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Value and Design of Traceability-Driven Blockchains

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Abstract. ***Problem definition*:** This paper provides a theoretical investigation into the value and design of a traceability-driven blockchain under different supply chain structures. ***Methodology/results*:** We use game theory to study the quality contracting equilibrium between one buyer and two suppliers and identify two fundamental functionalities of a traceability-driven blockchain. In serial supply chains, the ability to trace the sequential production process creates value by mitigating double moral hazard. In this case, traceability always improves product quality and all firms' profits and naturally creates a win-win. In parallel supply chains, the ability to trace the product origin enables flexible product recall, which can reduce product quality. In this case, traceability can benefit the buyer while hurting the suppliers, creating an incentive conflict. ***Managerial implications*:** Firms operating in different kinds of supply chains could face unique challenges when they adopt and design a traceability-driven blockchain. First, in serial supply chains, any firm can be the initiator of the blockchain, whereas in parallel supply chains, it may be critical for the buyer to take the lead in initiating the blockchain and properly compensate the suppliers. Second, in serial supply chains, a restricted data permission policy where each supplier shares their own traceability data with the buyer but not with each other can improve the supply chain profit, whereas in parallel supply chains, it is never optimal to restrict a firm's access to the traceability data. Third, the suppliers' incentive to enhance the governance of data quality is more aligned with the supply chain optimum in serial supply chains compared with parallel supply chains.

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1. Introduction

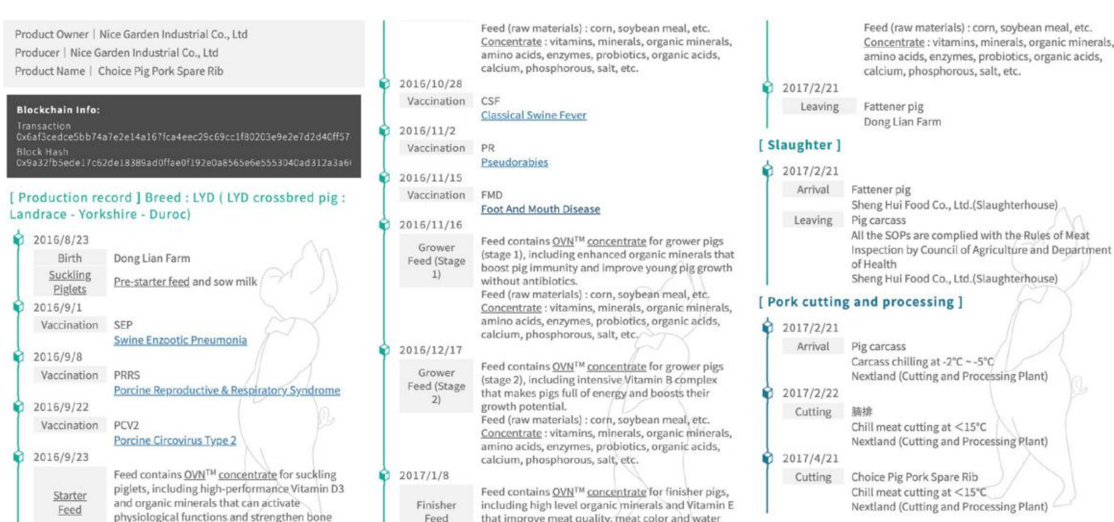
As supply chains become more complex and globalized, it is common for companies to outsource various stages of the production process to different suppliers and source the same product from multiple suppliers (Cohen et al. 2018). Because suppliers' efforts to improve quality are usually unobservable and noncontractible, moral hazard problems could arise, and quality-related issues could occur. Product recalls due to quality-related issues are widely observed in various industries, such as agri-food, pharmaceutical, automobile, and smartphones. For example, in 2006, an outbreak of foodborne illness caused by *Escherichia coli* bacteria found in spinach in 26 U.S. states resulted in 276 illnesses and three deaths, and all kinds of fresh spinach and spinach-containing products were recalled nationwide (CNN 2018). In 2007, Mattel, the world's largest toy company, recalled 19 million toys that contained excessive level of lead paint (Story and Barbozaaug 2007). In 2009, the massive amount of salmonella-tainted peanuts produced by Peanut Corp. of America resulted in 3,913 different kinds of products recalled from 361 companies (Basu 2015). In 2018, the U.S. Food and Drug Administration announced a list of medications that were tainted with a substance that may cause a higher risk of cancer, resulting in recalls in 23 countries (Christensen 2018). In all these examples, a common feature is that it is difficult to trace back to the source of the quality issue, which creates further challenges in quality management. However, the recent development of blockchain technologies is promising to help firms overcome the challenges that arise from the lack of traceability in supply chains (Chen et al. 2020b).

Blockchain, a decentralized digital ledger technology that can record transactions between two parties efficiently, verifiably, and permanently, is first known as the technology behind Bitcoin cryptocurrency. Integrated with Internet of Things (IoT) sensors, blockchain can enable traceability of the entire supply chain, such as by whom, when, where, and how a particular product was handled all the way from manufacturing to consumption. Thus far, an increasing number of blockchain platforms (e.g., Provenance, BlockVerify, Skuchain, Vechain, Factom, Ripe.io, Bext360, BartDigital, and OwlTing) have been developed worldwide to improve the traceability of supply chains for various kinds of products. The blockchain platforms have been used by several leading retailers. For example, by adopting Hyperledger Fabric, an enterprise-grade blockchain platform provided by IBM, Walmart has conducted a pilot project to test the use of blockchain to track pork supply chains in China (Nash 2016) and required its direct suppliers to join its food-tracking blockchain (Nash 2018b). China's e-commerce giants, Alibaba and JD.com, have also adopted blockchain to tackle fake goods problems (Xiao 2017). In the United States, a Food Trust group was founded by 10 leading retailers (e.g., Walmart) and food companies (e.g., Nestlé) to improve global food safety by tracing food and ingredients worldwide with blockchain (Aitken 2017). Blockchain has also been used in pharmaceutical and luxury goods industries (e.g., Merck & Co. Inc. and Everledger; Nash 2018a).

Figure 1 provides an example of the blockchain platform developed by OwlTing to trace pork supply chains. The information recorded in the blockchain includes (but is not limited to) supplier's name, date of production, package size and weight, and quality-related details, such as temperature, humidity, light condition, and vaccination. Many of the data recorded in the blockchain are created by high-tech sensors, tracking devices, and Radio-Frequency Identification chips (e.g., IBM Food Trust platform, IBM TrustChain, and Ambrosus blockchain-based ecosystem; Whang 2010, Aitken 2017, Bajpai 2019, Metcalfe 2019). When a defect occurs, such credible quality-related information can be used to identify which supplier(s) and which stage(s) of the supply chain are responsible for the defect. Furthermore, as an essential application of blockchain, smart contract, a self-enforcing protocol relying on tamper-proof consensus on contingent outcomes, can facilitate automation of payment in a supply chain. Thus, compensations can be paid automatically based on the suppliers' quality outcomes that are identified from the traceability data in the blockchain (Hui et al. 2018).

Given the rapid development of blockchain and its promise in improving supply chain traceability, this research aims to understand how traceability can impact supply chain operations and how firms should design a traceability-driven blockchain. Particularly, we are going to investigate the following research questions. First, how would supply chain traceability affect supply chain contracts and the resulting quality decisions of suppliers? Second, what is the value of traceability and how does the value depend on the structure of the supply chain? Third, who should be the initiator of a traceability-driven blockchain? Fourth, how should firms choose the optimal design of a traceability-driven blockchain regarding data permission, consensus mechanism, and data governance?

Figure 1. (Color online) Example of Blockchain Platform to Trace Pork Supply Chains



We consider two common but distinct supply chain structures: serial and parallel supply chains. First, to uncover the impact of traceability in a multistage production process, we analyze a *serial* supply chain structure where a buyer sources from a downstream supplier, who in turn sources from an upstream supplier. The two suppliers make the production in a sequential manner and jointly determine the quality of the end product. The serial supply chain structure leads to a double moral hazard, because the buyer faces the problem of incentivizing a two-tier supply chain, within which another moral hazard arises. We find that the double moral hazard would cause the upstream supplier to be underincentivized to improve quality. Moreover, without traceability, because the defect-causing supplier cannot be identified, both suppliers will be paid contingent on the quality outcome of the end product. The upstream supplier's incentive would be worsened even further because it may lose the payment due to the downstream supplier's fault. However, with traceability, the payment at each stage of the supply chain can be contingent on the quality outcome up to that stage, which means that the upstream supplier no longer has to pay for the downstream supplier's fault. This helps restore the upstream supplier's incentive to improve quality and will, in turn, boost the downstream supplier's incentive to improve quality. Therefore, in a serial supply chain, traceability creates value by *mitigating double moral hazard*.

Second, to uncover the impact of traceability in a multisourcing supply chain, we analyze a *parallel* supply chain structure where a buyer sources the same product from two suppliers who belong to the same tier of the supply chain. In addition to preventing a supplier from being penalized for another supplier's fault, which improves the suppliers' incentive to improve quality, traceability also impacts a parallel supply chain by *enabling flexible product recall*. Without traceability, once a defect occurs, the buyer would have to recall all products from the market even though some suppliers may not have been defective. With traceability, the buyer can convey to the consumers which products need to be recalled and avoid recalling products that are not defective. This makes the buyer less afraid of product defects and it would prefer to induce a lower quality as a result and pay lower wholesale prices to the suppliers. We further find that the buyer's incentive to induce a lower quality would dominate the suppliers' incentive to improve quality when the market loss under defect is sufficiently large, leading to a reduced product quality.

The previous results reveal that depending on the structure of the supply chain, traceability can create value and impact product quality in different ways. We further find that in a serial supply chain, the mitigation of double moral hazard improves the profit of all firms. Thus, *any* firm can be the initiator of the blockchain. By contrast, in a parallel supply chain, although traceability improves the total profit of the supply chain, it can hurt the suppliers' profits. Thus, it is critical for the *buyer* to take the lead in initiating the blockchain and compensate the suppliers. Because traceability is less likely to lead to an incentive conflict between firms in a serial supply chain, a traceability-driven blockchain may be easier to gain traction in a "long" (i.e., serial) supply chain as opposed to a "flat" (i.e., parallel) supply chain.

When adopting the blockchain, certain firms may have the incentive to form a subnetwork of data sharing and use the traceability data to design contracts among themselves. We find that this may not necessarily be a bad thing for the supply chain. In a serial supply chain, we identify a *restricted data permission* policy that can improve the supply chain profit. In this case, each supplier shares their own traceability data with the buyer but not with each other, and correspondingly, the buyer pays each supplier based on their own quality outcome. Thus, the optimal blockchain design may require an *access control layer* that restricts a firm's access to certain firms' traceability data. By contrast, in a parallel supply chain, it is never optimal to restrict a firm's access to the traceability data. However, the parallel suppliers may want to form a data-sharing subnetwork among themselves that excludes the buyer. To maximize the value of a traceability-driven blockchain, the data permission policy should be determined based on a *centralized consensus mechanism* led by the buyer rather than a decentralized consensus mechanism where all firms vote on the data permission policy.

Finally, the value of blockchain also depends on the quality of the traceability data recorded by the suppliers. We find that the suppliers' incentive to improve data quality is more aligned with the supply chain optimum in a serial supply chain compared with a parallel supply chain. This provides another reason why a traceability-driven blockchain 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 the suppliers for their efforts to improve data quality.

2. Literature Review

First, this paper is related to the literature on supply chain quality management. This stream of literature has studied how to improve supplier's quality efficiently from a variety of perspectives. Table A.1 in Online Appendix A summarizes the works in this stream, including our paper.

In the context of a dyadic supply chain consisting of one supplier and one buyer, a wide collection of contracts are proposed from the buyer's perspective to improve the product quality. Baiman et al. (2000) examine the moral hazard problem where neither the buyer's appraisal effort nor the supplier's quality effort is observable. Motivated by the practice of The International Organization for Standardization 9000, Hwang et al.

(2006) compare the product appraisal and vendor certification schemes. Babich and Tang (2012) and Rui and Lai (2015) compare the product inspection and deferred payment mechanisms to investigate which can better deter the supplier from product adulteration. Bondareva and Pinker (2019) study a repeated game in which the partnership can be terminated by the buyer if the supplier refuses to pay penalties for product failure. These papers assume that the product quality depends solely on the unique supplier's quality choice. Furthermore, Nikoofal and Gümüş (2018) assume that the product quality is also influenced by the supplier's private reliability and compare two inspection-based mechanisms, that is, to inspect the end product's quality or to inspect the supplier's actual quality effort. Balachandran and Radhakrishnan (2005), Chao et al. (2009), Dong et al. (2016) and Lee and Li (2018) further incorporate the buyer's quality decision.

Our work is more aligned with another stream in the quality management literature, which considers supply chains with multiple suppliers. Baiman et al. (2004) consider an assembly supply chain in which the buyer assembles an end product using outsourced parts from multiple symmetric suppliers. They compare the two contracts that require individual testing with the group warranty contract, in which all suppliers will be penalized as long as the end product fails. Although Dong et al. (2016) focus on quality management in a dyadic supply chain, they also consider the buyer's choice of outsourcing part of the work to an independent contract manufacturer, which can be viewed as a serial supply chain. However, they do not identify the double moral hazard issue, which is a key result of our paper. Mu et al. (2016) examine two quality-testing strategies to curb deliberate adulteration by milk farmers in a multisourcing context, which shares some similarity with our parallel supply chain, and investigate how to balance the high testing costs in individual testing and farmers' free-riding issue in mixed testing. However, they do not account for the efficiency loss caused by product recall, which is a critical driving force for blockchain-enabled traceability to create an impact in our setting. In sum, our work differentiates from these papers by identifying the unique challenges for quality contracting under the two common but distinct supply chain structures: serial and parallel supply chains. More importantly, our work captures the essential functionalities of a traceability-driven blockchain and shows how it can have opposite impacts under the two supply chain structures.

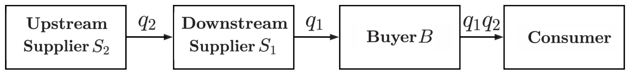
Besides quality management, the operations management literature has also examined other issues in multisupplier supply chains. Some papers explore the optimal procurement contract design of an assembly supply chain with the consideration of suppliers' competition (Jiang and Wang 2010), suppliers' private cost information (Fang et al. 2014), and contracting time (Hu and Qi 2018). Other papers consider contracting in a three-tier serial supply chain to uncover whether an OEM should delegate component procurement to the tier 1 supplier or control it directly (Kayiş et al. 2013, Bolandifar et al. 2016). Ang et al. (2017) investigate the optimal sourcing problem in three-tier supply chain networks including V-shaped and diamond-shaped supply chains. Gümüş et al. (2012) focus on managing disruption risk on the supply side when sourcing from multiple suppliers. Moreover, our study also relates to the responsible sourcing literature due to the commonality in considering costly and unobservable efforts of suppliers and uncertain outcomes (Lee and Li 2018). See Lee and Tang (2018) for an overview of the literature in this domain. In a two-tier dyadic supply chain, the buyer usually manages the supplier's social and environmental responsibility by either adopting an ex ante supplier certification program or implementing an ex post auditing process (Plambeck and Taylor 2016, Chen and Lee 2017, Caro et al. 2018, Fang and Cho 2020). Chen et al. (2020a) study a W-shaped assembly supply chain consisting of two buyers and three suppliers, whereas Huang et al. (2022) explore a three-tier serial supply chain.

Finally, our work is also related to the growing body of literature that investigates the operational impacts of blockchain. Babich and Hilary (2020) identify the key strengths and weaknesses of blockchain and propose directions for operations management research on blockchain. Chod et al. (2020) show that it is more efficient to signal a firm's quality to lenders through inventory transactions in blockchain rather than through loan requests. Pun et al. (2021) find that blockchain can be used to combat counterfeits and can be more efficient than a pricing strategy in eliminating the postpurchase regret and improving social welfare. Cui et al. (2022a) consider two types of supply chain transparency enabled by blockchain and study how to design a blockchain that aims to improve supply chain transparency. Dong et al. (2022) study blockchain adoption in a three-tier food supply chain and focus on its ability to identify contaminated tier-2 suppliers and eliminate the waste for the uncontaminated tier-2 suppliers. Our work contributes to this literature by identifying two fundamental functionalities of a traceability-driven blockchain (i.e., tracing a sequential production process and enabling flexible product recall), examining microlevel issues in forming and designing a traceability-driven blockchain, and exploring new contracting schemes that can be enabled by blockchain that involve all parties in the supply network.

3. Value of Blockchain in a Serial Supply Chain

In this section, we consider a serial supply chain that consists of a buyer, a downstream supplier (i.e., supplier 1), and an upstream supplier (i.e., supplier 2). The

Figure 2. Serial Supply Chain



production process has two stages, handled by the two suppliers in a sequential manner (Figure 2).

3.1. Model Primitives

Supplier $i \in \{1,2\}$ makes its own quality decision $q_i \in [0,1]$, which represents the probability of being not defective. Although the production outcome is subject to uncertainty, suppliers can incur additional costs to improve the chance of being not defective. A supplier's quality cost function is $C(q_i) = \theta q_i^{\gamma}$.[1] The quality level of the end product is *jointly* determined by the quality level of both suppliers.[2] Specifically, the end product is not defective with probability q_1q_2 and defective with probability $1 - q_1q_2$. In other words, the end product is defective if any of the production stages is defective. Such a feature is referred to as the "weakest link" property in the literature and has been widely adopted to study serial supply chains (Baiman et al. 2004, Balachandran and Radhakrishnan 2005, Dong et al. 2016, Lee and Li 2018).

The market demand is normalized to one (Hwang et al. 2006, Lee and Li 2018, Nikoofal and Gümüş 2018). If the end product turns out to not be defective, the buyer earns the retail price $p > 0$.[3] If the end product turns out to be defective, the buyer incurs a loss l. $l < 0$ would indicate that the buyer ends up with a positive net profit even with the defect. However, we require $l > -p$ because the buyer cannot earn more than the retail price in this case. $l \geqslant 0$ would indicate that the buyer incurs more cost in addition to not earning the retail price, such as the additional cost of handling product recalls and the potential customer dissatisfaction and reputation damage (Balachandran and Radhakrishnan 2005, Hwang et al. 2006, Chao et al. 2009).[4]

In a serial supply chain, contracts are signed between neighboring firms in a sequential manner. The quality level q_i chosen by supplier i is neither observable nor verifiable by outside parties, which means the quality level q_i is not contractible. Hence, we consider contracts where the payments to suppliers are contingent on the realized quality outcome. In particular, the buyer offers a contingent payment contract to the downstream supplier, who then, in turn, offers a contingent payment contract to the upstream supplier. Each contract is characterized by a wholesale price w_i. Depending on whether the supply chain is traceable or not, w_i may be paid under different conditions; we specify the payment mechanisms under each case in Section 3.2. The game consists of three stages. In stage 1, the buyer chooses the wholesale price to offer to the downstream supplier, w_1. Then, in stage 2, the downstream supplier chooses the wholesale price to offer to the upstream supplier, w_2. Finally, in stage 3, the two suppliers simultaneously choose their quality levels, q_1 and q_2. Denote π_B and π_{S_i} as the expected profits of the buyer and supplier i, $i \in \{1,2\}$, respectively.

We make the following technical assumptions.

Assumption 1. *An interior solution exists (i.e., $\theta > \frac{p+l}{\gamma}$).*

Assumption 2. *The interior solution is unique (i.e., $\gamma \geqslant 2$).*

The above two assumptions guarantee the existence of a unique interior solution. Specifically, Assumption 1 ensures the optimal solution to be achieved at an interior point, and Assumption 2 ensures the interior solution to be the unique global maximum. Table B.1 in Online Appendix B summarizes the definition of notation. All proofs in Section 3 are relegated to Online Appendix SA. We now proceed with the equilibrium analysis (Section 3.2) and results (Sections 3.3 and 3.4).

3.2. Contracting Equilibria

3.2.1. Equilibrium Without Traceability. We first consider the case without traceability. In this case, the quality outcome from the intermediate stages of the production process is not known. Thus, the payments along the entire supply chain will be contingent on the quality outcome of the end product. If the end product is not defective, the buyer receives a revenue of p and pays the downstream supplier w_1, and the downstream supplier pays the upstream supplier w_2. If the end product is defective, the buyer incurs a loss of l and does not pay the downstream supplier, and the downstream supplier does not pay the upstream supplier.[5]

The buyer's contracting problem in a serial supply chain without traceability is formulated as

$$\begin{aligned}
\max_{w_1}\ & \pi_B(w_1 \mid \tilde{q}_1(w_1,\tilde{w}_2(w_1)), \tilde{q}_2(w_1,\tilde{w}_2(w_1))) \\
&= p\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1)) - l\left[1 - \prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))\right] \\
&\quad - w_1\prod_{i=1}^{2}\tilde{q}_i(w_1,\tilde{w}_2(w_1))
\end{aligned}$$

$$\text{s.t.}\begin{cases}\pi_{S_1}(\tilde{w}_2(w_1), \tilde{q}_1(w_1,\tilde{w}_2(w_1)) \mid w_1, \tilde{q}_2(w_1,\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1)\\ \tilde{w}_2(w_1) = \arg\max_{w_2}\ \pi_{S_1}(w_2, \tilde{q}_1(w_1,w_2) \mid w_1, \tilde{q}_2(w_1,w_2)) & \end{cases}$$

$$\text{s.t.}\begin{cases}\pi_{S_2}(\tilde{q}_2(w_1,w_2) \mid w_2, \tilde{q}_1(w_1,w_2)) \geqslant 0, & (\text{IR}_2)\\ \tilde{q}_1(w_1,w_2) = \arg\max_{q_1}\ \pi_{S_1}(w_2, q_1 \mid w_1, q_2), & (\text{IC}_1)\\ \tilde{q}_2(w_1,w_2) = \arg\max_{q_2}\ \pi_{S_2}(q_2 \mid w_2, q_1), & (\text{IC}_2),\end{cases}$$

$$(1)$$

where $\pi_{S_1}(w_2, q_1 \mid w_1, q_2) = w_1q_1q_2 - C(q_1) - w_2q_1q_2$ and $\pi_{S_2}(q_2 \mid w_2, q_1) = w_2q_1q_2 - C(q_2)$ are the expected profit functions of the downstream and the upstream suppliers, respectively. In each stage of the game, the contract provider maximizes its expected profit subject to the corresponding constraints that include individual rationality and incentive compatibility. The following proposition characterizes the solution to (1), with superscript "N" denoting the case without traceability and "‡" denoting the equilibrium in a serial supply chain.

Proposition 1 (Equilibrium Without Traceability in a Serial Supply Chain). *In a serial supply chain without traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_1^{N\ddagger} = \frac{2(p+l)}{\gamma}$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{N\ddagger} = \frac{2(p+l)}{\gamma^2}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{N\ddagger} = \left[\frac{2(p+l)(\gamma-1)^{\frac{\gamma-1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$ *and* $q_2^{N\ddagger} = \left[\frac{2(p+l)(\gamma-1)^{\frac{1}{\gamma}}}{\theta\gamma^3}\right]^{\frac{1}{\gamma-2}}$, *respectively. Moreover,* $w_1^{N\ddagger}/w_2^{N\ddagger} = \gamma \geqslant 2$ *and* $q_1^{N\ddagger}/q_2^{N\ddagger} = (\gamma-1)^{\frac{1}{\gamma}} \geqslant 1$.

Proposition 1 shows that in a serial supply chain without traceability, the downstream supplier always chooses a *higher* quality level compared with the upstream supplier (i.e., $q_1^{N\ddagger} \geqslant q_2^{N\ddagger}$), even though the two suppliers have symmetric quality cost functions. This is uniquely driven by the sequential contracting feature in a serial supply chain. In this case, only the downstream supplier is directly incentivized by the buyer, whereas the upstream supplier is indirectly incentivized by the buyer through the downstream supplier. Thus, the downstream supplier plays a *dual* role. Besides offering a contract to the upstream supplier to incentivize its unobservable quality decision, the downstream supplier also makes an unobservable quality decision himself, which indicates that a double moral hazard arises between the upstream and the downstream suppliers (Cooper and Ross 1985).[6] When making the contracting decision, the downstream supplier needs to trade off between improving product quality himself and incentivizing the upstream supplier to improve product quality. The former is more efficient because the downstream supplier only incurs the quality cost, whereas for the latter it incurs both the quality cost and the agency cost from incentivizing the upstream supplier. Hence, the downstream supplier would prefer to allocate a larger proportion of the wholesale price received from the buyer to improve quality himself and a smaller proportion to incentivize the upstream supplier (i.e., $w_1^{N\ddagger} \geqslant 2w_2^{N\ddagger}$). Consequently, the upstream supplier is less incentivized and will choose a lower quality level compared with the downstream supplier.

3.2.2. Equilibrium with Traceability.

We next consider the case with traceability. In this case, because the quality outcome up to each stage of the production process is identifiable, the wholesale price can be paid accordingly at each stage, instead of based on the quality outcome of the end product. In particular, in each tier of the supply chain, the firm pays or does not pay its immediate supplier contingent on the quality outcome of the product that it receives from that immediate supplier.[7] Hence, if the quality outcome up to the upstream supplier is not defective, whereas the quality outcome up to the downstream supplier is defective, then the upstream supplier shall still receive the payment from the downstream supplier, whereas the downstream supplier does not receive the payment from the buyer.[8]

The buyer's contracting problem in a serial supply chain with traceability is formulated as

$$\begin{aligned}
\max_{w_1}\quad & \pi_B(w_1 \mid \tilde{q}_1(w_1,\tilde{w}_2(w_1)),\tilde{q}_2(\tilde{w}_2(w_1))) \\
&= p\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
&\quad - l[1-\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1))] \\
&\quad - w_1\tilde{q}_1(w_1,\tilde{w}_2(w_1))\tilde{q}_2(\tilde{w}_2(w_1)) \\
\text{s.t.}\quad & \begin{cases} \pi_{S_1}(\tilde{w}_2(w_1),\tilde{q}_1(w_1,\tilde{w}_2(w_1)) \mid w_1,\tilde{q}_2(\tilde{w}_2(w_1))) \geqslant 0, & (\text{IR}_1)\\ \tilde{w}_2(w_1) = \arg\max_{w_2}\ \pi_{S_1}(w_2,\tilde{q}_1(w_1,w_2) \mid w_1,\tilde{q}_2(w_2)) & \\ \text{s.t.} \begin{cases} \pi_{S_2}(\tilde{q}_2(w_2) \mid w_2) \geqslant 0, & (\text{IR}_2)\\ \tilde{q}_1(w_1,w_2) = \arg\max_{q_1}\ \pi_{S_1}(w_2,q_1 \mid w_1,q_2), & (\text{IC}_1)\\ \tilde{q}_2(w_2) = \arg\max_{q_2}\ \pi_{S_2}(q_2 \mid w_2), & (\text{IC}_2)\end{cases} \end{cases}
\end{aligned} \tag{2}$$

where $\pi_{S_1}(w_2,q_1 \mid w_1,q_2) = w_1q_1q_2 - C(q_1) - w_2q_2$, $\pi_{S_2}(q_2 \mid w_2) = w_2q_2 - C(q_2)$. The following proposition characterizes the solution to (2), with superscript "T" denoting the case with traceability.

Proposition 2 (Equilibrium with Traceability in a Serial Supply Chain). *In a serial supply chain with traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_1^{T\ddagger} = \frac{2(p+l)}{\gamma}$ *to the downstream supplier, the downstream supplier offers wholesale price* $w_2^{T\ddagger} = [2(p+l)]^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{2\gamma^2-2\gamma+1}{\gamma(\gamma-2)}}$ *to the upstream supplier, and the downstream and the upstream suppliers' quality levels are* $q_1^{T\ddagger} = \left[\frac{2(p+l)}{\theta\gamma^{2+\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$ *and* $q_2^{T\ddagger} = \left[\frac{2(p+l)}{\theta\gamma^{3-\frac{1}{\gamma}}}\right]^{\frac{1}{\gamma-2}}$, *respectively. Moreover,* $w_1^{T\ddagger}/w_2^{T\ddagger} = \gamma/q_1^{T\ddagger} > \gamma$ *and* $q_1^{T\ddagger}/q_2^{T\ddagger} = \gamma^{\frac{1}{\gamma}} > 1$.

Proposition 2 shows that in a serial supply chain with traceability, the downstream supplier still receives a higher wholesale price than what it offers to the upstream supplier (i.e., $w_1^{T\ddagger} > \gamma w_2^{T\ddagger}$), and it always chooses a higher quality level than the upstream supplier (i.e., $q_1^{T\ddagger} > q_2^{T\ddagger}$). The underlying rationale is similar to that in the case without traceability. However, unlike that case, the two suppliers do not always receive or lose the payments together with traceability. In this case, the downstream supplier is more likely to lose the payment than the upstream supplier; thus, it has an incentive to retain a greater share of the payment received from the buyer when contracting with the upstream supplier compared with the case without traceability (i.e., $w_1^{T\ddagger}/w_2^{T\ddagger} > \gamma = w_1^{N\ddagger}/w_2^{N\ddagger}$). Moreover, the equilibrium quality levels always differ from those in the case without traceability. We now proceed to compare the quality contracting equilibria in the two cases.

3.3. Impact of Traceability on Quality Contracting

Given the previous equilibria with and without traceability, we now study how traceability can impact the quality contracting outcome in a serial supply chain. The following theorem summarizes the comparison of equilibrium contracts characterized in Propositions 1 and 2.

Theorem 1 (Comparison of Contracts in a Serial Supply Chain). *In a serial supply chain,*

(a) *traceability does not change the wholesale price that the buyer offers to the downstream supplier, but always decreases the wholesale price that the downstream supplier offers to the upstream supplier;*

(b) *traceability always improves both suppliers' quality levels;*

(c) *traceability always increases the ratio of the wholesale prices paid to the downstream and the upstream suppliers and the ratio of their quality levels.*

Theorem 1 summarizes the impact of traceability on equilibrium wholesale prices and quality levels in a serial supply chain. We find that traceability leads to a bigger change on the equilibrium wholesale price in the upstream than in the downstream. Specifically, the equilibrium wholesale price that the buyer pays to the downstream supplier remains unchanged regardless of whether the supply chain is traceable or not.[9] With traceability, each supplier is paid based on the quality outcome of the product that it delivers to the next stage. Because the product that the downstream supplier delivers to the buyer is the end product, traceability would not directly change the probability that the downstream supplier is paid. However, traceability would affect the upstream supplier more fundamentally because it eliminates the chance that the upstream supplier would lose the payment when it is actually not defective. Without traceability, because the upstream supplier will be penalized more often, the downstream supplier needs to offer a higher wholesale price to induce the participation of the upstream supplier. Consequently, traceability reduces the wholesale price that the downstream supplier pays to the upstream supplier.

Furthermore, as we have previously mentioned, in a serial supply chain, the buyer indirectly controls the upstream supplier through its neighboring downstream supplier and faces the incentive problem of a two-tier supply chain with double moral hazard. Without traceability, the double moral hazard is worsened because the upstream supplier's payment received also depends on the quality outcome of the downstream supplier. Thus, the upstream supplier has even less incentive to improve quality. However, traceability will temper the adverse effect of double moral hazard. With traceability, the upstream supplier's payment received depends only on its own quality outcome; hence, it has a stronger incentive to improve quality. This will, in turn, boost the downstream supplier's incentive to improve quality, because it is less costly for him to incentivize the upstream supplier now, and it can retain a greater share of the buyer's wholesale price for its own quality improvement. Hence, the quality levels for both suppliers are always improved with traceability. Consequently, in a serial supply chain, traceability creates value by *mitigating double moral hazard* that results from the sequential contracting process, so that suppliers across all tiers along the supply chain are better incentivized to improve quality.

Theorem 1 also states that traceability always increases the discrepancy between the two suppliers' quality levels. Without traceability, the two suppliers will lose payments at the same time. By contrast, with traceability, the downstream supplier will lose payment w_1 if the end product is defective, whereas the upstream supplier will lose payment w_2 if it is defective itself. That is, the downstream supplier is more likely to be penalized than the upstream supplier. Thus, with traceability, the downstream supplier invests disproportionately more than the upstream supplier compared with the case without traceability. Correspondingly, the downstream supplier needs to be compensated more than the upstream supplier. Hence, the relative discrepancy between the wholesale prices paid to the downstream and the upstream suppliers is also increased with traceability.

3.4. Blockchain Adoption Implications

The following theorem summarizes how traceability can affect each firm's profit and the total supply chain profit, based on which we can derive insights for blockchain adoption in a serial supply chain.

Theorem 2 (Comparison of Firm Profits in a Serial Supply Chain). *In a serial supply chain,*

(a) *traceability always improves both the buyer's and the suppliers' expected profits, as well as the total supply chain profit;*

(b) *traceability always improves the upstream supplier's expected profit to a greater extent compared with the downstream supplier.*

We have shown that traceability always improves the quality levels in both tiers of the supply chain. This indicates that the end-product quality becomes closer to the first-best quality in the case with traceability than without. Thus, the supply chain becomes more efficient with traceability and the total supply chain profit can always be improved. Therefore, blockchain should be adopted in a serial supply chain.

Moreover, we further find that all firms can simultaneously benefit from traceability, implying a Pareto improvement. First, consider the buyer. In a serial supply chain, the total agency cost that the buyer pays to the downstream supplier includes the agency cost to (i) directly incentivize the downstream supplier's quality improvement and (ii) indirectly incentivize the upstream supplier's quality improvement. Because traceability helps disentangle the responsibility of the upstream supplier from that of the downstream supplier so that the upstream supplier is no longer penalized for the downstream supplier's fault, the second part of the agency cost can be reduced. Thus, the buyer can incentivize quality improvement across all tiers along the supply chain more efficiently, and traceability always improves the buyer's profit. Second, consider the downstream supplier. Due to the mitigated double moral hazard, the downstream supplier can incentivize quality improvement of the upstream supplier more efficiently with traceability. Thus, its agency cost paid to the upstream supplier is reduced, and the downstream supplier's profit can always be improved with traceability. Third, consider the upstream supplier. It is easy to see that the upstream supplier can directly benefit from traceability because it will no longer be penalized for the downstream supplier's fault. Hence, the upstream supplier's profit can always be improved with traceability. To summarize, the buyer and the suppliers in both tiers of the supply chain are *always* better off with traceability; thus, *all* stakeholders in a serial supply chain can be naturally coordinated to initiate blockchain.

Theorem 2 also shows that traceability always improves the upstream supplier's profit to a greater extent compared with the downstream supplier. Recall from Theorem 1 that compared with the case without traceability, the downstream supplier invests in quality disproportionately more than the upstream supplier in the case with traceability. This means that the downstream supplier will incur a disproportionately higher quality cost; thus, its profit is increased less significantly by traceability than that of the upstream supplier. In practice, suppliers who operate in the upstream of supply chains such as agri-food are often small-scale firms (e.g., smallholder farmers). These small suppliers can be vulnerable to defect penalizations, which would create a significant risk to the supply chain. Our findings indicate that traceability can protect the upstream entities of the supply chain from being whipsawed, hence the entire supply chain might be more likely to sustain.

4. Value of Blockchain in a Parallel Supply Chain

In this section, we consider a parallel supply chain that consists of a buyer and two suppliers who belong to the same tier of the supply chain (Figure 3). The buyer procures the same product from both suppliers and sells both suppliers' products to the market.

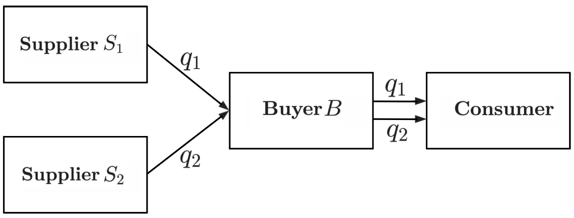
Supplier $i \in \{1,2\}$ decides its quality level $q_i \in [0,1]$ and incurs quality cost $C(q_i) = \theta q_i^\gamma$. The quality level of the product sold to consumers is *solely* determined by the quality level of the supplier who provided that product. Thus, the "weakest link" property does not apply.[10] Moreover, as explained next, the buyer can use the traceability information to keep track of which supplier provided which product and reduce the cost from product recall. Without loss of generality, we assume that the buyer procures half a unit of the product from each supplier and sells one unit in total to the market.[11]

In a parallel supply chain, the buyer offers a contingent payment contract with wholesale price w_i to supplier i, and the suppliers simultaneously choose their quality levels, q_1 and q_2. Depending on whether the supply chain is traceable or not, w_i may be paid under different conditions; we specify the payment mechanisms under each case in Section 4.1. Denote $\mathbf{w} \equiv (w_1, w_2)$ and $\mathbf{q} \equiv (q_1, q_2)$. All proofs in Section 4 are relegated to Online Appendix SB. We now proceed with the equilibrium analysis (Section 4.1) and results (Sections 4.2 and 4.3).

4.1. Contracting Equilibria

4.1.1. Equilibrium Without Traceability. We first consider the case without traceability. If no defect occurs, that is, if both suppliers turn out to not be defective, the buyer receives a total revenue of p and pays each supplier w_i. However, once a defect occurs, that is, if at least one supplier turns out to be defective, the buyer incurs a total loss of l and does not pay either supplier.[12] Without traceability, the buyer does not keep track of which supplier provided which product; so as long as a defective product is identified, it would have to recall all

Figure 3. Parallel Supply Chain



products from the market (CNN 2018, Goldschmidt 2018, Gasparro 2019).

The buyer's contracting problem in a parallel supply chain without traceability is formulated as

$$\max_{\mathbf{w}} \quad \pi_B(\mathbf{w} \mid \tilde{\mathbf{q}}(\mathbf{w})) = p\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w}) - l\left[1 - \prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})\right] - \left(\sum_{i=1}^{2} w_i\right)\prod_{i=1}^{2}\tilde{q}_i(\mathbf{w})$$
$$\text{s.t.} \begin{cases} \pi_{S_i}(\tilde{q}_i(\mathbf{w}) \mid w_i, \tilde{q}_{-i}(\mathbf{w})) \geqslant 0, i \in \{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(\mathbf{w}) = \arg\max_{q_i} \pi_{S_i}(q_i \mid w_i, q_{-i}), i \in \{1,2\} & (\text{IC}_i), \end{cases} \tag{3}$$

where $\pi_{S_i}(q_i \mid w_i, q_{-i}) = w_i q_i q_{-i} - C(q_i)$ is the expected profit function of supplier $i \in \{1,2\}$. The buyer maximizes its expected profit subject to the suppliers' individual rationality and incentive compatibility constraints. Given the contract offered by the buyer, the suppliers choose their quality levels simultaneously as self-interested profit maximizers. The following proposition characterizes the solution to (3), with superscript "†" denoting the equilibrium in a parallel supply chain.

Proposition 3 (Equilibrium Without Traceability in a Parallel Supply Chain). *In a parallel supply chain without traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{N\dagger} = \frac{p+l}{\gamma}$ *to supplier* $i \in \{1,2\}$, *and supplier i chooses quality level* $q_i^{N\dagger} = \left(\frac{p+l}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Unlike in a serial supply chain, double moral hazard does not arise in a parallel supply chain. Instead, only the single moral hazard between the buyer and each supplier arises. However, without traceability, the buyer has to recall all products from the market once a defective product is identified. This means that a supplier can be penalized for the other supplier's fault even though it may not be defective itself. The moral hazard can be worsened because of this.

4.1.2. Equilibrium with Traceability.

We next consider the case with traceability. Traceability will not have an impact if both suppliers turn out to not be defective (in which case the buyer will receive a revenue of p) or defective (in which case the buyer will incur a loss of l). However, traceability will have an impact if only one supplier turns out to be defective. In this case, the buyer is able to distinguish between defective and not defective products because it knows who the supplier is for each product sold (Nash 2018b, Gaur and Gaiha 2020). Thus, he would be able to recall only the defective products from the market and incur a loss of $\frac{1}{2}l$, while receiving a revenue of $\frac{1}{2}p$ from selling the not defective products. Correspondingly, the buyer only pays the supplier who turns out to not be defective.

The buyer's contracting problem in a parallel supply chain with traceability is formulated as

$$\max_{\mathbf{w}} \quad \pi_B(\mathbf{w} \mid \tilde{q}_1(w_1), \tilde{q}_2(w_2)) = p\prod_{i=1}^{2}\tilde{q}_i(w_i) - l\prod_{i=1}^{2}[1 - \tilde{q}_i(w_i)] + \frac{1}{2}(p-l)\sum_{i=1}^{2}\tilde{q}_i(w_i)[1 - \tilde{q}_{-i}(w_{-i})] - \sum_{i=1}^{2} w_i\tilde{q}_i(w_i)$$
$$\text{s.t.} \begin{cases} \pi_{S_i}(\tilde{q}_i(w_i) \mid w_i) \geqslant 0, i \in \{1,2\} & (\text{IR}_i) \\ \tilde{q}_i(w_i) = \arg\max_{q_i} \pi_{S_i}(q_i \mid w_i), i \in \{1,2\} & (\text{IC}_i), \end{cases} \tag{4}$$

where $\pi_{S_i}(q_i \mid w_i) = w_i q_i - C(q_i)$ for $i \in \{1,2\}$. The following proposition characterizes the solution to (4).

Proposition 4 (Equilibrium with Traceability in a Parallel Supply Chain). *In a parallel supply chain with traceability, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{T\dagger} = \frac{p+l}{2\gamma}$ *to supplier* $i \in \{1,2\}$, *and supplier i chooses quality level* $q_i^{T\dagger} = \left(\frac{p+l}{2\theta\gamma^2}\right)^{\frac{1}{\gamma-1}}$.

With traceability, because the buyer saves the cost of recalling not defective products, the equilibrium wholesale price and the resulting quality level of the suppliers differ from the case without traceability. We now proceed to compare the quality contracting equilibria in the two cases.

4.2. Impact of Traceability on Quality Contracting

The following theorem summarizes the comparison of equilibrium contracts characterized in Propositions 3 and 4.

Theorem 3 (Comparison of Contracts in a Parallel Supply Chain). *In a parallel supply chain,*

(a) *traceability always decreases the wholesale prices;*

(b) *there exists a threshold for the loss under defect,* $\bar{l} \equiv \frac{\theta\gamma^2}{2^{\gamma-2}} - p$, *such that traceability improves the suppliers' quality levels if* $l \leqslant \bar{l}$, *and reduces the suppliers' quality levels if* $l > \bar{l}$.

Theorem 3 shows that compared with the case without traceability, the buyer will always offer a lower wholesale price to the suppliers in the case with traceability. A supplier stands a higher chance of losing its wholesale price payment without traceability because it will also lose the payment if the other supplier is defective even though it may not be defective itself. Thus, the buyer needs to offer a higher wholesale price to induce the suppliers to participate. By contrast, with traceability, a supplier will only lose its wholesale price payment if it is defective itself. Thus, the buyer can use a lower wholesale price to induce the suppliers to participate.[13]

Theorem 3 also shows that, in a parallel supply chain, traceability can either improve or reduce the suppliers' quality levels. On the one hand, with traceability, a supplier will no longer be penalized for the other supplier's fault. This mitigates moral hazard and increases the suppliers' incentive to improve quality. On the other hand, traceability can significantly reduce the cost incurred by the buyer when a defect occurs. Without traceability, the buyer may have to recall all products from the market once a defect occurs and lose the revenue for both defective and not defective products. However, with traceability, the buyer can recall only the defective products and still receive the revenue for not defective products. As a result, the buyer is less worried about product defects and would prefer to induce a lower quality level with traceability by offering a lower wholesale price. Furthermore, when the loss is large (i.e., $l > \bar{l}$), the buyer's cost saving due to flexible product recall is substantial. In this case, the buyer's incentive to induce a lower quality level will dominate the suppliers' incentive to improve quality due to the mitigated moral hazard, and hence traceability will reduce the equilibrium quality levels. The opposite occurs when the loss is small (i.e., $l \leqslant \bar{l}$), and hence traceability will improve the equilibrium quality levels.

To summarize, in a parallel supply chain, in addition to the improved efficiency due to the mitigated moral hazard, traceability also impacts the supply chain by *enabling flexible product recall*. These two effects impact the equilibrium quality levels in opposite directions. Hence, traceability can reduce product quality in a parallel supply chain. Moreover, although common intuition might suggest that enabling traceability is always better for consumers, our results indicate that the opposite could occur. In particular, when the buyer's loss under defect is large, consumers may face lower-quality products in the case with traceability. This indicates that enabling traceability in a parallel supply chain may hurt consumer welfare.[14]

4.3. Blockchain Adoption Implications

We now turn to blockchain adoption implications for a parallel supply chain. The following theorem summarizes the comparison of firms' equilibrium profits with and without traceability.

Theorem 4 (Comparison of Firm Profits in a Parallel Supply Chain). *In a parallel supply chain,*

(a) *traceability always improves the buyer's expected profit and the total supply chain profit;*

(b) *traceability improves the suppliers' expected profits if* $l \leqslant \bar{l}$, *and reduces the suppliers' expected profits if* $l > \bar{l}$.

We have seen that blockchain impacts a parallel supply chain in two ways. First, traceability enables flexible product recall and eliminates the loss from recalling not defective products. Second, traceability mitigates moral hazard by eliminating the possibility of a supplier being penalized by the other supplier's fault. It is easy to see that both factors improve the total supply chain profit, and hence blockchain should be adopted in a parallel supply chain.

Moreover, traceability always improves the buyer's profit because it benefits from both the reduced loss due to flexible product recall and the reduced agency cost due to mitigated moral hazard. However, the suppliers can be worse off with traceability. As discussed previously, although traceability can benefit the suppliers because they will not be penalized by each other's fault, it can also hurt the suppliers if the buyer decides to substantially reduce the wholesale price due to flexible product recall. We have known from Theorem 3 that when the buyer's loss under defect is large (i.e., $l > \bar{l}$), traceability will lead him to reduce the wholesale price so significantly that the suppliers have less incentive to improve quality. In this case, traceability will reduce the suppliers' profits. This implies that the buyer and suppliers can have *opposite* preferences for blockchain adoption in a parallel supply chain. Although traceability improves the total supply chain profit, blockchain cannot be implemented unless the buyer is willing to share its profit gain with the suppliers so that the suppliers can also be better off with traceability. When the buyer's loss under defect is small (i.e., $l \leqslant \bar{l}$), traceability will improve the suppliers' profits, and blockchain can be initiated by any firm in a parallel supply chain.

5. Design of Blockchain

Thus far, we have focused on the impact of traceability and found that traceability can have different impacts on product quality and have different implications on blockchain adoption depending on the supply chain structure. When adopting a blockchain, firms also need to design how the blockchain operates. For example, supply chain practitioners need to design the membership profiles for blockchain participants through an access control layer, including whether a firm is permitted to join the blockchain, what data it can access and record, and what activities it can perform on the blockchain (Frankenfield 2020, Gaur and Gaiha 2020). Moreover, it is also important to design the control mechanisms for blockchain implementation, including whether a firm should pay for accessing other firms' data, how consensus is reached, and how contracts can be automatically executed through smart contracts (Cui and Gaur 2021). In this section, we investigate several issues related to the design of a traceability-driven blockchain. In Section 5.1, we study the optimal data permission policy for traceability data. In Section 5.2, we examine what kind of consensus mechanism can induce the optimal data permission policy to be chosen. In Section 5.3, we investigate issues related to data governance. In Section 5.4, we discuss the implications of these findings for blockchain design.

5.1. Data Permission

When a blockchain is adopted in a supply chain, it is important to understand whether all participants in the blockchain should automatically be granted access to the traceability data (Frankenfield 2020, Seth 2021). Thus far, we have assumed that all firms can access the data. However, it could be possible that certain firms may want to form a subgroup to share data among themselves and derive a different form of contract based on the data they share, while excluding other firms from accessing the data. We now consider such potential restricted data permission schemes in serial and parallel supply chains, and analyze alternative contracting schemes that may arise under restricted data permission. By comparing restricted and unrestricted data permission schemes, we uncover the optimal data permission policy for a traceability-driven blockchain. The model formulation and supplemental results for Sections 5.1 and 5.2 can be found in Online Appendix C, and the proofs are relegated to Online Appendix SC.

5.1.1. Serial Supply Chain. In a serial supply chain, a potential restricted data permission scheme is one where each supplier shares their own traceability data with the buyer but not with each other. In this case, without gaining access to the traceability data of the upstream supplier, the downstream supplier cannot pay the upstream supplier contingent on the upstream supplier's quality outcome. However, the buyer can directly contract with both suppliers and pay wholesale price w_i to supplier i if and only if supplier i is not defective himself. Figure 4(b) illustrates such a scenario,[15] whereas Figure 4(a) illustrates the case with unrestricted data permission (i.e., the setting analyzed in Section 3.2.2).[16]

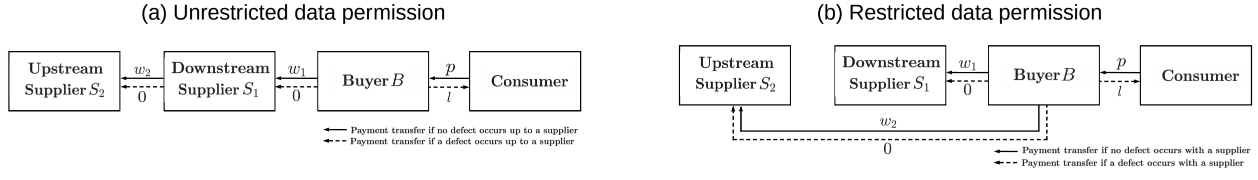
Proposition 5 (Equilibrium Under Restricted Data Permission in a Serial Supply Chain). *In a serial supply chain under restricted data permission, there exists a unique equilibrium such that the buyer offers wholesale price* $w_i^{R\ddagger} = (p+l)^{\frac{\gamma-1}{\gamma-2}}\left(\frac{1}{\theta}\right)^{\frac{1}{\gamma-2}}\left(\frac{1}{\gamma}\right)^{\frac{\gamma}{\gamma-2}}$ *to supplier* $i \in \{1,2\}$, *and the downstream and the upstream suppliers choose quality level* $q_i^{R\ddagger} = \left(\frac{p+l}{\theta\gamma^2}\right)^{\frac{1}{\gamma-2}}$.

Proposition 5 characterizes the equilibrium under restricted data permission, with superscript "R" representing this case. Because the buyer directly contracts with both suppliers, the sequential contracting feature under unrestricted data permission is removed and both suppliers receive the same wholesale price. Thus, the restricted data permission changes the contracting scheme similar to that in an assembly supply chain, where the end product quality is still jointly determined by all suppliers but the buyer controls all suppliers' quality directly. The following theorem derives the optimal data permission policy for the supply chain, by comparing the equilibria under restricted (Proposition 5) and unrestricted (Proposition 2) data permission.

Theorem 5 (Optimal Data Permission in a Serial Supply Chain). *In a serial supply chain, there exists a threshold* $\bar{\gamma}_1$ *such that the total supply chain profit is higher under unrestricted data permission if* $\gamma \leqslant \bar{\gamma}_1$, *and higher under restricted data permission if* $\gamma > \bar{\gamma}_1$. *Moreover,* $\bar{\gamma}_1$ *is the unique solution to* $(\gamma^2-2)\gamma^{\frac{\gamma-1}{\gamma-2}} = (\gamma^3-2\gamma-2)2^{\frac{2}{\gamma-2}}$ *in the range of* $\gamma > 2$.

Theorem 5 shows that whether the supply chain should adopt restricted or unrestricted data permission depends on the suppliers' cost to improve quality, and restricted data permission is optimal when quality improvement is less costly (i.e., $\gamma > \bar{\gamma}_1$). Compared with unrestricted data permission, the restricted data permission scheme eliminates double moral hazard because the buyer directly contracts with both suppliers. Meanwhile, a single moral hazard arises in the contract between the buyer and each supplier. Thus, the comparison between the two data permission schemes boils down to comparing the inefficiency caused by the single and double moral hazard. When the quality cost is lower, the suppliers are more willing to improve quality themselves, and hence the inefficiency caused by the single moral hazard is reduced. However, the inefficiency caused by the double moral hazard is less sensitive to the quality cost. Recall that the double moral hazard gives the downstream supplier an incentive to retain a greater share of the buyer's wholesale price to improve quality himself rather than compensating the upstream

Figure 4. Contracts Under Different Data Permission Schemes in a Serial Supply Chain



supplier to improve quality. When the quality cost is lower, the downstream supplier becomes more willing to improve its own quality, which means that its incentive to compensate the upstream supplier can be further reduced. This would create a counterforce for the upstream supplier to improve quality and limit the supply chain's overall ability to benefit from the lower quality cost. Hence, the supply chain is more efficient with restricted data permission when the quality cost is sufficiently low. Therefore, in a serial supply chain, the optimal design of a traceability-driven blockchain may not grant data access to all firms, and *one-on-one data sharing* (between the buyer and each supplier) can be better for the supply chain than network data sharing.

5.1.2. Parallel Supply Chain.

In a parallel supply chain, a potential restricted data permission scheme is one where the suppliers share the traceability data with each other but not with the buyer.[17] In this case, the buyer will not be able to achieve flexible product recall. Hence, it will pay the suppliers if and only if no defect occurs. However, because the suppliers can use the traceability data to identify who is defective, they can agree on a contract where the defective supplier shall pay the not defective supplier t_i if only one supplier turns out to be defective. Figure C.1(b) in Online Appendix C illustrates such a scenario, while Figure C.1(a) illustrates the case with unrestricted data permission (i.e., the setting analyzed in Section 4.1.2).[18]

Parallel to Proposition 5 and Theorem 5, Proposition C.1 and Theorem C.1 in Online Appendix C summarize the results for a parallel supply chain. In a parallel supply chain, it is always optimal not to restrict any firm's data permission. Under restricted data permission, the equilibrium transfer payment from the defective supplier to the not defective supplier is zero. Given any transfer payment offered by the other supplier, a supplier will always have an incentive to offer a lower transfer payment, resulting in both suppliers offering a zero transfer payment in equilibrium so that the equilibrium would reduce to that without traceability (see Proposition 3). Therefore, unlike a serial supply chain, a parallel supply chain always benefits from *network data sharing* when adopting a traceability-driven blockchain.

5.2. Consensus Mechanism

In Section 5.1, we have identified the optimal data permission policy that maximizes the supply chain profit. However, whether the optimal data permission policy can be chosen or not will depend on how this decision is made when firms form the blockchain. We next consider two kinds of decision-making methods, a centralized consensus mechanism and a decentralized consensus mechanism, and study which mechanism can lead to a better data permission policy. In the centralized consensus mechanism, the buyer (i.e., the principal of the contract) decides on the data permission policy. This could correspond to industries where the retailer (e.g., Walmart) has dominating power in the supply chain. However, the decentralized nature of blockchain may prompt firms to resort to a decentralized decision-making method. We thus consider a typical decentralized consensus mechanism where all firms in the blockchain will vote on the data permission policy and the data permission policy of the blockchain will be chosen based on the majority rule.[19]

5.2.1. Serial Supply Chain.

To study how firms will reach consensus, we first need to understand each firm's individual preference. The following proposition summarizes the results for individual firms' preferences regarding the data permission schemes in a serial supply chain.

Proposition 6 (Individual Firm Preferences for Data Permission in a Serial Supply Chain). *In a serial supply chain, there exist thresholds $\bar{\gamma}_2$ and $\bar{\gamma}_3$ (where $\bar{\gamma}_3 < \bar{\gamma}_1 < \bar{\gamma}_2$) such that*

(a) *the buyer prefers unrestricted data permission if $\gamma \leqslant \bar{\gamma}_2$, and prefers restricted data permission if $\gamma > \bar{\gamma}_2$;*

(b) *the downstream supplier always prefers unrestricted data permission;*

(c) *the upstream supplier prefers unrestricted data permission if $\gamma \leqslant \bar{\gamma}_3$, and prefers restricted data permission if $\gamma > \bar{\gamma}_3$.*

Moreover, $\bar{\gamma}_2 = 4$, and $\bar{\gamma}_3$ is the unique solution to $\gamma^{\gamma-1} = 2^{\gamma}$ in the range of $\gamma > 2$.

First, the buyer's preference hinges on how efficient it is to incentivize the suppliers to improve quality. As we have seen from Theorem 5, when the quality cost is higher, the suppliers are more willing to improve quality under unrestricted data permission; the opposite occurs when the quality cost is lower. Thus, as shown by Proposition 6, the buyer prefers unrestricted data permission when the quality cost is sufficiently high (i.e., $\gamma \leqslant \bar{\gamma}_2$), and prefers restricted data permission otherwise (i.e., $\gamma > \bar{\gamma}_2$). Second, the downstream supplier always prefers unrestricted data permission. This is because under unrestricted data permission, the downstream supplier can take advantage of its role as the principal in its contract with the upstream supplier to retain a greater share of the buyer's wholesale price itself and pay less to the upstream supplier. Third, the upstream supplier's preference once again depends on the quality cost. As discussed previously, the restricted data permission scheme eliminates the double moral hazard arising from the upstream supplier's contract with the downstream supplier and replacing it with the single moral hazard arising from the upstream supplier's contract with the buyer. We have also known that when the quality cost is lower, the suppliers are more willing to improve quality themselves and the inefficiency caused by the single moral hazard is reduced. Anticipating this, the buyer would become more willing to pay each supplier to improve quality. As a result, the upstream supplier benefits from direct contracting with the buyer and thus prefers restricted data permission when the quality cost is low (i.e., $\gamma > \bar{\gamma}_3$). The opposite occurs when the quality cost is high (i.e., $\gamma \leqslant \bar{\gamma}_3$), and the upstream supplier prefers unrestricted data permission. Given the individual firms' preferences, the following theorem summarizes the data permission policies chosen under the two consensus mechanisms and compares them to the optimal data permission policy for a serial supply chain.

Theorem 6 (Data Permission Chosen in a Serial Supply Chain). *In a serial supply chain, the centralized and decentralized consensus mechanisms lead to the same data permission policy. Under both mechanisms,*

(a) *if* $\gamma \leqslant \bar{\gamma}_1$, *unrestricted data permission will be chosen, which is the optimal policy for the supply chain;*

(b) *if* $\bar{\gamma}_1 < \gamma \leqslant \bar{\gamma}_2$, *unrestricted data permission will be chosen, which is not the optimal policy for the supply chain;*

(c) *if* $\gamma > \bar{\gamma}_2$, *restricted data permission will be chosen, which is the optimal policy for the supply chain.*

Theorem 6 shows that in a serial supply chain, the centralized and decentralized consensus mechanisms will lead to the same data permission policy. As indicated by Proposition 6, there always exists at least one supplier whose preference is consistent with the buyer's. Hence, the buyer's preferred data permission will be chosen even if all firms vote on the data permission policy. In particular, when the quality cost is sufficiently high (i.e., $\gamma \leqslant \bar{\gamma}_2$), unrestricted data permission will be chosen; otherwise, restricted data permission will be chosen. However, recall from Theorem 5 that the optimal policy for the supply chain is characterized by a different threshold $\bar{\gamma}_1$. Because $\bar{\gamma}_2 > \bar{\gamma}_1$, the consensus mechanisms will lead to unrestricted data permission being chosen more often, whereas restricted data permission *should* be chosen when the quality cost is moderate (i.e., $\bar{\gamma}_1 < \gamma \leqslant \bar{\gamma}_2$).

5.2.2. Parallel Supply Chain. Parallel to Proposition 6 and Theorem 6, Proposition C.2 and Theorem C.2 in Online Appendix C summarize the results for a parallel supply chain. In a parallel supply chain, the buyer always prefers unrestricted data permission, because having access to the suppliers' traceability data can enable the buyer to achieve flexible product recall. Thus, the centralized consensus mechanism will lead to unrestricted data permission always being chosen. Moreover, this is also the optimal policy for the supply chain. By contrast, the suppliers would prefer restricted data permission when the buyer's loss under defect is large (i.e., $l > \bar{l}$), because unrestricted data permission can allow the buyer to transfer more loss to the suppliers through a significantly decreased wholesale price. Because the suppliers outnumber the buyer in a parallel supply chain, the decentralized consensus mechanism will lead to restricted data permission being chosen in this case, which will hurt the supply chain profit. Therefore, the *centralized consensus mechanism* should be used to determine the data permission policy in a parallel supply chain, which is different from the case of a serial supply chain.

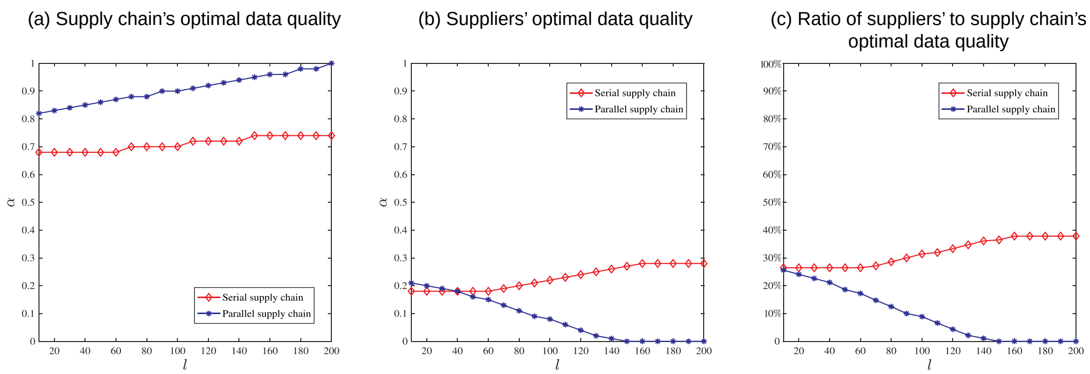
5.3. Data Governance

Data governance is a set of principles and practices that ensure the high quality of data in terms of authenticity, consistency, and usability. In the case of a traceability-driven blockchain, the quality of traceability data can depend on what kind of data are recorded into the blockchain and whether the way of data recording can be susceptible to fraud. Such factors can critically affect how effectively the supply chain can identify the defect-causing supplier and the defective product. For example, data related to ex post measures (e.g., color of food products) could be more indicative of a supplier's quality outcome than ex ante measures (e.g., time of production). Moreover, data automatically recorded by IoT sensors are more credible than those recorded with more human intervention. In this section, we investigate the suppliers' incentive to improve data quality in the blockchain. Specifically, we assume that the suppliers choose the quality of traceability data, $\alpha \in [0,1]$, which represents the probability that the traceability data can be used to identify the defect-causing supplier and the defective product, and the cost of improving data quality is $G(\alpha) = \frac{1}{2}\kappa\alpha^2$. The model formulation can be found in Online Appendix D. Due to limited tractability, we resort to numerical studies. Figure 5 illustrates the main results.

First, we examine the optimal data quality of the supply chain. Figure 5(a) shows that the optimal data quality is always higher in a parallel supply chain than in a serial supply chain. In a serial supply chain, a higher level of data quality would correspond to a higher probability to identify defect-causing suppliers. In a parallel supply chain, a higher level of data quality would correspond to not only a higher probability to identify defect-causing suppliers but also more flexible recall of defective products, thus generating a higher value to the supply chain.

Second, we examine the data quality chosen by the suppliers. Figure 5(b) shows that the data quality chosen by the suppliers decreases in the loss under defect, l, in a parallel supply chain, and increases in l in a serial supply chain. In a parallel supply chain, as l increases, the buyer can benefit more from flexible recall and hence wants to induce a lower quality level. Correspondingly, the buyer offers a lower wholesale price to the suppliers, making them unwilling to improve data quality. However, in a serial supply chain, the upstream supplier benefits from the elimination of over-penalization and this benefit becomes higher as l increases. Thus, it would prefer a

Figure 5. (Color online) Comparison of Optimal Data Quality ($p = 800$, $\theta = 300$, $\gamma = 5$, $\kappa = 20$)



higher data quality to benefit further from the elimination of over-penalization.

Third, as Figure 5(c) shows, the ratio of the suppliers' optimal data quality level to the supply chain's optimal data quality level is higher in a serial supply chain than in a parallel supply chain. This indicates that the suppliers' incentive to enhance data governance is *more aligned* with the supply chain optimum in a serial supply chain. Moreover, as l increases, the incentive misalignment becomes less severe in a serial supply chain but becomes severer in a parallel supply chain.

5.4. Blockchain Design Implications

When being used as a decentralized ledger system for cryptocurrencies, blockchains are typically created as public blockchains (e.g., Bitcoin, Ethereum, and Litecoin), where anyone can join the blockchain, access the data, and participate in the decision-making process (Sharma 2019, Seth 2021). Differently, blockchains for supply chains should naturally be private blockchains (e.g., Hyperledger Fabric, Quorum, and R3 Corda), where only authorized participants can join the blockchain and firms' access to the data may be restricted (Jaeger 2018, Vitasek et al. 2022).

Our results from Sections 5.1 and 5.2 highlight that when creating a traceability-driven blockchain, firms need to incorporate *centralized* features in designing the membership profiles and control mechanisms. In a serial supply chain, the blockchain should not automatically grant data access to all firms. Instead there needs to be an *access control layer* to govern firms' access to the traceability data (e.g., Walmart adopted a private blockchain to restrict participants' data access; Vitasek et al. 2022), and we further identify that when the suppliers' cost to improve quality is low, restricting the suppliers' permission to access each other's traceability data can nudge them to directly and separately contract with the buyer, which improves supply chain efficiency. In a parallel supply chain, although access to the traceability data does not need to be restricted, there needs to be a *centralized consensus mechanism*, led by the buyer, that governs the data permission policy of the blockchain to prevent suppliers from forming a subnetwork for data sharing.

Furthermore, our results from Section 5.3 indicate that *data governance* is more critical when a traceability-driven blockchain is implemented in a parallel supply chain than in a serial supply chain (e.g., Walmart highlighted the importance of improving data accuracy on the blockchain; Bhattacharyya 2022). On the one hand, ensuring the high quality of traceability data being recorded into the blockchain can generate a higher value to a parallel supply chain. On the other hand, the suppliers' incentive to enhance data governance is less aligned with the supply chain optimum in a parallel supply chain. Thus, to uncover the full potential of a traceability-driven blockchain, supply chain practitioners should be more cautious about what types of data are recorded (e.g., ex post or ex ante measures of quality) and how they are recorded in the blockchain (e.g., through IoT sensors or tracking devices) for parallel supply chains. Moreover, the buyer should be willing to compensate the suppliers, particularly in a parallel supply chain, for their efforts to improve data quality, so that the supply chain can be moved closer to the optimal data governance regime.

6. Conclusion and Discussion

This paper provides a theoretical investigation into the value and design of a traceability-driven blockchain. Our analyses and results highlight the different impacts of traceability when enabled under different supply chain structures, as well as the unique challenges faced by firms operating in different kinds of supply chains when they adopt and design a traceability-driven blockchain.

The two supply chain structures studied in this paper each capture a distinct and commonly observed feature of supply chains in practice. Needless to say, there could exist other supply chain features. For example, an alternative (and simpler) supply chain structure would be an assembly supply chain, where each supplier provides a different component to the buyer and the end product quality is jointly determined by all suppliers. Compared with the two supply chain structures studied, an assembly supply chain does not have a sequential production process as in a serial supply chain or face the need for flexible recall as in a parallel supply chain, the two features that give rise to the functionalities of a traceability-driven blockchain. In Online Appendix G, we verify that without these features, traceability would not impact the equilibrium quality or firm profits in an assembly supply chain. In an assembly supply chain, traceability can increase the probability that the suppliers receive the wholesale price because a supplier won't be penalized for another supplier's fault. However, anticipating a higher probability of paying the wholesale price, the buyer will reduce the wholesale price so that the suppliers' expected payment remains the same in equilibrium. Hence, traceability will not lead to a change in the equilibrium quality, or the firm profits. Thus, the value of traceability does not simply come from making the suppliers' quality outcomes verifiable, but is deeply rooted in the interaction with the supply chain features identified in this paper.

Our paper is one of the first to investigate the impact of blockchain on supply chain operations. Our work could serve as a stepping stone for future research in this domain. Future research could consider more complicated supply chain structures (e.g., by incorporating assembly features) and provide more generalized guidelines for implementing traceability-driven blockchains. Future research could also investigate how blockchain-enabled traceability can interact with other instruments for quality management (e.g., supplier penalization). Finally, it is also worth studying how blockchain-enabled traceability can create an impact if the sales quantity is quality dependent.

Endnotes

[1] The power cost function with $\gamma > 1$ is twice continuously differentiable on $[0, 1]$ and convexly increasing in quality, which is consistent with the quality contracting literature (Baiman et al. 2001, Balachandran and Radhakrishnan 2005, Chao et al. 2009, Plambeck and Taylor 2016, Bondareva and Pinker 2019). Moreover, the model can be extended to account for heterogeneous suppliers (i.e., θ is different for different suppliers) and the main insights carry through.

[2] We focus on the suppliers' quality decisions and do not consider the buyer's quality decision, which is consistent with the literature (Baiman et al. 2000, Hwang et al. 2006, Babich and Tang 2012, Rui and Lai 2015, Nikoofal and Gümüş 2018). The main insights of the paper would carry through if the buyer's quality decision is incorporated. Besides, we do not consider the case in which the downstream supplier inspects the product delivered by the upstream supplier. Thus, the downstream supplier does not observe the quality outcome of the upstream supplier. This could correspond to situations in which inspection of incoming product is too costly or infeasible (Mu et al. 2016).

[3] We assume that the retail price p is exogenously given, which is a common assumption in the literature on supply chain quality management (Baiman et al. 2000, 2004; Balachandran and Radhakrishnan 2005; Hwang et al. 2006; Chao et al. 2009; Babich and Tang 2012; Dong et al. 2016; Lee and Li 2018; Nikoofal and Gümüş 2018; Bondareva and Pinker 2019). Moreover, in Online Appendix H, we extend our model to incorporate the scenario in which the buyer inspects the product before selling to the market and chooses the optimal inspection level.

[4] In Online Appendix I, we extend our model to incorporate the scenario in which the suppliers will also incur an exogenous loss when the product is defective.

[5] The contingent payment contract is equivalent to one where the buyer (respectively, the downstream supplier) pays w_1 (respectively, w_2) up front and receives a refund w_1 (respectively, w_2) if the product turns out to be defective. Moreover, in practice, big retailers (such as Walmart, Amazon, and Target) usually do not pay their suppliers until they receive the revenue from selling the products (Strom 2015). This is consistent with the evidence provided in the academic literature (Kim and Shin 2012) that in a serial supply chain, suppliers are paid in a sequential manner and payments are usually delayed. Thus, if the end product is defective, the buyer does not receive any revenue from the market and would not pay the downstream supplier (Moore 2017), and consequently, the downstream supplier would not pay the upstream supplier. This would correspond to our model where none of the suppliers receives a payment if the end product is defective.

[6] Double moral hazard has previously been studied in a bilateral relationship between two parties, both of whom make unobservable effort decisions that result in moral hazard (Cooper and Ross 1985, Balachandran and Radhakrishnan 2005, Hwang et al. 2006). However, we consider a more generalized setting by adding one more layer on top of a traditional two-tier supply chain, which makes the incentive problem more complicated and can generate new insights. In our setting with a three-tier supply chain, moral hazard arises in a sequential manner, and the double moral hazard between the upstream and the downstream suppliers can interact with the single moral hazard between the buyer and the two-tier supply chain, which has not been explored in the literature.

[7] It would be suboptimal for the buyer to choose the wholesale price solely based on the quality outcome of the downstream supplier himself, rather than the quality outcome up to the downstream supplier that reflects the joint quality level of both the upstream and the downstream suppliers. To see this, consider the sample path in which the upstream supplier is defective, whereas the downstream supplier is not defective. If the wholesale price is paid based on whether the immediate supplier is defective or not, then the buyer will have to pay the downstream supplier while incurring a loss from the market because the end product is defective. Meanwhile, the downstream supplier does not have to pay the upstream supplier. Hence, the downstream supplier would actually prefer the upstream supplier to be defective and offer a zero wholesale price to the upstream supplier. Anticipating that the end product will be defective, the buyer will offer a zero wholesale price to the downstream supplier. Therefore, this payment rule will result in a supply chain failure where no one exerts any effort and a zero end-product quality level is induced. Consequently, in this paper, we consider a payment rule that is based on the quality outcome of the product delivered by each supplier, rather than the quality outcome of each supplier himself.

[8] When it is realized that the upstream supplier is not defective, whereas the downstream supplier is defective, the downstream supplier may have an incentive to withhold the payment to the upstream supplier because it is not paid by the buyer. The smart contract (which is typically integrated as a component of the blockchain) can ensure that payments are automatically executed once certain condition is satisfied (e.g., a supplier is deemed faulty/

non-faulty based on the traceability information retrieved from the blockchain). This would eliminate firms' ex post deviation from the contracting terms. Moreover, in Online Appendix E, we extend our model to incorporate the downstream supplier's limited liability constraint. Additionally, in Online Appendix F, we consider an alternative way for the traceability information to be used.

[9] If we consider a more complicated serial supply chain model by incorporating other factors, the buyer's equilibrium wholesale price can change with traceability. This is the case in our extension where the buyer inspects the end product before selling to the market (see Online Appendix H), and in another extension where the suppliers also suffer from reputation damage and market loss under defect (see Online Appendix I). Importantly, in both extensions, we continue to observe the same result that traceability leads to a bigger change on the equilibrium wholesale price in the upstream than in the downstream (see Figure H.1 in Online Appendix H and Figure I.1 in Online Appendix I).

[10] A parallel supply chain is different from an assembly supply chain. In an assembly supply chain, the buyer assembles the different components sourced from different suppliers and sells the end product to the market, and as a result, the "weakest link" property applies. In Online Appendix G, we formally study the case of an assembly supply chain.

[11] Our main insights carry through if the buyer procures different proportions from the two suppliers.

[12] The contingent payment contract is equivalent to one where the buyer pays w_i up front and receives a refund w_i from supplier i if the product turns out to be defective.

[13] In a parallel supply chain, the total equilibrium wholesale price paid by the buyer can exceed the retail price. We further find that this would occur when the buyer's loss under defect is large enough. In this paper, we do not explicitly consider the buyer's non-negative cash flow constraint that the total wholesale price cannot exceed the retail price. If the buyer's non-negative cash flow constraint is incorporated, the equilibrium wholesale prices may be downward distorted so that the buyer cannot effectively incentivize the suppliers to choose the desired quality levels. This is more likely to occur in the case without traceability compared with the case with traceability because the equilibrium wholesale prices are higher without traceability. Therefore, in a parallel supply chain, traceability can help improve the buyer's cash flow feasibility (Cui et al. 2022b).

[14] In a parallel supply chain, we can measure consumer surplus as Prob(both suppliers are non-defective) $\cdot (V-p)^+$ for the case without traceability, and Prob(both suppliers are non-defective) $\cdot (V-p)^+ +$ Prob(only one supplier is non-defective) $\cdot \frac{1}{2}(V-p)^+$ for the case with traceability, where V represents the valuation of consumers when receiving a non-defective product and p is the retail price. When traceability reduces the suppliers' quality levels significantly, the probability for consumers to earn a positive surplus will be reduced, and thus traceability will hurt consumer surplus. In a serial supply chain, we can measure consumer surplus as Prob(end product is non-defective) $\cdot$ $(V-p)^+$ for both cases with and without traceability. Following our findings in Section 3, traceability always increases the suppliers' quality levels, and thus it will always improve consumer surplus.

[15] Because the downstream supplier does not have access to the upstream supplier's traceability data, if the upstream supplier also contracts with the downstream supplier, the downstream supplier would have to pay the upstream supplier regardless of whether the upstream supplier is defective or not. We find that in this case, the downstream supplier will offer a zero wholesale price to the upstream supplier, which means that the contract will reduce to that in Figure 4(b).

[16] An alternative restricted data permission scheme would be one where the suppliers share the traceability data with each other but not with the buyer. In this case, the buyer would pay the downstream supplier contingent on the quality outcome of the end product, whereas the downstream supplier can pay the upstream supplier contingent on the quality outcome of the upstream supplier. This would result in an equivalent contract as the unrestricted data permission scheme in Section 3.2.2.

[17] Horizontal information sharing among firms within the same tier of a supply chain is not rare in practice. For example, according to a survey conducted by the Organization for Economic Co-operation and Development (OECD), information exchange occurs frequently between competing firms via trade associations in the United States (Shamir and Shin 2018; see also https://www.oecd.org/competition/cartels/48379006.pdf). Meanwhile, a stream of literature has investigated whether competing firms can have an incentive to exchange information with each other (Shamir and Shin 2016).

[18] It is easy to see that the alternative restricted data permission scheme, one where the suppliers share the traceability data with the buyer but not with each other, is equivalent to the unrestricted data permission scheme, because the contract under unrestricted data permission scheme (Section 4.1.2) does not require the suppliers to know the quality outcome of each other.

[19] The majority rule is widely observed in business practice. For example, many companies (e.g., Walt Disney and Intel) adopt the majority rule and shareholders have the opportunity to cast a vote for the re-election of directors (Marr 2005, Plitch 2006). Moreover, because the decentralized nature of blockchain can make voting more accessible, secure, temper-proof, and trustworthy (Malkov 2021), there have been an increasing number of blockchain-based voting platforms in practice (e.g., Polys, Follow My Vote, VoteWatcher, and VotoSocial).

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