wholesale price directly, while it is conditional to raising the demand, retail price, and FSC profits, depending on the service fee of the third-party BTS. Equal SBT cost sharing between the manufacturer and the retailer results in no difference in BTS implementation leadership. Otherwise, the manufacturer benefits from leading. For the retailer, when the manufacturer shares less than half of the cost, the retail price is higher in Model SM, but the retailer profit is smaller. When the manufacturer shares more than half, these results are reversed.

6.2 Managerial implications

Our research provides several managerial implications for the operations of the FSC with blockchain.

The operational solutions of FSC in determining the adoption of blockchain: In Non-blockchain-based tracing systems, the probability of identifying unsafe food is related to the level of food traceability, so food merchants need to weigh the trade-off between NBT costs and guaranteeing the food quality. For the FSC members who do not adopt the BTS, targeting submarkets valuing food traceability and reducing NBT costs are advantageous strategies, which can further avoid price dropping due to the higher food safety risk. When the BTS is adopted, food merchants need to notice the potential increase in retail price resulting from the rise in third-party BTS service fees. Besides, alleviating privacy concerns and enhancing cybersecurity are crucial for blockchain adoption in FSC.

From the government's perspective, the government can help FSC members make better operational decisions by providing information, education, and incentives for using blockchain or non-blockchain-based tracing systems. The government can also help FSC members target submarkets that value food traceability and quality, and reduce their costs of non-blockchain-based tracing. Moreover, the government can play a key role in alleviating privacy concerns and enhancing cybersecurity for blockchain adoption in FSC, by setting standards, regulations, and best practices for data protection and risk management.

The value of blockchain in the FSC: Manufacturers and retailers can increase prices with blockchain adoption, as traceability-sensitive consumers may prioritize traceability over price. Enhanced consumer information protection by BTS further incentivizes purchases of blockchain-certified food. In addition to the two mentioned value-adding measures that result in price growth, the FSC members also need to be aware of the forced price increase caused by the service fees charged by third-party BTS. When the service fees of BTS are relatively low, using blockchain is always a more profitable choice. However, when the service fees of BTS increase, if third-party BTS cannot provide BBT levels that match their service prices, or if consumer privacy concerns exceed a certain level, using blockchain is not economically viable. In this case, using blockchain technology to satisfy consumer traceability preferences may not be financially rewarding for the FSC. This is because some consumers might be reluctant (e.g., because of concerns about privacy issues) to blockchain certified food products. Considering the benefits that blockchain brings to the FSC, the manufacturer is more likely to accept the transition to adopt the BTS due to the relatively small impact of service fees, which may harm the retailer's interests.

From the government's perspective, the government can increase the value of blockchain in the FSC by creating a favorable environment and demand for blockchain-certified food products. The government can do this by raising consumer awareness and trust in blockchain technology, and by promoting its benefits for food safety, quality, and traceability. The government can also monitor and control the service fees of third-party BTS, and ensure that they are reasonable and transparent. Furthermore, the government can balance the interests of different FSC members, and prevent conflicts or unfairness caused by blockchain adoption. The government can also benefit from the increased prices and profits of FSC members, by collecting taxes or fees from them.

The implications of the ways to adopt blockchain: Compared to purchasing a third-party BTS, FSC members need to pay extra attention to two key factors when self-implementing the BTS: the cost coefficient and the cost-sharing arrangement of SBT. Taking the manufacturer-led BTS implementation as an example, if the cost borne by the retailer exceeds 1/3, only when the cost coefficient reaches the threshold will the negative utility of the blockchain affect the retailer's profit. Moreover, if the SBT cost coefficient is too high, an increase in the BBT effort level may instead reduce the manufacturer's profit. If the SBT cost coefficient can be controlled, self-implementing the BTS can achieve a more competitive advantage over outsourcing. Meanwhile, the FSC members should promptly determine the threshold of third-party BTS service fees that can determine whether outsourcing BTS or self-implementing the BTS is more profitable. Besides, when the BTS leader bears less SBT cost, both the prices and traceability level of the FSC will be higher. Plus, the retailer needs to pay extra attention once they need to bear higher costs. They should choose to lead the BTS implementation themselves.

From the government's perspective, the government can provide guidance and incentives for FSC members to choose the most suitable way to adopt BTS, whether it is outsourcing or self-implementing. The government should consider two key factors when evaluating the different ways to adopt BTS: the cost coefficient and the cost-sharing arrangement of SBT. For example, if the government wants to promote self-implementation of BTS, it can subsidize the SBT cost or regulate the cost-sharing among FSC members. The government should also monitor the service fees of third-party BTS and ensure that they are reasonable and transparent. Moreover, the government should encourage FSC members to cooperate and coordinate on the BTS implementation, and avoid conflicts of interest or power imbalance among them. The government can also benefit from having more control and oversight over the BTS, which can help them improve food safety, quality, and traceability.

6.3 Future studies

We note some potential directions for future research. Firstly, the FSC is a complex system. Given the numerous stages involved in food production and processing, it would be interesting to explore a multi-level supply chain model. Additionally, as crypto-currency transactions are becoming more common within the FSC, it would be valuable to investigate the impact of crypto-currency on the fairness of FSC transactions and FSC structure. Finally, it would be interesting to investigate how the risk-averse attitudes of FSC members may influence their investments in BTS.

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Appendix A

Table A1. The results of the sensitivity analyses in Model SM.

	$\boldsymbol{\theta}\uparrow$	$\boldsymbol{g}\uparrow$	$\boldsymbol{t_b}\uparrow$	$\boldsymbol{k_s}\uparrow$	$\boldsymbol{\varphi}\uparrow$
$\boldsymbol{p_{sm}}^*$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$
$\boldsymbol{w_{sm}}^*$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$
$\boldsymbol{t_{sm}}^*$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$
$\boldsymbol{\pi_{r-sm}}^*$	$\uparrow$: $\frac{1}{2}<\varphi<\frac{2}{3}$ && $k_s>\frac{\theta^2-\theta^2\varphi}{-4\varphi+8\varphi^2}$	$\downarrow$: $(0<\varphi\leq\frac{2}{3}$&&$k_s>\frac{\theta^2-\theta^2\varphi}{2\varphi^2})\|\|(\frac{2}{3}<\varphi<1$&&$k_s>\frac{\theta^2}{4\varphi})$	$\downarrow$: $\varphi<\frac{2}{3}$&&$\frac{\theta^2}{4\varphi}<k_s<\frac{\theta^2-\theta^2\varphi}{2\varphi^2}$	$\downarrow$: $\frac{1}{2}<\varphi<\frac{2}{3}$&&$k_s>\frac{\theta^2-\theta^2\varphi}{-4\varphi+8\varphi^2}$ or $\varphi>\frac{2}{3}$	$\uparrow$: $\varphi\leq\frac{2}{3}$ or $\varphi>\frac{2}{3}$&&$\frac{\theta^2}{8(1-\varphi)}<k_s$
$\boldsymbol{\pi_{m-sm}}^*$	$\uparrow$	$\downarrow$	$\downarrow$: $k_s>\frac{B\theta+t_b\theta^2}{4b\varphi}$ $\uparrow$: $\frac{\theta^2}{4\varphi}<k_s<\frac{B\theta+t_b\theta^2}{4b\varphi}$	$\downarrow$	$\downarrow$

Table A2. Comparison of optimal decision between Model SM and Model SR.

Parameter	Differences
$\Delta\boldsymbol{D_s}^*$	$\varphi=\frac{1}{2}$: $D_{sm}=D_{sr}$;
	$\varphi\neq\frac{1}{2}$: $D_{sm}>D_{sr}$
$\Delta\boldsymbol{w_s}^*$	$0<\varphi<\frac{1}{2}$: $w_{sm}^*>w_{sr}^*$;
	$\varphi=\frac{1}{2}$: $w_{sm}^*=w_{sr}^*$;
	$\frac{1}{2}<\varphi<1$: $w_{sm}^*<w_{sr}^*$
$\Delta\boldsymbol{p_s}^*$	$0<\varphi<\frac{1}{2}$: $p_{sm}^*>p_{sr}^*$;
	$\varphi=\frac{1}{2}$: $p_{sm}^*=p_{sr}^*$;

	$\frac{1}{2} < \varphi < 1$: ${p_{sm}}^* < {p_{sr}}^*$
$\Delta \boldsymbol{t_s}^*$	$0 < \varphi < \frac{1}{2}$: ${t_{sm}}^* > {t_{sr}}^*$;
	$\varphi = \frac{1}{2}$: ${t_{sm}}^* = {t_{sr}}^*$;
	$\frac{1}{2} < \varphi < 1$: ${t_{sm}}^* < {t_{sr}}^*$
$\Delta \boldsymbol{\pi_{r-s}}^*$	$0 < \varphi < \frac{1}{2}$: ${\pi_{r-sm}}^* < {\pi_{r-sr}}^*$;
	$\varphi = \frac{1}{2}$: ${\pi_{r-sm}}^* = {\pi_{r-sr}}^*$;
	$\frac{1}{2} < \varphi < 1$: ${\pi_{r-sm}}^* > {\pi_{r-sr}}^*$
$\Delta \boldsymbol{\pi_{m-s}}^*$	$\varphi = \frac{1}{2}$: ${\pi_{m-sm}}^* = {\pi_{m-sr}}^*$;
	$\varphi \neq \frac{1}{2}$: ${\pi_{m-sm}}^* > {\pi_{m-sr}}^*$

Table A3. Comparison of optimal decision between Model SM and Model B.

Parameter	Differences
$\Delta \boldsymbol{D_{sm}}^*$	${D_{sm}}^* > {D_b}^*$
$\Delta \boldsymbol{w_{sm}}^*$	${w_{sm}}^* > {w_b}^*$
$\Delta \boldsymbol{p_{sm}}^*$	$c < \min\left[\frac{3B\theta^2}{2E}, \frac{B}{2}\right] : {p_{sm}}^* > {p_b}^*$;
	$\frac{3B\theta^2}{2E} < c < \frac{B}{2}$ *and* $k_s > \frac{\theta^2}{\varphi}$: ${p_{sm}}^* < {p_b}^*$
$\Delta \boldsymbol{\pi_{r-sm}}^*$	$\min\left[0, \frac{BE - 2\sqrt{2k_s({t_b}^2E^2(\varphi-1) + B^2(E - E\varphi + 2k_s\varphi(3\varphi-2)))}}{2E}\right] < c < \frac{B}{2}$: ${\pi_{r-sm}}^* > {\pi_{rb}}^*$;
	$0 < c < \frac{BE - 2\sqrt{2k_s({t_b}^2E^2(\varphi-1) + B^2(E - E\varphi + 2k_s\varphi(3\varphi-2)))}}{2E}$: ${\pi_{r-sm}}^* < {\pi_{rb}}^*$
$\Delta \boldsymbol{\pi_{m-sm}}^*$	$\min[0, \frac{B}{2} - \sqrt{\frac{B^2k\varphi - b^2Ek\varphi}{E}}] < c < \frac{B}{2}$: ${\pi_{m-sm}}^* > {\pi_{mb}}^*$; $0 < c < \frac{B}{2} - \sqrt{\frac{B^2k\varphi - b^2Ek\varphi}{E}}$, : ${\pi_{m-sm}}^* < {\pi_{mb}}^*$

Where $B = 1 - g + \theta t_b$; $E = 4k_s\varphi - \theta^2$

Table A4. Comparison of optimal decision between Model SR and Model B.

Parameter	**Differences**
$\Delta \boldsymbol{D_{sr}}^*$	$c > min\left[0, \frac{B\theta^2(-2+3\varphi)}{2F}\right] : D_{sr}{}^* > D_b{}^*$; $c < \frac{B\theta^2(-2+3\varphi)}{2F}$ and $\varphi > 2/3$: $D_{\mathrm{sr}}{}^* < D_b{}^*$
$\Delta \boldsymbol{w_{sr}}^*$	$w_{sr}{}^* > w_b{}^*$
$\Delta \boldsymbol{p_{sr}}^*$	$c < min[\frac{B\theta^2(2-\varphi)}{2F}, \frac{B}{2}]: p_{sr}{}^* > p_b{}^*$; $\frac{B\theta^2(2-\varphi)}{2F} < c < \frac{B}{2}$ $and\ k_s > \frac{\theta^2}{(1-\varphi)}$: $p_{sr}{}^* < p_b{}^*$
$\Delta \boldsymbol{\pi_{r-sr}}^*$	$min\left[0, \frac{3BF+2\sqrt{2k(1-\varphi)(9b^2F^2+B^2(\theta^2+F(3\varphi-4)+2k(1-\varphi)^2(3\varphi-1)))}}{6F}\right] < c < \frac{B}{2}$: $\pi_{r-sr}{}^* > \pi_{rb}{}^*$; $0 < c < \frac{3BF+2\sqrt{2k(1-\varphi)(9b^2F^2+B^2(\theta^2+F(3\varphi-4)+2k(1-\varphi)^2(3\varphi-1)))}}{6F}$: $\pi_{r-sr}{}^* < \pi_{rb}{}^*$
$\Delta \boldsymbol{\pi_{m-sr}}^*$	$min\left[0, \frac{B}{2} - \sqrt{\frac{B^2k-2B^2k\varphi-b^2Fk\varphi+B^2k\varphi^2}{F}}\right] < c < \frac{B}{2} : \pi_{m-sr}{}^* > \pi_{mb}{}^*$; $0 < c < \frac{B}{2} - \sqrt{\frac{B^2k-2B^2k\varphi-b^2Fk\varphi+B^2k\varphi^2}{F}}$: $\pi_{m-sr}{}^* < \pi_{mb}{}^*$

$Where\ B = 1 - g + \theta t_{sr};\ F = 4k_s(1-\varphi)^2 + \theta^2(3\varphi - 2)$

Appendix B

Proofs in Model N

The demand function is as follows: $D_n = 1 - p_n - \alpha + \alpha t_n + \theta t_n$.

$$\pi_{rn}(p_n) = (p_n - w_n)D_n$$
$$= (p_n - w_n)(1 - p_n - \alpha + \alpha t_n + \theta t_n)$$
$$\frac{\partial \pi_{rn}}{\partial p_n} = 1 - 2p + w - \alpha + t\alpha + t\theta$$
$$\frac{\partial^2 \pi_{rn}}{\partial {p_n}^2} = -2 < 0$$

Let $\partial \pi_{rn}/\partial p_n = 0$, we have

$$(1 - \theta\alpha + \theta\alpha t_n) - 2p_n + w_n = 0$$
$$\boldsymbol{{p_n}^* = \frac{1}{2}(1 + w - \alpha + t\alpha + t\theta)}$$

Putting ${p_n}^*(w_n, t_n)$ into D_n, we have

$${D_n}^*(w_n, t_n) = 1 - {p_n}^*(w_n, t_n) - \alpha + \alpha t_n + \theta t_n$$
$$= \boldsymbol{\frac{1}{2}(1 - w + (-1 + t)\alpha + t\theta)}$$

Putting ${D_n}^*(w_n, t_n)$ into π_{mn}, we have:

$$\pi_{mn}(w_n, t_n) = w_n {D_n}^*(w_n, t_n) - K_n(t)$$
$$= w_n(\boldsymbol{\frac{1}{2}(1 - w + (-1 + t)\alpha + t\theta)}) - k{t_n}^2/2$$

first-order condition:

$$\frac{\partial \pi_{mn}}{\partial w_n} = \frac{1}{2}(1 - 2w + (-1 + t)\alpha + t\theta)$$
$$\frac{\partial \pi_{mn}}{\partial t_n} = -kt + \frac{1}{2}w(\alpha + \theta)$$

second-order condition:

$$\frac{\partial^2 \pi_{mn}}{\partial {w_n}^2} = -1, \qquad \frac{\partial^2 \pi_{mn}}{\partial {t_n}^2} = -k, \qquad \frac{\partial^2 \pi_{mn}}{\partial w_n \partial t_n} = \frac{\theta + \alpha}{2}$$

$$H_{\pi_{mn}} = \begin{bmatrix} -1 & \theta + \alpha/2 \\ \theta + \alpha/2 & -k \end{bmatrix} = k > \frac{(\theta + \alpha)^2}{4}$$

By checking the Hesse matrix, we find that π_{mn} is jointly concave in w_n and t_n , when $k > \frac{(\theta+\alpha)^2}{4}$. Thus, we characterize the equilibrium wholesale price w_n and the traceability level t_n that will maximize π_{mn} .

Let $\partial\pi_{mn}/\partial w_n$ and $\partial\pi_{mn}/\partial t_n$ equals to zero, we derive

Let $\frac{\partial\pi_{mn}}{\partial w_n} = \frac{1}{2}(1 - 2w + (-1 + t)\alpha + t\theta) = 0$ Let $\frac{\partial\pi_{mn}}{\partial t_n} = -kt + \frac{1}{2}w(\alpha + \theta) = 0$

$$w_n(t_n) = \frac{1}{2}(1 - \alpha + t\alpha + t\theta) \qquad t_n(w_n) = \frac{w(\alpha + \theta)}{2k}$$

$$\boldsymbol{w_n}^* = -\frac{2k(-1+\alpha)}{4k - (\alpha+\theta)^2} = \frac{2k_n(1-\alpha)}{4k_n - (\alpha+\theta)^2} = \boldsymbol{2k_nA}$$

$$\boldsymbol{t_n}^* = \frac{(-1+\alpha)(\alpha+\theta)}{-4k + (\alpha+\theta)^2} = \frac{(1-\alpha)(\alpha+\theta)}{4k_n - (\alpha+\theta)^2} = \boldsymbol{(\alpha+\theta)A}$$

Where, $A = \frac{(1-\alpha)}{4k_n - (\alpha+\theta)^2}$

Putting $w_n{}^*$ and $t_n{}^*$ into $\boldsymbol{p_n}^*$, we derive:

$$p_n{}^* = \frac{1}{2}(1 + w - \alpha + t\alpha + t\theta) = -\frac{3k(-1+\alpha)}{4k - (\alpha+\theta)^2} = \frac{\boldsymbol{3k_n(1-\alpha)}}{\boldsymbol{4k_n - (\alpha+\theta)^2}} = \boldsymbol{3k_nA}$$

Putting $w_n{}^*$ and $t_n{}^*$ into D_n, we derive:

$$D_n{}^* = \frac{1}{2}(1 - w + (-1 + t)\alpha + t\theta) = \frac{k - k\alpha}{4k - (\alpha+\theta)^2} = \frac{\boldsymbol{k_n(1-\alpha)}}{\boldsymbol{4k_n - (\alpha+\theta)^2}} = \boldsymbol{k_nA}$$

Putting $w_n{}^*$ and $t_n{}^*$ into π_{mn}, we derive:

$$\pi_{mn}{}^{*} = w_n{}^{*} D_n - K_n(t_n)$$

$$= \frac{k(-1+\alpha)^2}{8k - 2(\alpha+\theta)^2}$$

$$= \frac{\boldsymbol{k_n(1-\alpha)^2}}{\boldsymbol{2(4k_n - (\alpha+\theta)^2)}} = \frac{\boldsymbol{k_n(1-\alpha)}}{\boldsymbol{2}}\boldsymbol{A}$$

Then we have:

$$\pi_{rn}{}^{*} = (p_n{}^{*} - w_n{}^{*}) D_n{}^{*}$$

$$= \frac{k^2(-1+\alpha)^2}{(-4k + (\alpha+\theta)^2)^2}$$

$$= \frac{\boldsymbol{k_n{}^2(1-\alpha)^2}}{\boldsymbol{(4k_n - (\alpha+\theta)^2)^2}} = \boldsymbol{k_n{}^2 A^2}$$

Proofs in Model B

The demand function is as follows: $D_b = 1 - p_b - g + \theta t_b$.

$$\pi_{rb}(p_b) = (p_b - w_b - c_b)D_b$$
$$= (p_b - w_b - c_b)(1 - p_b - g + \theta t_b)$$
$$\frac{\partial \pi_{rb}}{\partial p_b} = 1 + c - 2p + w - g + t\theta$$
$$\frac{\partial^2 \pi_{rb}}{\partial {p_b}^2} = -2 < 0$$

Let $\partial \pi_{rb}/\partial p_b = 0$, we have

$$c - g - 2p + w + \gamma + t\theta = 0$$
$$\boldsymbol{{p_b}^*(w_b) = \frac{1}{2}(1 + c + w - g + t\theta)}$$

Putting ${p_b}^*(w_b)$ into D_b, we have

$$\boldsymbol{{D_b}^*(w_b)} = 1 - \boldsymbol{{p_b}^*} - g + \theta t_b$$
$$= \boldsymbol{\frac{1}{2}(1 - c - w - g + \theta t_b)}$$

Putting ${D_b}^*(w_b)$ into $\pi_{mb}(w_b)$, we have:

$$\pi_{mb}(w_b) = (w_b - c_b){D_b}^*$$
$$= (w_b - c_b)(\boldsymbol{\frac{1}{2}(1 - c - w - g + t\theta)})$$
$$\frac{\partial \pi_{mb}}{\partial w_b} = \frac{c - w}{2} + \frac{1}{2}(1 - c - w - g + t\theta)$$
$$\frac{\partial^2 \pi_{mb}}{\partial {w_b}^2} = -1 < 0$$

Let $\partial \pi_{mb}/\partial w_b = 0$, we have

$$\frac{1}{2}(1 - 2w - g + t\theta) = 0$$
$$\boldsymbol{{w_b}^* = \frac{1}{2}(1 - g + \theta t_b)}$$

Putting ${w_b}^*$ into ${p_b}^*(w_b)$, we derive ${p_b}^*$

$$p_b{}^* = \frac{1}{2}(1 - c - \boldsymbol{w_b}{}^* - g + t\theta)$$
$$= \boldsymbol{\frac{1}{4}(3 + 2c - 3g + 3\theta t_b)}$$

Putting $w_b{}^*$ into $D_b{}^*(w_b)$, we derive:

$$\boldsymbol{D_b}{}^* = \frac{1}{2}(1 - c - \boldsymbol{w_b}{}^* - g + t\theta)$$
$$= \boldsymbol{\frac{1}{4}(1 - 2c - g + \theta t_b)}$$

Putting $w_b{}^*$ into $\pi_{mb}(w_b)$, we derive:

$$\boldsymbol{\pi_{mb}}{}^* = (w_b{}^* - c_b)D_b{}^*$$
$$= \frac{1}{8}(1 - 2c - \boldsymbol{g} + \boldsymbol{\theta t_b})^2$$

Then we have $\pi_{rb}{}^*$:

$$\boldsymbol{\pi_{rb}}{}^* = (p_b{}^* - w_b{}^* - c_b)D_b{}^*$$
$$= \frac{1}{16}(1 - 2c - \boldsymbol{g} + \boldsymbol{\theta t_b})^2$$

Proofs in Model SM

The demand function is as follows:$D_{sm} = 1 - p_{sm} - g + \theta t_{sm}$.

$$\pi_{r-sm}(p_{sm}) = (p_{sm} - w_{sm})D_{sm} - (1-\phi)K_{sm}(t_{sm})$$
$$= (p_{sm} - w_{sm})(1 - p_{sm} - g + \theta t_{sm}) - (1-\phi)K_{sm}(t_{sm})$$
$$\frac{\partial \pi_{r-sm}}{\partial p_{sm}} = 1 - 2p + w - g + t_{sm}\theta$$
$$\frac{\partial^2 \pi_{r-sm}}{\partial {p_{sm}}^2} = -2 < 0$$

Let $\partial \pi_{r-sm}/\partial p_{sm} = 0$, we have

$$1 - 2p + w - g + t_{sm}\theta = 0$$
$$\boldsymbol{p_{sm}}^* = \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1} + \boldsymbol{w} - \boldsymbol{g} + t_{sm}\boldsymbol{\theta})$$

Putting ${p_s}^*(w_{sm}, t_{sm})$ into D_s, we have

$$\boldsymbol{D_{sm}}^*(\boldsymbol{w_{sm}}, \boldsymbol{t_{sm}}) = 1 - {p_{sm}}^*(w_{sm}, t_{sm}) - g + \theta t_{sm}$$
$$= \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1} - \boldsymbol{w} - \boldsymbol{g} + \boldsymbol{t_{sm}\theta})$$

Putting ${D_s}^*(w_{sm}, t_{sm})$ into π_{ms}, we have:

$$\pi_{m-sm}(w_{sm}, t_{sm}) = w_{sm}D_{sm} - \phi K_{sm}(t_{sm})$$
$$= w_{sm} * \frac{1}{2}(1 - w - g + t_{sm}\theta) - \phi\,[k_s {t_b}^2 + k_s(t_{sm} - t_b)^2]/2$$

first-order condition:

$$\frac{\partial \pi_{m-sm}}{\partial w_{sm}} = \frac{1}{2}(1 - 2w - g + t_{sm}\theta)$$
$$\frac{\partial \pi_{m-sm}}{\partial t_{sm}} = \frac{w\theta}{2} - k(-t_b + t_{sm})\varphi$$

second-order condition:

$$\frac{\partial^2 \pi_{m-sm}}{\partial {w_s}^2} = -1, \qquad \frac{\partial^2 \pi_{m-sm}}{\partial {t_{sm}}^2} = -k\varphi, \qquad \frac{\partial^2 \pi_{m-sm}}{\partial w_s \partial t_{sm}} = \frac{\theta}{2}$$

$$H_{\pi_{ms}} = \begin{bmatrix} -1 & \frac{\theta}{2} \\ \frac{\theta}{2} & -k_s\varphi \end{bmatrix} = k_s > \frac{\theta^2}{4\varphi}$$

By checking the Hesse matrix, we find that π_{ms} is jointly concave in w_{sm} and t_{sm} , when $k_s > \frac{\theta^2}{4\varphi}$. Thus, we characterize the equilibrium wholesale price w_{sm} and the traceability level t_{sm} that will maximize π_{m-sm} .

Let $\partial\pi_{ms}/\partial w_{sm}$ and $\partial\pi_{ms}/\partial t_{sm}$ equals to zero, we derive

Let$\frac{\partial\pi_{m-sm}}{\partial w_{sm}} = \frac{1}{2}(1-2w-g+t_{sm}\theta) = 0$ Let$\frac{\partial\pi_{m-sm}}{\partial t_{sm}} = \frac{w\theta}{2} - k_s(-t_b+t_{sm})\varphi = 0$

$$w_{sm}(t_{sm}) = \frac{1}{2}(1-g+t_{sm}\theta) \qquad t_{sm}(w_{sm}) = \frac{w\theta+2bk_s\varphi}{2k_s\varphi}$$

$$\boldsymbol{w_{sm}}^* = -\frac{2k_s(-1+g-t_b\theta)\varphi}{-\theta^2+4k_s\varphi} = \frac{2k_s(1-g+\theta t_b)\varphi}{4k_s\varphi-\theta^2} = \boldsymbol{2}k_s\boldsymbol{\varphi B/E}$$

$$\boldsymbol{t_{sm}}^* = -\frac{\theta-g\theta+4t_bk_s\varphi}{\theta^2-4k_s\varphi} = \frac{\theta-\theta g+4k_s\varphi t_b}{E}$$

Where, $E = 4k_s\varphi - \theta^2$

Putting $w_s{}^*$ and $t_s{}^*$ into p_s, we derive:

$$p_{sm}{}^* = \frac{3k_s(1-g+\theta t_b)\varphi}{4k_s\varphi-\theta^2} = \boldsymbol{3k_s\varphi B/E}$$

Putting $w_s{}^*$ and $t_s{}^*$ into D_s, we derive:

$$D_s{}^* = \frac{k_s(1-g+\theta t_b)\varphi}{4k_s\varphi-\theta^2} = \boldsymbol{k_s\varphi B/E}$$

Putting $w_s{}^*$ and $t_s{}^*$ into π_{ms}, we derive:

$$\pi_{m-sm}{}^* = w_{sm}D_{sm} - \phi K_{sm}(t_{sm}) = \frac{k_s\varphi\left(B^2 - t_b{}^2(4k_s\varphi-\theta^2)\right)}{8k_s\varphi-2\theta^2}$$

$$= \frac{(\boldsymbol{B^2 - t_b{}^2 E) k_s \varphi}}{\boldsymbol{2E}}$$

Then we have:

$$\begin{aligned}
\pi_{r-sm}{}^* &= (p_{sm} - w_{sm}) D_{sm} - (1 - \phi) K_{sm}(t_{sm}) \\
&= \frac{k_s}{2} [t_b{}^2(-1 + \varphi) + \frac{B^2(\theta^2(-1 + \varphi) + 2k_s\varphi^2)}{(4k_s\varphi - \theta^2)^2}] \\
&= \frac{\boldsymbol{k_s B^2 [E - E\varphi + 2k_s\varphi(3\varphi - 2)]}}{\boldsymbol{2E^2}} - \frac{\boldsymbol{k_s t_b{}^2 (1 - \varphi)}}{\boldsymbol{2}}
\end{aligned}$$

Proofs in Proposition SR

The demand function is as follows:$D_{sr} = 1 - p_{sr} - g + \theta t_{sr}$.

first-order condition of the two decision variables $p_s\ and\ t_s$:

$$\pi_{rs}(p_s) = (p_s - w_s)D_s - (1-\phi)K_s(t_s)$$
$$= (p_s - w_s)(1 - p_s - g + \theta t_s) - (1-\phi)K_s(t_s)$$
$$\frac{\partial \pi_{rs}}{\partial p_s} = 1 - 2p + w - g + t\theta$$
$$\frac{\partial \pi_{rs}}{\partial t_s} = (p - w)\theta - k(-b + t)(1 - \varphi)$$

second-order condition:

$$\frac{\partial^2 \pi_{rs}}{\partial {p_s}^2} = -2, \qquad \frac{\partial^2 \pi_{rs}}{\partial {t_s}^2} = -k(1-\varphi), \qquad \frac{\partial^2 \pi_{rs}}{\partial w_s \partial t_s} = \theta$$

$$H_{\pi_{mn}} = \begin{bmatrix} -2 & \theta \\ \theta & -k_s(1-\varphi) \end{bmatrix} = k_s > \frac{\theta^2}{2(1-\varphi)}$$

By checking the Hesse matrix, we find that π_{ms} is jointly concave in p_s and t_s , when $k_s > \frac{\theta^2}{2(1-\varphi)}$. Thus, we characterize the equilibrium wholesale price p_s and the traceability level t_s that will maximize π_{rs} .

Let $\partial \pi_{rs}/\partial p_s$ and $\partial \pi_{rs}/\partial t_s$ equals to zero, we derive

Let $\frac{\partial \pi_{rs}}{\partial p_s} = 1 - 2p + w - g\beta + t\theta = 0$, we have:

$$p_s(t_s) = \frac{1}{2}(1 - g + t\theta)$$

Let$\frac{\partial \pi_{rs}}{\partial t_s} = \frac{-bk_s - p\theta + w\theta + bk_s\varphi}{k(-1+\varphi)} = 0$, we have:

$$t_s(p_s) = \frac{-bk_s - p\theta + w\theta + bk_s\varphi}{k_s(-1+\varphi)}$$

Then we have:

$$\boldsymbol{p_s}^*(w_s) = \frac{w\theta^2 + k_s(1 + w - g + b\theta)(-1+\varphi)}{\theta^2 + 2k_s(-1+\varphi)}$$

$$\boldsymbol{t_s}^*(w_s) = -\frac{2bk_s + \theta - g\theta - w\theta - 2bk_s\varphi}{-2k + \theta^2 + 2k_s\varphi}$$

Putting $\boldsymbol{p_s}^*(w_s)$ **and** $\boldsymbol{t_s}^*(w_s)$ into $D_s = 1 - p_s - g + \theta t_s$, we have

$$D_s^*(w_s) = 1 - \boldsymbol{p_s}^*(w_s) - \beta g + \theta \boldsymbol{t_s}^*(w_s)$$
$$= -\frac{k_s(-1 + w + g - b\theta)(-1 + \varphi)}{\theta^2 + 2k_s(-1 + \varphi)}$$

Putting $D_s^*(w_s)$ and $\boldsymbol{t_s}^*(w_s)$ into π_{ms}, we have:

$$\pi_{ms}(w_s) = w_s D_s - \phi K_s(t_s)$$
$$= w_s * (-\frac{k_s(-1 + w + g - b\theta)(-1 + \varphi)}{\theta^2 + 2k(-1 + \varphi)})$$
$$- \phi\left[k_s {t_b}^2 + k_s((-\frac{2bk_s + \theta - g\theta - w\theta - 2bk_s\varphi}{-2k_s + \theta^2 + 2k\varphi}) - t_b)^2\right]/2$$

first-order condition of w_s:

$$\frac{\partial \pi_{ms}}{\partial w_s} = -\frac{k_s(2k_s(-1 + g + 2w - b\theta)(-1 + \varphi)^2 + \theta^2(g(-1 + 2\varphi) - (1 + b\theta)(-1 + 2\varphi) + w(-2 + 3\varphi)))}{(\theta^2 + 2k_s(-1 + \varphi))^2}$$

second-order condition of w_s:

$$\frac{\partial^2 \pi_{ms}}{\partial {w_s}^2} = \frac{k_s(\theta^2(2 - 3\varphi) - 4k_s(1 - \varphi)^2)}{(\theta^2 + 2k(-1 + \varphi))^2} < 0$$

Let $\partial \pi_{ms}/\partial w_s = 0$, we have

$$\frac{k_s(2k_s(-1 + 2w + g - b\theta)(-1 + \varphi)^2 + \theta^2((-1 + g - b\theta)(-1 + 2\varphi) + w(-2 + 3\varphi)))}{(\theta^2 + 2k_s(-1 + \varphi))^2} = 0$$

$$w_s^* = \frac{B(2F + \theta^2 - 2k_s(1 - \varphi)^2)}{3F}$$

Where$-(-1 + g - b\theta) = B,\ 4k_s(1 - \varphi)^2 + \theta^2(-2 + 3\varphi) = F > 0.$

Putting w_s^* into $D_s^*(w_s)$, we derive:

$$D_s^* = -\frac{k_s(-1 + w_s^* + g - b\theta)(-1 + \varphi)}{\theta^2 + 2k_s(-1 + \varphi)}$$

$$= \frac{Bk_s(1-\varphi)^2}{F}$$

Putting $w_s{}^*$ into $\boldsymbol{p_s}^*(w_s)$, we derive:

$$\boldsymbol{p_s}^* = \frac{w\theta^2 + k_s(1 + w - g\beta + b\theta)(-1+\varphi)}{\theta^2 + 2k_s(-1+\varphi)}$$
$$= \frac{B(2F + \theta^2 + k_s(1-\varphi)^2)}{3F}$$

Putting $w_s{}^*$ into $\boldsymbol{t_s}^*(w_s)$, we derive:

$$\boldsymbol{t_s}^* = -\frac{2bk_s + \theta - w\theta - g\beta\theta - 2bk_s\varphi}{-2k_s + \theta^2 + 2k_s\varphi}$$
$$= \frac{(-1+g\beta)\theta(-1+\varphi) + 4bk_s(-1+\varphi)^2 + b\theta^2(-1+2\varphi)}{4k_s(-1+\varphi)^2 + \theta^2(-2+3\varphi)}$$
$$= t_b + \frac{\theta(1-\varphi)B}{F}$$

Putting all the equilibrium results into π_{ms}, we derive:

$$\pi_{ms}{}^* = w_s D_s - \phi K_s(t_s)$$
$$= \frac{k_s(B^2(-1+\varphi)^2 - b^2\varphi(4k_s(-1+\varphi)^2 + \theta^2(-2+3\varphi)))}{8k_s(-1+\varphi)^2 + \theta^2(-4+6\varphi)}$$
$$= \frac{k(B^2(1-\varphi)^2 - t_b{}^2\varphi F)}{2F}$$

Then we have:

$$\pi_{rn}{}^* = (p_s - w_s)D_s - (1-\phi)K_s(t_s)$$
$$= \frac{k_s(1-\varphi)(9b^2F^2 + B^2(\theta^2 + F(-4+3\varphi) + 2k_s(-1+\varphi)^2(-1+3\varphi)))}{18F^2}$$

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1. Topic origin and background:

With the growth of China's per capita income and the advancement of science and technology, people's focus on food issues has gradually shifted from quantity to quality, and people will spend more time on safety issues such as food sources and shelf life. In recent years, governments around the world have also begun to pay attention to food safety management. Although the food supply chain(FSC) has effectively solved some food safety issues, food safety is still an unsolvable problem. In subsequent research, we found that blockchain, as an emerging technology and solution, can effectively solve food safety. We hope to apply blockchain security to food supply chain security and effectively protect food safety on the consumer side.

2. About our team members:

Shi Jingchen: Participate in topic selection discussion and research, main body writing part of the article, and literature collection part; article proofreading and inspection

Shi Zibo: Topic selection discussion and research, mathematical model analysis, and article proofreading and inspection

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