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# Blockchain Adoption in a Supply Chain with Manufacturer Market Power

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**Abstract**

We examine a supply chain with a single risk-averse manufacturer who purchases from suppliers and sells to consumers. Within this context, we focus on two channels that drive blockchain adoption by the manufacturer: manufacturer risk aversion and consumer information asymmetry. With regard to the first channel, blockchain enables efficient tracing of defective products so that the manufacturer can selectively recall defective products rather than conducting a full recall. This tracing ability reduces the risk involved in the manufacturer purchasing from multiple suppliers and thereby leads the manufacturer to endogenously diversify across suppliers when blockchain is adopted. The diversification enhances the manufacturer's welfare due to her risk aversion and thus drives her to adopt blockchain. With regard to the second channel, blockchain stores details from the manufacturing process and reveals them to consumers, thereby ameliorating consumer information asymmetry. This reduction in information asymmetry improves consumer decision-making which, in isolation, would enhance consumer welfare. However, the manufacturer responds by increasing the consumer price, thereby transferring potential consumer welfare gains to the manufacturer, and consequently serving as a second channel to drive blockchain adoption by the manufacturer.

**Keywords:** Blockchain, Blockchain Adoption, Supply Chain, Market Power

**JEL Classification: G00, O30**

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# 1 Introduction

Blockchain is a technology with significant value for supply chain management (Biais et al. 2023). Nonetheless, that value does not guarantee blockchain adoption due to misaligned economic incentives (see Iyengar et al. 2023). As a consequence, it is of particular importance to understand the economic settings that ensure blockchain adoption in a supply chain. To that end, this paper identifies conditions that ensure blockchain adoption in a supply chain with a manufacturer that has market power. In more detail, we examine whether blockchain adoption arises in equilibrium for a supply chain in which the entity that sells directly to consumers possesses market power. We refer to this entity as the manufacturer and by market power we mean that the manufacturer has the ability to set prices with both consumers and suppliers without any competition. In this context, we establish that blockchain adoption always strictly improves manufacturer welfare, and therefore the manufacturer will adopt blockchain if the implementation cost is low enough. Additionally, we demonstrate that each of the manufacturer's suppliers also adopt blockchain so long as the profit from selling to the manufacturer exceeds each supplier's blockchain implementation cost. Notably, a supplier adopts blockchain even when adoption *reduces* that supplier's welfare because such adoption is preferable to losing the profits from selling to the manufacturer.

An important contribution of our work is that we establish novel economic channels that enhance manufacturer welfare and thereby drive blockchain adoption. In particular, we demonstrate that, when the manufacturer possesses market power, blockchain adoption can arise due to two economic channels: manufacturer risk aversion and consumer information asymmetry. More explicitly, we show that blockchain adoption increases the manufacturer's welfare more so when she is risk-averse as compared to if she were risk-neutral. Additionally, we show that blockchain adoption increases the manufacturer's welfare more so when consumers are not well-informed about the product quality in the absence of blockchain. Crucially, neither of these channels has been studied in the literature. In fact, the prior literature on blockchain for supply chain is silent on the implications of manufacturer risk aversion. Furthermore, although there is prior work that examines the role of blockchain in reducing consumer information asymmetry, it does so in the context of a different manufacturer market structure and finds the exact opposite result, i.e., blockchain adoption does not enhance manufacturer welfare even though it reduces consumer information asymmetry (see Iyengar et al. 2023). Our work thus highlights that both risk aversion and market power have significant economic implications.

Formally, we model a supply chain with three layers: a finite number of homogeneous suppliers, a single manufacturer, and a unit measure of consumers.[1] The manufacturer possesses a type that is unknown to consumers. Each consumer also possesses a type that reflects her preference over the type of the manufacturer. Consumers do not know the manufacturer's type but receive an imperfect signal of the manufacturer's type prior to making purchase decisions.

Our economic analysis consists of three periods. In the first period, the manufacturer and consumers learn their types, and then the manufacturer determines whether or not to adopt blockchain. At the beginning of the second period, the manufacturer sets a consumer price while simultaneously placing orders with suppliers to fill the anticipated consumer demand. Thereafter, still within the second period, each supplier who received an order from the manufacturer reacts by either accepting or rejecting the order where accepting an order from the manufacturer entails implementing blockchain and paying any associated implementation costs if the manufacturer has opted to adopt blockchain. The inability of the supplier to refuse blockchain adoption if she accepts the manufacturer's order reflects the manufacturer's market power in practice (see Section 2). Each supplier who accepts a manufacturer order also simultaneously selects an effort level with effort being costly to the supplier and where the effort level determines the likelihood that her batch of goods will be defective. At the end of the second period, each supplier who accepts a manufacturer's order sends the goods to the manufacturer. The manufacturer then places all goods on store shelves at the end of the second period.

Finally, at the beginning of the third period, consumers observe signals regarding the manufacturer type. Then, throughout the period, consumers arrive sequentially and uniformly to stores and immediately make purchase decisions and consume their purchased goods. In more detail,

[1] Our results generalize when there are finitely many manufacturers so long as each manufacturer sells a good that is sufficiently differentiated from the goods sold by any other manufacturer so that each manufacturer maintains pricing power.

when a consumer arrives at a store, she has knowledge of her signal and also the price of the manufacturer's good, and is matched uniformly at random to a good. She then decides whether to purchase the good (if it has not yet been recalled) or else selects an outside option. Any consumer consuming a defective good has an immediate adverse reaction (e.g., illness from defective food) and reports the defect to the manufacturer. Since consumers are matched to goods uniformly at random, the measure of consumers matched to a good from a given supplier's batch is proportional to the fraction of goods produced by that supplier. In turn, since all goods in a defective batch are defective, some consumers will necessarily be matched to a defective good from a defective batch at the beginning of the third period, if any defective batches exist, and thus the manufacturer always discovers the existence of a defective batch, if any exist, at the beginning of the third period. If the manufacturer has invested in a technology that supports tracing, e.g., a blockchain, then she traces defects to their defective batches and consequently recalls only the defective batches at the beginning of the third period; in that case, the manufacturer provides a refund to any consumers who had consumed the products and also requires suppliers who produced the defective batches to refund their received payments to her. In contrast, if the manufacturer cannot trace those defects, she recalls *all* goods as a precautionary measure since she knows that defective batches exist but cannot identify those defective batches. In this second case, the manufacturer receives a refund from all suppliers. If goods are not recalled at the beginning of the period, then they remain on store shelves throughout the period.

Our model assumptions reflect the reality that defects generally cannot be detected by manufacturer testing; rather defects are typically discovered through consumer reporting. In practice, defects are reported in time for the manufacturer to recall the goods avoiding adverse consequences to almost all consumers. We model this ability of the manufacturer to avert negative consequences to most consumers with the limiting case where she learns of the defect after a zero measure of consumers has consumed.

The blockchain enters our analysis in two ways. First, blockchain enables the manufacturer to trace a defective good to its batch so that blockchain adoption enables the manufacturer to recall only defective batches in contrast to the case in which blockchain is not adopted where a single defective batch from a supplier causes a recall of *all* goods. Second, blockchain adoption improves the accuracy of consumer signals, which reflects the fact that a blockchain can store various relevant details of the manufacturing process; this improvement in the accuracy of consumer signals reduces consumer information asymmetry regarding the manufacturer's type. These two ways in which blockchain enters our analysis relate directly to the previously mentioned economic channels that drive blockchain adoption, and we clarify that relationship subsequently. To reiterate, the two economic channels that our analysis uncovers as being drivers of blockchain adoption are manufacturer risk aversion and consumer information asymmetry.

With regard to the first economic channel, manufacturer risk aversion drives blockchain adoption because the blockchain enables the manufacturer to reduce the risk of a recall, and that risk reduction is valued by the manufacturer precisely when the manufacturer is risk-averse. Without a blockchain, the risk-averse manufacturer sources from a single supplier because sourcing from multiple suppliers increases the expected number of recalls, since she must recall *all* goods if *any* supplier produces a defective batch. In contrast, the blockchain enables the manufacturer to trace defective goods to the supplier who supplied it and conduct targeted recalls. Targeted recalls allow the manufacturer to diversify away individual supplier recall risks in equilibrium by spreading her purchase order across many suppliers. Note that the manufacturer faces the same *expected* number of recalled goods with and without blockchain because suppliers are homogeneous; nonetheless, blockchain adoption leads to a lower variance of the distribution of recalled goods because of the diversification across suppliers, and the manufacturer benefits from this reduced variance due to her risk aversion.

With regard to the second economic channel, consumer information asymmetry drives blockchain adoption because the blockchain reduces that asymmetry, thereby improving consumer welfare. In turn, the manufacturer anticipates this consumers' welfare gain and extracts the associated welfare by raising the consumer price. In more detail, the blockchain enables each consumer to more accurately identify the manufacturer's type; consequently, when a consumer receives a signal that aligns her type with that of the manufacturer, she values the manufacturer's good more so than in the absence of blockchain. The manufacturer rationally reacts to the increased consumer valuation by raising the price charged to the consumer, thereby extracting the increase in consumer surplus, and enhancing her own welfare.

The discussion above focuses on manufacturer welfare because blockchain adoption arises in equilibrium whenever it benefits the manufacturer. More formally, we demonstrate that suppliers adopt blockchain in equilibrium even when such adoption reduces their welfare so long as selling to the manufacturer is profitable when blockchain is adopted. This is because the manufacturer possesses market power. Consequently, if the manufacturer gains from blockchain adoption, she implements blockchain and requires all suppliers supplying to her to also implement blockchain; then, as long as filling the manufacturer's order is profitable for a supplier, she accepts the manufacturer's order and implements blockchain. To reiterate, suppliers implement blockchain even if their profit in the presence of blockchain is lower than their profit in the absence of blockchain so long as filling the manufacturer's order entails a positive pay-off; this is because each supplier prefers a positive profit to a zero pay-off.

Our paper contributes to the literature examining economic questions associated with blockchains. Most of that literature focuses on settings not applicable to operations management. In particular, much of the literature examines Bitcoin (e.g., Biais et al. 2019, Easley et al. 2019, Huberman et al. 2021, Pagnotta 2022, and Hinzen et al. 2022), Bitcoin alternatives (e.g, Saleh 2021, Rosu and Saleh 2021, and John et al. 2022b), decentralized finance platforms (e.g., Cong et al. 2021, Gan et al. 2021, and Mayer 2021), and decentralized finance applications (e.g., Hasbrouck et al. 2022, Capponi et al. 2023, and Rivera et al. 2023). John et al. (2022a) provide an overview of the literature examining Bitcoin and Bitcoin alternatives, whereas John et al. (2023) provide an overview of the literature examining decentralized finance. Our work differs from the referenced literature in that we focus on a business setting, supply chain in particular.

The literature studying the impact of blockchains for operations management is small but growing. Some notable papers include Babich and Hilary (2020), Chod et al. (2020), Cui et al. (2023a), and Ma et al. (2022). Babich and Hilary (2020) provide an overview of strengths and weaknesses of blockchain in a supply chain context. Chod et al. (2020) study how blockchain can impact a firm's lending and demonstrate that blockchain enables a firm to signal quality to lenders more efficiently than otherwise. Cui et al. (2023a) and Ma et al. (2022) both study economic implications from blockchain enhancing supply chain transparency for a manufacturer sourcing from multiple suppliers. Our paper relates most closely to Cui et al. (2023b), Dong et al. (2023) and Iyengar et al. (2023). In particular, Cui et al. (2023b) and Dong et al. (2023) predate our work and also model blockchain as a technology that enables tracing of defective goods. We build upon Cui et al. (2023b) and Dong et al. (2023) by allowing for manufacturer risk aversion and by allowing the set of sourcing suppliers to be endogenous. These two refinements are crucial for studying how blockchain's traceability function interacts with the manufacturer's risk aversion; in particular, we are the first to demonstrate that blockchain's traceability function benefits a manufacturer more so when she is risk-averse as compared to when she is risk-neutral. This increased welfare result arises because traceability allows the manufacturer to diversify across many suppliers, whereas the manufacturer specializes to a single supplier without the blockchain. Notably, the manufacturer benefits from such diversification across suppliers because she is risk-averse and thus allowing for both risk aversion and an endogenous selection of suppliers is crucial for understanding welfare implications of a traceability technology such as blockchain. Our work also builds upon Cui et al. (2023b) and Dong et al. (2023) by modeling another function of blockchain, namely that it reduces consumer information asymmetry. Iyengar et al. (2023) also model blockchain as a technology that reduces consumer information asymmetry; however, Iyengar et al. (2023) neither incorporate manufacturer risk aversion nor model blockchain's traceability function. Moreover, Iyengar et al. (2023) model a market structure with a competitive manufacturing sector, whereas we focus on the setting where manufacturers possess market power. This difference in market structure leads to opposite conclusions regarding blockchain adoption while Iyengar et al. (2023) find that blockchain is *not* adopted in equilibrium in a competitive manufacturing sector even when adoption costs are arbitrarily small, we establish that blockchain adoption arises without additional conditions for all sufficiently small adoption costs when the manufacturer possesses market power. Thus, our work contributes to the existing literature by demonstrating the importance of market structure for blockchain adoption, and also by highlighting the role of manufacturer risk aversion in determining the welfare enhancement from blockchain adoption.

Beyond the blockchain literature, our paper also relates to the literature on supply chains that involves risk-averse agents. Notably, this work is the first to incorporate risk aversion into an analysis of blockchain, and thus, is also the first to clarify how blockchain welfare implications depend upon risk aversion. Papers in the non-blockchain supply chain literature that involve risk-averse agents include Gan et al. (2004), Tomlin (2006), and Chen et al. (2007). Gan et al. (2004) examine the issue of coordination in supply chains involving risk-averse agents and design contracts to achieve Pareto-optimal solutions. Tomlin (2006) studies the management of disruption risk faced by supply chains and demonstrates that a mixed mitigation strategy can be optimal when the buying firm possesses risk-averse preferences. Chen et al. (2007) consider inventory management for a risk-averse decision maker and demonstrate that the optimal inventory policy for a decision maker with an exponential utility function is almost identical to the optimal inventory policy of a risk-neutral decision maker. Related to the supply chain literature with risk-averse agents is the literature on supplier diversification (see, e.g., Chod et al. 2019); we also add to this latter literature by demonstrating how blockchain technology can facilitate supplier diversification in equilibrium.

The rest of this paper is organized as follows. Section 2 provides background context, clarifying how blockchains are used in practice in supply chains for detecting defective items and also for improving consumer information regarding products. Section 3 formally states our economic model and provides the solution. Section 4 provides our main results, demonstrating that blockchain adoption arises whenever the manufacturer gains from such adoption and also demonstrating how manufacturer risk aversion and consumer information asymmetry drive adoption. For exposition, our baseline model abstracts from supplier blockchain implementation costs; nonetheless, Section 5 generalizes our main model by explicitly incorporating a supplier blockchain implementation cost, and Section 5 establishes that our findings hold even in this more general setting. Section 6 examines aggregate welfare effects of blockchain adoption, highlighting that blockchain adoption has ambiguous welfare effects because it can arise even when it reduces the welfare of suppliers so long as it increases welfare for the manufacturer. Section 7 concludes.

## 2 Institutional Background

In this paper, we model a blockchain as an immutable database distributed across a finite number of participants, each of whom is trusted to write to the database (see, e.g., Haber and Stornetta 1991). The participants of the blockchain are the manufacturer and the suppliers, and they write any data relevant to the tracking of goods being produced to the blockchain. Thus, the blockchain we study is an instance of a *permissioned* blockchain, a type of blockchain that is currently being employed in practice for supply chain. Notably, this implementation of blockchain differs significantly from a permissionless blockchain, which is the type of blockchain employed for the settlement of prominent cryptoassets such as bitcoin (see Nakamoto 2008).

As previously discussed, blockchain serves at least two functions within supply chains. First, blockchain enables goods to be traced effectively so that a manufacturer can easily identify a batch of defective items when discovering only a single defective item. Second, blockchain enables consumers to access relevant information regarding each item through a front-end interface that displays information recorded by the manufacturer and the suppliers. In this section, we provide concrete examples of each of these functions in currently existing blockchains.

IBM Food Trust[2] is a prominent example of using a blockchain to trace defective goods within a supply chain. IBM Food Trust requires supply chain participants to upload data regarding food products to the blockchain and provides a module called Trace which leverages the uploaded data. In more detail, the Trace module uses the uploaded data to "provide the provenance of [the] product through immediate access to end-to-end (E2E) data" and also to "show real-time location and status [thereby enabling] expedited product recalls." Walmart uses IBM Food Trust for some of its product lines and, for those product lines, requires all suppliers "to implement end-to-end traceability using blockchain technology" and also to ensure that the suppliers are "capable of sending [the required] data to the IBM Food Trust blockchain."[3] Walmart's requirement for its suppliers to interact with the blockchain aligns with our modeling of the relationship between the manufacturer and her suppliers. In particular, within our model, the manufacturer requires

[2]Source: `https://www.ibm.com/downloads/cas/8QABQBDR`

[3]Source: `https://corporate.walmart.com/media-library/document/leafy-greens-food-safety-traceability-requirements-_proxyDocument?id=00000166-0c8e-dc77-a7ff-4dff95cb0001`

each supplier who accepts an order from her to implement blockchain whenever the manufacturer implements blockchain.

Turning to blockchain's second function in a supply chain, Carrefour[4] has implemented a blockchain to enhance consumer information. Carrefour notes, "consumers always want more transparency and assurance about the products they buy" and that "blockchain can be used to store information about the product... [and thereby] guarantees consumers complete transparency on the circuit followed by the products." In addition to implementing blockchain, Carrefour has also created a front-end interface that provides consumers with information from the blockchain. More specifically, Carrefour has enabled that "consumers can access information about a given product simply by scanning the QR code on its label." The referenced information consumers can access is information stored by the manufacturer and her suppliers on the blockchain, and this information includes "origin and the pathway" (e.g. "producer name, field location, packaging location, transport means"), "quality" (e.g., "harvest date, analysis results, variety and seasonality") and "organic certification" (e.g., "conversion date, official certificate, additional initiatives implemented by the producer").[5]

Importantly, in both these examples, there exists a large manufacturer with market power (Walmart and Carrefour, respectively) who can leverage its market power to compel adoption by suppliers when blockchain adoption is beneficial for the manufacturer – in particular, the large manufacturer forces suppliers to choose between adopting blockchain or forgoing the profit from supplying to the large manufacturer. Our model reflects these realities by allowing the manufacturer to choose whether to adopt blockchain and specifying that suppliers may reject the manufacturer's order and decline to adopt blockchain but that accepting the manufacturer's order necessarily requires implementing blockchain.

[4]Source: `https://www.carrefour.com/en/group/food-transition/food-blockchain`
[5]Source: `https://www.carrefour.com/sites/default/files/2022-04/CARREFOUR_bio_blockchain.pdf`

## 3 Model

We consider a model with three periods indexed by $t \in \{0, 1, 2\}$. Our model consists of finitely many homogeneous suppliers with no production constraints, one manufacturer of an unknown type, and a unit measure of consumers with heterogeneous types. The manufacturer possesses market power in that she sets prices with both suppliers and consumers and also sources goods from a subset of suppliers that she selects.

Our model evolves as follows:

- Period 0: At the beginning of this period, the manufacturer and consumers each learn their types. The manufacturer then decides whether to adopt blockchain at the end of the period.

- Period 1: At the beginning of this period, the manufacturer sets a consumer price and places order(s) with supplier(s) on the basis of anticipated consumer demand. Since each consumer is infinitesimal, demand aggregates to a non-random quantity across consumers; in turn, consumer demand is perfectly anticipated by the manufacturer, i.e. there exists a known deterministic consumer demand curve. At the end of this period, supplier(s) respond to manufacturer orders and provide goods. In more detail, any supplier who received an order from the manufacturer decides whether to accept the order and, if so, selects an effort level to exert in fulfilling the order – the effort level determines the likelihood that the full batch of goods produced will be defective.[6] After producing goods, suppliers send those goods to the manufacturer who places those goods in stores.

- Period 2: At the beginning of period $t = 2$, each consumer receives a signal regarding the manufacturer's type. Thereafter, consumers arrive continuously and uniformly over the period, and each arriving consumer is matched to a good uniformly at random. If the good matched to an incoming consumer has not been recalled, the consumer decides whether to purchase the manufacturer's good or else to select an outside option - note that this decision is made with knowledge of the consumer's signal and the price of the good. In case the matched

[6]We assume that each supplier produces her entire order as a single batch. Within our model, it is not incentive-compatible for the supplier to split her order.

good had been recalled, then the consumer necessarily selects her outside option.

If the consumer purchases the manufacturer's good, she immediately consumes it and reports to the manufacturer if the good is defective. On receiving a defect report, the manufacturer is able to trace the defect to the batch from a particular supplier only if she has invested in a tracing technology, i.e., if she has adopted blockchain; in that case, the manufacturer recalls all the goods from that particular batch. In contrast, if the manufacturer has not adopted blockchain, then she is not able to trace the defect to its batch, and therefore she recalls all products. The manufacturer receives a full refund from any supplier(s) from whom she recalls goods.

Note that a manufacturer always discovers the existence of a defective batch at the beginning of period $t = 2$ if any defects exist. Since consumers are infinitesimal and matched to goods uniformly at random, the proportion of consumers who are matched with a good to a supplier batch equals the proportion of goods produced by the supplier. Therefore, in any arbitrarily small interval at the beginning of $t = 2$, a strictly positive measure of consumers are matched to a defective batch, if any exist; hence, by the end of this arbitrarily small interval, the manufacturer becomes aware of the existence of a defective batch, if any exist. In turn, taking the limit as this interval length goes to zero implies that the manufacturer is made aware of any defective batch at the beginning of $t = 2$ due to defect reports from a zero measure of consumers.

### 3.1 Suppliers

There exist $N \in \mathbb{N}$ homogeneous suppliers indexed by $j \in S := \{1, ..., N\}$, each of which is unconstrained in her production capacity.[7] As discussed earlier, at $t = 0$, the manufacturer decides whether to place an order with each supplier $j$; any such order is characterized by a quantity, $Q_j \geq 0$, and a price per unit, $\Psi_j \geq 0$. Each supplier who receives an order must accept or reject the order and also must select an effort level if she accepts the order. We denote the accept/reject decision of supplier $j$ by $\theta_j \in \{0, 1\}$, and her effort level by $e_j \in [0, 1]$. The expected profit $\mathcal{S}_{\mathcal{NB}}$

[7] Our main result holds for arbitrary $N$, but it is useful to assume that $N$ is large for some of our supporting results. We provide comprehensive details in Appendix A.

(resp. $\mathcal{S}_{\mathcal{B}}$) of supplier $j$ when the blockchain is not adopted (resp. adopted) is given as follows:

$$\begin{aligned} \mathcal{S}_{\mathcal{NB}} &= \theta_j \cdot \left(\pi_{\mathcal{NB}}(e_j, e_{-j}) \cdot \Psi_j \cdot Q_j - \tfrac{e_j}{2} \cdot Q_j\right) \\ \mathcal{S}_{\mathcal{B}} &= \theta_j \cdot \left(\pi_{\mathcal{B}}(e_j, e_{-j}) \cdot \Psi_j \cdot Q_j - \tfrac{e_j}{2} \cdot Q_j\right) \end{aligned} \tag{1}$$

where $\pi_{\mathcal{NB}}(e_j, e_{-j})$ (resp. $\pi_{\mathcal{B}}(e_j, e_{-j})$) denotes the probability that supplier $j$'s batch is not recalled when the blockchain is not adopted (resp. adopted), and $\frac{e_j}{2}$ corresponds to a linear effort cost per unit good produced. Since a supplier must refund sales for all recalled items, supplier $j$ therefore receives the revenue $\Psi_j \cdot Q_j$ only when her batch is not recalled, i.e., with probability $\pi_{\mathcal{NB}}(e_j, e_{-j})$ (resp. $\pi_{\mathcal{B}}(e_j, e_{-j})$) when blockchain is not adopted (resp. adopted). Note that supplier $j$'s effort cost, $\frac{e_j}{2} \cdot Q_j$, is sunk once the batch is produced so that supplier $j$ incurs this cost irrespective of a recall (i.e., with probability one). Note also that $\theta_j = 1$ (resp. $\theta_j = 0$) corresponds to supplier $j$ accepting (resp. rejecting) the manufacturer's order so that $\theta_j = 0$ implies a zero pay-off for supplier $j$. We assume that supplier $j$ accepts the offer only if the expected profit at the optimal effort level $e_j$ is higher than the zero pay-off she receives from rejecting the manufacturer's order.

Blockchain enters our analysis for the suppliers because blockchain adoption affects the relationship between the probability that supplier $j$'s product is recalled, $\pi_{\mathcal{NB}}(e_j, e_{-j})$ and $\pi_{\mathcal{B}}(e_j, e_{-j})$, and the supplier effort levels, $e_j$ and $e_{-j}$. In the absence of the blockchain, the manufacturer must recall *all* defective batches whenever *any* batch is defective, whereas, when blockchain is adopted, the manufacturer recalls a supplier's batch only if that supplier's batch is defective.[8] Let $\rho(e_j) \in [0, 1]$ denote the probability that supplier $j$'s batch is defective, then the probability $\pi_{\mathcal{NB}}(e_j, e_{-j})$ that supplier $j$'s batch is not recalled when blockchain is not adopted is given by:

$$\pi_{\mathcal{NB}}(e_j, e_{-j}) = \prod_{j:j \in \Gamma} (1 - \rho(e_j)), \tag{2}$$

where $\Gamma \subseteq S$ denotes the set of suppliers that receive and accept the manufacturer's order. In contrast, when blockchain is adopted, then the probability $\pi_{\mathcal{B}}(e_j, e_{-j})$ that supplier $j$'s batch is not

[8] Our assumptions are consistent with practice as blockchain has been shown to produce practically relevant reductions in tracing times. See, for example, `https://www.hyperledger.org/learn/publications/walmart-case-study` which demonstrates a reduction of tracing times from 7 days to 2.2 seconds.

recalled is given as follows:

$$\pi_{\mathcal{B}}(e_j, e_{-j}) = 1 - \rho(e_j). \tag{3}$$

Note that $\pi_{\mathcal{NB}}(e_j, e_{-j})$ depends on the effort levels of all suppliers $j \in \Gamma$ that produce orders for the manufacturer and is the same for all $j \in \Gamma$. In contrast, $\pi_{\mathcal{B}}(e_j, e_{-j})$ depends only upon supplier $j$'s effort level $e_j$. We specify $\rho(e_j) = 1 - \sqrt{e_j}$ so that $\rho(e_j)$ is a well-defined probability for all effort levels (i.e., $\rho(e_j) \in [0, 1]$ for all $e_j \in [0, 1]$) and increasing effort level $e_j$ generates lower defect probability (i.e., $\rho'(e_j) < 0$ for all $e_j \in [0, 1]$).

As an aside, in some of the related literature (e.g., Cui et al. 2023b) the supplier's objective function (1) is formulated in a manner that is mathematically equivalent to our formulation, but the framing is different. In particular, within this alternative approach, the non-defect probability, $1 - \rho(e)$, is referred to as quality, $\tilde{q} \in [0, 1]$, and the per unit cost of achieving a quality $\tilde{q}$ is given by an exogenous strictly increasing and convex function $c(\tilde{q})$. Our model specifies that the effort $e \in [0, 1]$ results in a per unit cost of $\frac{e}{2}$ and a quality $\tilde{q} = 1 - \rho(e)$; thus, the per unit cost as a function of the quality $\tilde{q}$ is $\frac{1}{2}\rho^{-1}(1 - \tilde{q})$. Since we assume $\rho(e)$ is strictly decreasing and convex, it follows that the implied cost $\frac{1}{2}\rho^{-1}(1 - \tilde{q})$ in terms of the quality $\tilde{q}$ is strictly increasing and convex. Note that, for our particular choice of $\rho(e) = 1 - \sqrt{e}$, the implied cost function is quadratic (i.e., $\frac{1}{2}\rho^{-1}(1 - \tilde{q}) = \frac{1}{2}\tilde{q}^2$).

## 3.2 Consumers

There exists a unit mass of consumers $k \in [0, 1]$. Each consumer $k$ has a type $t_k \in \{A, B\}$ with $t_k$ being $A$ or $B$ with equal probability. As we discuss in Section 3.3, the manufacturer also possesses a type $q \in \{A, B\}$. A consumer prefers a good from a manufacturer that is of her own type. More formally, the realized utility $V_k$ of a consumer with type $t_k$ from consuming the manufacturer's good is given by:

$$V_k = v_0 + v_\Delta \cdot \Big(\mathcal{I}\big(q = t_k\big) - \mathcal{I}\big(q \neq t_k\big)\Big), \tag{4}$$

where $\mathcal{I}(\cdot) \in \{0, 1\}$ is the indicator function, $v_0 > 0$ corresponds to the utility from an outside option available to all consumers, and $v_\Delta > 0$ corresponds to the incremental positive (resp. negative) value if the manufacturer's good is aligned (resp. misaligned) with the consumer's preferences. The outside option represents a generic good with a utility value $v_0$ that is the same for all consumers, whereas the manufacturer's good has additional features that increase utility for some consumers but decrease utility for other consumers because consumers possess heterogeneous preferences. Explicitly, a generic consumer $k$ accrues utility $v_0 + v_\Delta > v_0$ when consuming a good of her own type (i.e., when $q = t_k$), whereas she accrues utility $v_0 - v_\Delta < v_0$ when consuming a good of the opposite type (i.e., when $q \neq t_k$). We normalize $v_\Delta = 1$ and assume that $v_0 \geq 1$ so that consumer utility from consuming a good of either type is weakly positive. Note that $v_0 = 1$ corresponds to the special case that a consumer receives no utility from a good that does not match her type.

We assume that consumers do not know the manufacturer's type but that each consumer has access to a *signal* which provides information regarding the manufacturer's type. More formally, consumer $k \in [0, 1]$ receives a random signal $\tilde{q}_k \in \{A, B\}$ where the distribution of the signal depends upon whether blockchain is adopted. When blockchain is not adopted, the probability law $\mathbb{P}_{\mathcal{NB}}$ for the signal $\tilde{q}_k$ is given as follows:

$$\mathbb{P}_{\mathcal{NB}}(\tilde{q}_k = \tilde{q} \mid q) = \begin{cases} \alpha & \text{if } \tilde{q} = q \\ 1 - \alpha & \text{if } \tilde{q} \neq q \end{cases} \tag{5}$$

with $\alpha \in [\underline{\alpha}, \overline{\alpha}]$ where $\frac{1}{2} < \underline{\alpha} < \overline{\alpha} < 1$ so that a signal does not fully reveal the manufacturer's type but nonetheless allows each consumer to possess some imperfect information regarding the manufacturer's type.

If the manufacturer adopts the blockchain, the signal observed by any consumer $k \in [0, 1]$ reveals the manufacturer's type with a higher probability. More precisely, when blockchain is adopted, consumer $k$'s signal, $\tilde{q}_k \in \{A, B\}$, is generated according to the following probability law:

$$\mathbb{P}_{\mathcal{B}}(\tilde{q}_k = \tilde{q} \mid q) = \begin{cases} \alpha + \delta \cdot (1 - \alpha) & \text{if } \tilde{q} = q \\ 1 - \alpha - \delta \cdot (1 - \alpha) & \text{if } \tilde{q} \neq q \end{cases} \tag{6}$$

where $\delta \in (0, 1]$ represents the proportion of previously unknown information that the blockchain reveals to consumers. Thus, the probability of a correct signal $\mathbb{P}_{\mathcal{B}}(\tilde{q}_k = q \mid q)$ when blockchain is adopted always exceeds the probability of a correct signal $\mathbb{P}_{\mathcal{NB}}(\tilde{q}_k = q \mid q)$ when blockchain is not adopted, and the difference $\mathbb{P}_{\mathcal{B}}(\tilde{q}_k = q \mid q) - \mathbb{P}_{\mathcal{NB}}(\tilde{q}_k = q \mid q) = \delta \cdot (1 - \alpha)$.

Consumer $k$ observes her own signal and the manufacturer's good price prior to making her purchase decision. As a consequence, consumer $k$'s conditional expected utility $\mathcal{C}_{\mathcal{NB},k}$ (resp. $\mathcal{C}_{\mathcal{B},k}$) from purchasing and consuming the manufacturer's good when blockchain is not adopted (resp. adopted) is given by:

$$\mathcal{C}_{\mathcal{NB},k} = \mathbb{E}_{\mathcal{NB}}[V_k - P \mid \tilde{q}_k, P], \qquad \mathcal{C}_{\mathcal{B},k} = \mathbb{E}_{\mathcal{B}}[V_k - P \mid \tilde{q}_k, P] \tag{7}$$

where $P \geq 0$ denotes the manufacturer's price for consumers and the expectation $\mathbb{E}_{\mathcal{NB}}$ (resp. $\mathbb{E}_{\mathcal{B}}$) is with respect to the probability law defined in Equation (5) (resp. Equation (6)).

Note that the manufacturer type, $A$ or $B$, represents a horizontal differentiation; therefore, in equilibrium, the manufacturer selects the same price $P$ irrespective of her type. Hence, the price $P$ does not provide the consumer with any information regarding the manufacturer type. In our equilibrium solution, we formally establish that the price $P$ does not depend on the manufacturer type, and thus $\mathbb{E}_{\mathcal{NB}}[V_k \mid \tilde{q}_k, P] = \mathbb{E}_{\mathcal{NB}}[V_k \mid \tilde{q}_k]$ and $\mathbb{E}_{\mathcal{B}}[V_k \mid \tilde{q}_k, P] = \mathbb{E}_{\mathcal{B}}[V_k \mid \tilde{q}_k]$.

When a consumer does not receive her good due to a recall, we assume that she is still able to avail herself of her outside option. In turn, consumer $k$ selects the manufacturer's good initially only when her conditional overall expected utility weakly exceeds her outside option $v_0$. Thus, the consumer demand $s_{\mathcal{NB}}$ (resp. $s_{\mathcal{B}}$) for the manufacturer's good when blockchain is not adopted (resp. adopted) is given by:

$$s_{\mathcal{NB}} = \int_0^1 \mathcal{I}(\mathcal{C}_{\mathcal{NB},k} \geq v_0)\ dk, \qquad s_{\mathcal{B}} = \int_0^1 \mathcal{I}(\mathcal{C}_{\mathcal{B},k} \geq v_0)\ dk. \tag{8}$$

Since the signals, $\{\tilde{q}_k\}_{k\in[0,1]}$, are independent, the idiosyncratic consumer demands aggregate across the continuum of consumers and therefore there is no aggregate uncertainty. In particular, the consumer demand $s_{\mathcal{NB}}$ (resp. $s_{\mathcal{B}}$) is non-random and given explicitly as follows:

$$s_{\mathcal{NB}} = \frac{\mathcal{I}\big(P \leq 2\alpha - 1\big)}{2}, \qquad s_{\mathcal{B}} = \frac{\mathcal{I}\big(P \leq 2(\alpha + \delta \cdot (1-\alpha)) - 1\big)}{2}. \tag{9}$$

Note that we do not explicitly incorporate the case that a consumer receives a defective good. This is because we assume that consumers are made whole by manufacturers for any adverse effects from consuming defective goods. Recall that only a zero measure of consumers experience a defective good if there exist any defective batches; consequently, the total expense to manufacturers for making whole consumers is zero, and these expenses do not affect any of our model calculations.

### 3.3 Manufacturer

There is a single risk-averse manufacturer with type $q \in \{A, B\}$, which is unknown to consumers. We assume that the manufacturer's type is equally likely to be $A$ or $B$. To capture risk aversion, we specify the manufacturer's utility $\mathcal{M}(\Pi)$ for a random profit $\Pi$ to be $\mathcal{M}(\Pi) = \mathbb{E}[\Pi] - \frac{\gamma}{2} \cdot Var[\Pi]$, where $\gamma \in (0,1)$ denotes the level of risk aversion for the manufacturer. Thus, the utility $\mathcal{M}_{\mathcal{NB}}$ (resp. $\mathcal{M}_{\mathcal{B}}$) when blockchain is not adopted (resp. adopted) is given by:

$$\mathcal{M}_{\mathcal{NB}} = \mathbb{E}[\Pi_{\mathcal{NB}}] - \frac{\gamma}{2} \cdot Var[\Pi_{\mathcal{NB}}], \qquad \mathcal{M}_{\mathcal{B}} = \mathbb{E}[\Pi_{\mathcal{B}}] - \frac{\gamma}{2} \cdot Var[\Pi_{\mathcal{B}}] \tag{10}$$

where $\Pi_{\mathcal{NB}}$ (resp. $\Pi_{\mathcal{B}}$) denotes the random manufacturer profit when blockchain is not adopted (resp. adopted). To our knowledge, we are the first to incorporate risk aversion into an analysis of blockchain in the context of supply chain. Note that our model also allows for a risk-neutral manufacturer since as $\gamma \to 0^+$, the manufacturer's utility depends only upon expected profits.

At $t = 1$, the manufacturer selects a consumer price, $P \geq 0$, and a subset of supplier(s), $\Xi \subseteq S$, with which to place order(s). A supplier order entails selecting a price and quantity for each order, $\{(\Psi_j, Q_j)\}_{j \in \Xi}$. In turn, the set of suppliers that receive and accept orders from the manufacturer, $\Gamma \subseteq \Xi \subseteq S$, is determined as $\Gamma = \{j \in \Xi : \theta_j = 1\}$. Following prior literature, we assume that the manufacturer anticipates consumer demand and splits that demand evenly across suppliers when she selects multiple suppliers. Therefore, the manufacturer's random profit $\Pi_{\mathcal{NB}}$ (resp. $\Pi_{\mathcal{B}}$), when blockchain is not adopted (resp. adopted), is given by:

$$\Pi_{\mathcal{NB}} = \sum_{j:j\in\Gamma} (P - \Psi_j) \cdot \frac{s_{\mathcal{NB}}}{|\Xi|} \cdot \xi_{\mathcal{NB},j}, \qquad \Pi_{\mathcal{B}} = \sum_{j:j\in\Gamma} (P - \Psi_j) \cdot \frac{s_{\mathcal{B}}}{|\Xi|} \cdot \xi_{\mathcal{B},j} \tag{11}$$

where $\xi_{\mathcal{NB},j}$ (resp. $\xi_{\mathcal{B},j}$) is an indicator random variable that takes the value 1 if and only if supplier $j$'s batch is not recalled when the blockchain is not adopted (resp. adopted). Note that, as per Section 3.1, $\xi_{\mathcal{NB},j} = 1$ with probability $\pi_{\mathcal{NB}}(e_j, e_{-j})$ given by Equation (2), and $\xi_{\mathcal{B},j} = 1$ with probability $\pi_{\mathcal{B}}(e_j, e_{-j})$ given by Equation (3). As a technical aside, the expressions in Equation (11) are valid only when $|\Xi| > 0$; in the case that $|\Xi| = 0$, the production and profit are both trivially zero, and we omit writing this case explicitly for exposition.

We assume that blockchain adoption entails an implementation cost $\chi > 0$ for the manufacturer at $t = 0$. In turn, the manufacturer adopts blockchain if and only if her incremental utility from blockchain adoption exceeds her implementation cost:

$$\Omega := \mathcal{M}_{\mathcal{B}} - \mathcal{M}_{\mathcal{NB}} \geq \chi. \tag{12}$$

### 3.4 Model Solution

We solve for a Subgame Perfect Nash Equilibrium (SPNE). Since suppliers are homogeneous, we focus upon symmetric equilibria such that each supplier acts symmetrically and the manufacturer offers the same price to each supplier.

**Proposition 3.1.** ***Equilibrium Solution***

*The symmetric equilibrium for the model is defined as follows:*

1. *$t = 2$: Consumer Demand*

   *The equilibrium consumer demand $s^\star_{\mathcal{NB}}$ (resp. $s^\star_{\mathcal{B}}$) when the blockchain is not adopted (resp. adopted) is given as follows:*

$$s^\star_{\mathcal{NB}} = \frac{1}{2} \cdot \mathcal{I}\Big(P \leq 2\alpha - 1\Big), \qquad s^\star_{\mathcal{B}} = \frac{1}{2} \cdot \mathcal{I}\Big(P \leq 2(\alpha + \delta \cdot (1 - \alpha)) - 1\Big),$$

*where $P$ denotes the price charged to consumers. Note that $P$ is determined in equilibrium by the manufacturer and the associated equilibrium solutions are given in 3 of this proposition.*

2. *End of $t = 1$: Supplier Effort Decision*

*The symmetric supplier effort $e^{\star}_{\mathcal{NB}}$ (resp. $e^{\star}_{\mathcal{B}}$) where blockchain is not adopted (resp. adopted) is given as follows:*

$$e^{\star}_{\mathcal{NB}} = \begin{cases} \min\{\Psi^2, 1\} & \text{if } |\Xi| = 1 \\ 0 & \text{if } |\Xi| > 1 \end{cases}, \qquad e^{\star}_{B} = \min\{\Psi^2, 1\},$$

*where $\Psi$ denotes the price offered by the manufacturer, and $|\Xi|$ is the number of suppliers who receive offers. Note that $\Psi$ and $|\Xi|$ are determined in equilibrium by the manufacturer and the associated equilibrium solutions are given in 3 below. Additionally, the symmetric accept/ reject decision of each supplier who receives an order $\theta^{\star}_{\mathcal{NB}}$ (resp. $\theta^{\star}_{\mathcal{B}}$) when blockchain is not adopted (resp. adopted) is given as follows:*

$$\theta^{\star}_{\mathcal{NB}} = \begin{cases} 1 & \text{if } |\Xi| = 1 \text{ and } \Psi > 0 \\ 0 & \text{otherwise} \end{cases}, \qquad \theta^{\star}_{B} = \begin{cases} 1 & \text{if } \Psi > 0 \\ 0 & \text{if } \Psi = 0 \end{cases}.$$

3. *Beginning of $t = 1$: Manufacturer Decisions*

*The number of suppliers $|\Xi^{\star}_{\mathcal{NB}}|$ (resp. $|\Xi^{\star}_{\mathcal{B}}|$) chosen in equilibrium when blockchain is not adopted (resp. adopted) is given as follows:*

$$|\Xi^{\star}_{\mathcal{NB}}| = 1, \qquad |\Xi^{\star}_{\mathcal{B}}| = N.$$

*The price $P^{\star}_{\mathcal{NB}}$ (resp. $P^{\star}_{\mathcal{B}}$) charged to the consumers in equilibrium when the blockchain is not adopted (resp. adopted) is given as follows:*

$$P^{\star}_{\mathcal{NB}} = 2\alpha - 1, \qquad P^{\star}_{\mathcal{B}} = 2(\alpha + \delta \cdot (1 - \alpha)) - 1.$$

*The price* $\Psi^\star_{\mathcal{NB}}$ *(resp.* $\Psi^\star_{\mathcal{B}}$*) offered to suppliers in equilibrium when the blockchain is not adopted (resp. adopted) is the unique solution to the following equation:*

$$\Lambda(\Psi^\star_{\mathcal{NB}}, 2\alpha - 1, 1) = 0, \qquad \Lambda(\Psi^\star_{\mathcal{B}}, 2(\alpha + \delta \cdot (1-\alpha)) - 1, N) = 0,$$

*where* $\Lambda$ *is defined explicitly as follows:*

$$\Lambda(\Psi, P, N) = \frac{1}{2} \cdot (P - 2\Psi) - \frac{\gamma}{8N} \cdot (P - \Psi) \cdot \big(4\Psi^2 - (2P+3)\Psi + P\big).$$

4. *$t = 0$: Blockchain Adoption Decision*

   *Blockchain is adopted in equilibrium if and only if the manufacturer's incremental welfare* $\Omega^\star$ *in equilibrium from adopting blockchain satisfies*

$$\Omega^\star \geq \chi.$$

   *Here* $\Omega^\star$ *is determined from Equations* (10) - (12) *by replacing the quantities of interest by the equilibrium values given in 2 - 3 above. In particular, the manufacturer anticipates all future actions and adopts blockchain only if doing so is beneficial when all agents act optimally (i.e., in equilibrium).*

# 4 Main Results

We begin by establishing that the manufacturer's incremental welfare $\Omega^\star$ from blockchain adoption is strictly positive. Then, since the manufacturer's incremental welfare $\Omega^\star$ does not depend on the implementation cost (see Proposition 3.1), the blockchain is adopted whenever $0 < \chi \leq \Omega^\star$. More explicitly, we have the following result:

**Proposition 4.1.** ***Blockchain Adoption in Equilibrium***

*The manufacturer's incremental welfare* $\Omega^\star$ *from blockchain adoption is strictly positive (i.e.,* $\Omega^\star > 0$*). Moreover, blockchain adoption arises in equilibrium for the manufacturer and all suppliers if the* *manufacturer blockchain implementation cost* $\chi$ *is sufficiently small (i.e., whenever* $0 < \chi \leq \Omega^\star$*).*

The finding in Proposition 4.1, that $\Omega^\star > 0$, does not apply to arbitrary market settings. In particular, Iyengar et al. (2023) demonstrate that when the manufacturing sector is competitive, the gains from blockchain adoption are competed away to consumers through price competition, and hence $\Omega^\star = 0$. In contrast, we examine a setting in which the manufacturer possesses market power and therefore prices as a monopolist; consequently, the gains from blockchain are not competed away. In fact, as we discuss subsequently, due to the manufacturer's market power, the manufacturer is able to extract welfare gains from consumers by raising prices on consumers and thus contributing to our result of $\Omega^\star > 0$.

To better understand Proposition 4.1, we decompose $\Omega^\star$ as follows:

$$\begin{aligned}\Omega^\star &= \Big(\mathbb{E}[\Pi^\star_{\mathcal{B}}] - \frac{\gamma}{2} Var[\Pi^\star_{\mathcal{B}}]\Big) - \Big(\mathbb{E}[\Pi^\star_{\mathcal{NB}}] - \frac{\gamma}{2} Var[\Pi^\star_{\mathcal{NB}}]\Big) \\ &= \underbrace{\mathbb{E}[\Pi^\star_{\mathcal{B}}] - \mathbb{E}[\Pi^\star_{\mathcal{NB}}]}_{\Phi^\star} + \underbrace{\frac{\gamma}{2} \cdot \Big(Var[\Pi^\star_{\mathcal{NB}}] - Var[\Pi^\star_{\mathcal{B}}]\Big)}_{\Sigma^\star}, \end{aligned} \tag{13}$$

where $\Sigma^\star$ denotes the manufacturer's incremental welfare due to endogenous changes in the variance, or risk, of the profit, and $\Phi^\star$ denotes the manufacturer's incremental welfare due to endogenous changes in the manufacturer's expected profit. Note that $\Sigma^\star$ does not enter into manufacturer welfare if the manufacturer is risk-neutral (i.e., if $\gamma = 0$, then $\Sigma^\star = 0$); thus, our model enables us to discuss novel welfare implications relating to risk aversion in contrast to existing supply chain blockchain literature that typically assumes risk-neutral preferences (e.g., Iyengar et al. 2023).

We proceed by demonstrating that blockchain adoption increases manufacturer welfare both due to a reduction in profit variance, i.e., $\Sigma^\star > 0$, and due to an increase in expected profit, i.e., $\Psi^\star > 0$. Moreover, we clarify the associated economic channels. More explicitly, in Section 4.1 we establish that $\Sigma^\star > 0$ and show how this effect arises due to manufacturer risk aversion (i.e., $\gamma > 0$), whereas in Section 4.2 we demonstrate that $\Phi^\star > 0$ and show that this effect arises both due to manufacturer risk aversion (i.e., $\gamma > 0$) and a reduction in information asymmetry (i.e., $\delta > 0$).

### 4.1 Manufacturer Profit Risk Reduction $\Sigma^\star$

We demonstrate that blockchain adoption results in the manufacturer endogenously diversifying across all suppliers, thereby driving down the variance of the manufacturer's profit. Then, since the manufacturer is risk-averse (i.e., $\gamma > 0$), the reduced risk increases the manufacturer's utility, making blockchain adoption incentive-compatible for sufficiently small adoption costs as per Proposition 4.1. We formalize this insight with the following result:

**Proposition 4.2.** ***Manufacturer Diversification Benefits***

*The following results hold:*

1. *Blockchain Endogenously Generates Supplier Diversification*

   *For all* $\gamma$*,* $\delta \in (0,1)$*:* $N = |\Xi^\star_{\mathcal{B}}| = |\Gamma^\star_{\mathcal{B}}| > |\Gamma^\star_{\mathcal{NB}}| = |\Xi^\star_{\mathcal{NB}}| = 1.$

2. *Diversification Benefits are Always Strictly Positive*

   *For all* $\gamma, \delta \in (0,1)$*:* $\Sigma^\star > 0.$

3. *Diversification Benefits Depend on Risk Aversion*

   *For all* $\delta \in (0,1)$*:* $\lim_{\gamma \to 0^+} \Sigma^\star = 0.$

Proposition 4.2.1 establishes that in the presence of blockchain, the manufacturer switches from purchasing from a *single* supplier (i.e., $|\Gamma^\star_{\mathcal{NB}}| = |\Xi^\star_{\mathcal{NB}}| = 1$) to purchasing from *all* available suppliers (i.e., $|\Gamma^\star_{\mathcal{B}}| = |\Xi^\star_{\mathcal{B}}| = N$). This effect arises endogenously because the blockchain enables the manufacturer to trace a defective item to the responsible supplier, thereby allowing a targeted recall of only defective items. Without blockchain, the manufacturer cannot trace defective items and must recall all items from all suppliers, whenever a single defect is detected. The manufacturer internalizes the increase in recall probability when she sources from multiple suppliers in the absence of blockchain, and therefore, endogenously specializes to sourcing from a single supplier. In contrast, when the blockchain is adopted, only defective items are recalled even when the manufacturer purchases from multiple suppliers. Since purchasing from many suppliers no longer increases the recall probability, and, in fact, reduces the manufacturer's profit variance; it is optimal for the manufacturer to diversify recall risks by splitting her order over all available suppliers. Thus, the manufacturer always gains from the discussed risk reduction (i.e., $\Sigma^\star > 0$). Moreover, the manufacturer's gain arises specifically due to risk aversion and it consequently vanishes without risk aversion (i.e., $\lim_{\gamma \to 0^+} \Sigma = 0$).

## 4.2 Manufacturer Expected Profit Gains $\Phi^\star$

Blockchain adoption not only reduces the manufacturer's risk but also increases the manufacturer's expected profit. We demonstrate that the increase in the manufacturer's expected profit arises endogenously both due to her risk aversion (i.e., $\gamma > 0$) and because the blockchain ameliorates consumer information asymmetry (i.e., $\delta > 0$). Our next result formalizes those insights:

**Proposition 4.3.** ***Expected Profit Gains***

*The following results hold:*

1. *Blockchain Endogenously Enhances Expected Profit*

   *For all* $\gamma, \delta \in (0,1)$*:* $\Phi^\star > 0$.

2. *At Least One of Risk Aversion and Information Asymmetry Reduction is Necessary*

   $\lim_{\gamma,\delta \to 0^+} \Phi^\star = 0$.

3. *Risk Aversion is Sufficient*

   *For all* $\gamma > 0$*:* $\lim_{\delta \to 0^+} \Phi^\star > 0$.

4. *Information Asymmetry Reduction is Sufficient*

   *For all* $\delta > 0$*:* $\lim_{\gamma \to 0^+} \Phi^\star > 0$.

The increase in the manufacturer's expected profit under blockchain adoption (i.e., $\Phi^\star > 0$) arises due to two factors: the manufacturer's risk aversion (i.e., $\gamma > 0$) and the blockchain's information asymmetry reduction (i.e., $\delta > 0$). More explicitly, Proposition 4.3 establishes that at least one of the two factors must be present for blockchain adoption to increase the manufacturer's expected profit, and each factor is separately sufficient for blockchain adoption to increase the manufacturer's expected profit.

Our next result clarifies the underlying economic channels that interact with the manufacturer's risk aversion and the blockchain's information asymmetry reduction to generate the aforementioned increase in the manufacturer's expected profit:

**Proposition 4.4.** ***Determinants of Increased Expected Profit***

*The following results hold:*

1. *Consumer Price Increases with Blockchain Adoption due to Information Asymmetry Reduction*

   *For all* $\gamma, \delta \in (0,1)$*:* $P_{\mathcal{B}}^{\star} > P_{\mathcal{NB}}^{\star}$ *but for all* $\gamma \in (0,1) : \lim_{\delta \to 0^+} \frac{P_{\mathcal{B}}^{\star}}{P_{\mathcal{NB}}^{\star}} = 1.$

2. *Supplier Pass-Through Decreases with Blockchain Adoption due to Risk Aversion*

   *For all* $\gamma, \delta \in (0,1)$*:* $\frac{\Psi_{\mathcal{B}}^{\star}}{P_{\mathcal{B}}^{\star}} < \frac{\Psi_{\mathcal{NB}}^{\star}}{P_{\mathcal{NB}}^{\star}}$ *but for all* $\delta \in (0,1) : \lim_{\gamma \to 0^+} \frac{\Psi_{\mathcal{B}}^{\star}/P_{\mathcal{B}}^{\star}}{\Psi_{\mathcal{NB}}^{\star}/P_{\mathcal{NB}}^{\star}} = 1.$

Proposition 4.4 clarifies that the increase in the manufacturer's expected profit arises both because of an increase in her marginal revenue and because of a decrease in the extent to which her marginal revenue is passed through to suppliers. More explicitly, blockchain adoption implies an increase in the consumer price (i.e., $P_{\mathcal{B}}^{\star} > P_{\mathcal{NB}}^{\star}$), which increases the manufacturer's marginal revenue and thereby her expected profit. Furthermore, blockchain adoption decreases the fraction of the manufacturer's marginal revenue that is passed through to suppliers (i.e., $\frac{\Psi_{\mathcal{B}}^{\star}}{P_{\mathcal{B}}^{\star}} < \frac{\Psi_{\mathcal{NB}}^{\star}}{P_{\mathcal{B}}^{\star}}$), which reduces the manufacturer's marginal cost per unit revenue and thereby increases the manufacturer's expected profit. Proposition 4.4 also establishes that the increase in the consumer price arises due to the reduction in information asymmetry from the blockchain (i.e., $P_{\mathcal{B}}^{\star} > P_{\mathcal{NB}}^{\star}$ when $\delta > 0$ but $\frac{P_{\mathcal{B}}^{\star}}{P_{\mathcal{NB}}^{\star}} \to 1$ as $\delta \to 0^+$), whereas the decrease in the supplier pass-through arises due to the manufacturer's risk aversion (i.e., $\frac{\Psi_{\mathcal{B}}^{\star}}{P_{\mathcal{B}}^{\star}} < \frac{\Psi_{\mathcal{NB}}^{\star}}{P_{\mathcal{NB}}^{\star}}$ when $\gamma > 0$ but $\frac{\Psi_{\mathcal{B}}^{\star}/P_{\mathcal{B}}^{\star}}{\Psi_{\mathcal{NB}}^{\star}/P_{\mathcal{NB}}^{\star}} \to 1$ as $\gamma \to 0^+$).

## 5 Supplier Blockchain Implementation Costs

In this section, we generalize Proposition 4.1 to the setting where suppliers incur a strictly positive blockchain implementation cost $\kappa > 0$ when the manufacturer adopts blockchain. Explicitly, we generalize the expected profit function $\mathcal{S}_{\mathcal{B},\kappa}$ for supplier $j$ when blockchain is adopted as follows:

$$\mathcal{S}_{\mathcal{B},\kappa} = \mathcal{S}_{\mathcal{B}} - \theta_j \cdot \kappa, \tag{14}$$

where $\mathcal{S}_{\mathcal{B}}$ is given in Equation (1). With this generalization of our baseline model, we re-establish our main finding:

**Proposition 5.1.** ***Blockchain Adoption with Supplier Adoption Costs***
*Blockchain adoption arises in equilibrium for the manufacturer and all suppliers whenever the manufacturer blockchain implementation cost is sufficiently small (i.e., whenever $0 < \chi \leq \Omega^\star$) and supplier pay-offs are weakly positive after paying the supplier blockchain implementation cost (i.e., whenever $\kappa \leq \mathcal{S}_{\mathcal{B}}^\star$ where $\mathcal{S}_{\mathcal{B}}^\star$ is equilibrium supplier pay-off from the baseline model solved in Proposition 3.1).*

The result in Proposition 5.1 follows from the fact that the manufacturer has market power. In particular, a supplier can only accept or reject the manufacturer's offered price but cannot set a price with the manufacturer. Consequently, since rejecting the manufacturer's order entails a zero pay-off, it is optimal for the supplier to fill the manufacturer's order so long as the implementation cost $\kappa$ is sufficiently small to ensure a positive pay-off for the supplier. Notably, as we discuss in Section 6, suppliers accept the manufacturer's orders and implement blockchain even when supplier profits are higher in the absence of blockchain; this is because accepting the manufacturer's order and implementing blockchain is preferable to rejecting the manufacturer's order and receiving a zero pay-off whenever accepting the manufacturer's order entails a positive pay-off.

As an aside, our analysis examines a static model where the supplier receives only one order from the manufacturer and therefore accepts the manufacturer order only if that one order is profitable despite the blockchain implementation cost. In a more general model with multiple periods, the supplier would implement the blockchain so long as the present value of *all* future orders from the manufacturer exceeds the supplier's blockchain implementation cost. Given that the present value of all future orders is likely to be large, a fixed supplier blockchain implementation cost $\kappa$ is unlikely to impact whether blockchain adoption arises in a model allowing for multiple periods. This is consistent with the real-world examples discussed in Section 2 where large manufacturers are able to generate blockchain adoption among their suppliers.

# 6 Aggregate Welfare

We conclude by examining the aggregate welfare implications of blockchain adoption. Our main finding regarding aggregate welfare is that, due to the manufacturer's market power, blockchain adoption can arise in equilibrium even if blockchain adoption reduces aggregate welfare. In particular, since the manufacturer possesses market power, blockchain adoption arises because blockchain enhances the manufacturer's welfare, yet aggregate welfare need not increase when manufacturer welfare increases. To formalize this point, we offer the following result:

**Proposition 6.1.** ***Blockchain Adoption can Arise, Yet Aggregate Welfare Decreases*** *Assume that the blockchain reduces information asymmetry (i.e., $\delta > 0$). Then, there exists a risk aversion coefficient $\overline{\gamma} > 0$ such that for all manufacturer risk aversion $\gamma < \overline{\gamma}$, there exists a manufacturer blockchain implementation cost $\chi > 0$ and a supplier blockchain implementation cost $\kappa > 0$ that ensure blockchain adoption arises in equilibrium (as given by Proposition 3.1), and yet aggregate welfare is lower than that in the case without blockchain.*

Proposition 6.1 arises because blockchain adoption depends upon whether blockchain increases the manufacturer's welfare irrespective of its effect on aggregate welfare. More specifically, if the manufacturer's blockchain implementation cost $\chi$ is sufficiently small that the manufacturer gains from blockchain adoption (i.e., $\chi < \Omega^{\star}$), yet sufficiently large that the manufacturer's incremental welfare gain is small (i.e., $\chi = \Omega^{\star} - \varepsilon$), then blockchain adoption would arise in equilibrium as per Propositions 4.1 and 5.1. Additionally, if the supplier adoption cost $\kappa$ is sufficiently large that it decreases supplier welfare by more than the manufacturer's welfare gain yet sufficiently small that the supplier profits remain positive, then each supplier accepts the manufacturer's order despite the reduction in welfare. Moreover, in such a case, aggregate welfare decreases from blockchain adoption due to the decrease in supplier welfare; however, blockchain adoption arises in equilibrium despite the decrease in aggregate welfare.

While Proposition 6.1 clarifies that blockchain adoption can arise despite a decrease in aggregate welfare, this result is not generic. Rather, blockchain adoption can arise in equilibrium even in cases when aggregate welfare increases. Our subsequent result formalizes that point:

**Proposition 6.2.** ***Blockchain Adoption can Arise when Aggregate Welfare Increases*** *Assume that the blockchain reduces information asymmetry (i.e.,* $\delta > 0$*). Then, there exists a risk aversion coefficient* $\overline{\gamma} > 0$ *such that for all manufacturer risk aversion* $\gamma < \overline{\gamma}$*, there exists a manufacturer blockchain implementation cost* $\chi > 0$ *and a supplier blockchain implementation cost* $\kappa > 0$ *that ensure blockchain adoption arises in equilibrium (as given by Proposition 3.1), and aggregate welfare is higher than that in the case without blockchain.*

Proposition 6.2 arises because when both manufacturer and supplier blockchain implementation costs are sufficiently small, then blockchain adoption enhances aggregate welfare. More specifically, when the manufacturer blockchain implementation cost is sufficiently small, then manufacturer welfare increases from blockchain adoption. Moreover, if supplier implementation costs are sufficiently small, then any welfare losses from suppliers are necessarily sufficiently small that aggregate welfare increases with blockchain adoption.

We omit explicit discussion regarding consumer welfare when explaining our aforementioned aggregate welfare results because consumer welfare is *unaffected* by blockchain adoption. In more detail, since the manufacturer possesses market power, she sets the consumer price as a monopolist and is able to extract all consumers' welfare gains from blockchain adoption. We formalize this in our final result:

**Proposition 6.3.** ***Consumer Welfare is Invariant to Blockchain Adoption*** *The total consumer welfare, integrated over all consumers, without blockchain adoption equals the total consumer welfare, integrated over all consumers, with blockchain adoption.*

Proposition 6.3 draws a stark contrast between the competitive manufacturing sector setting studied by Iyengar et al. (2023) and our setting where the manufacturer has market power. More specifically, Iyengar et al. (2023) find that welfare gains accrue to consumers because manufacturers compete away those gains through lower prices; in contrast, we find that all gains accrue to the manufacturer because the manufacturer has pricing power and thus can raise the price to extract consumer gains.

# 7 Conclusion

Our analysis establishes that blockchain adoption generically arises in equilibrium when the manufacturer has market power. In particular, when the manufacturer has the power to adjust prices and thereby extract gains accrued to other supply chain participants, then blockchain adoption is incentive-compatible for sufficiently small adoption costs. Our main result contrasts with that of Iyengar et al. (2023), which establishes that blockchain adoption does not arise in equilibrium when the manufacturing sector is competitive. Thus, our work highlights market structure as a crucial determinant of whether blockchain adoption arises.

Our results also clarify the role of two different economic channels in blockchain adoption. We find that both manufacturer risk aversion and consumer information asymmetry drive blockchain adoption. The blockchain enables the manufacturer to diversify across suppliers, and thereby reduce risk. However, this risk reduction increases the manufacturer's welfare only if she is risk-averse. The blockchain reduces consumer information asymmetry and thereby increases consumer welfare. The manufacturer responds optimally to the increased consumer welfare by increasing the consumer price, and extracting all the welfare gains. Thus, the reduction in consumer information asymmetry serves as a second incentive for the manufacturer to adopt blockchain and compel such adoption for her suppliers as well.

# References


Babich V, Hilary G (2020) OM forum—distributed ledgers and operations: What operations management researchers should know about blockchain technology. *Manufacturing & Service Operations Management* 22(2):223–240, URL `http://dx.doi.org/10.1287/msom.2018.0752`.

Biais B, Bisiere C, Bouvard M, Casamatta C (2019) The blockchain folk theorem. *Review of Financial Studies* 32(5):1662–1715.

Biais B, Capponi A, Cong LW, Gaur V, Giesecke K (2023) Advances in blockchain and crypto economics. *Management Science* Forthcoming.

Capponi A, Iyengar G, Sethuraman J, et al. (2023) Decentralized finance: Protocols, risks, and governance. *Foundations and Trends® in Privacy and Security* 5(3):144–188.

Chen X, Sim M, Simchi-Levi D, Sun P (2007) Risk aversion in inventory management. *Operations Research* 55(5):828–842, ISSN 0030364X, 15265463, URL `http://www.jstor.org/stable/25147125`.

Chod J, Trichakis N, Tsoukalas G (2019) Supplier diversification under buyer risk. *Management Science* 65(7):3150–3173.

Chod J, Trichakis N, Tsoukalas G, Aspegren H, Weber M (2020) On the financing benefits of supply chain transparency and blockchain adoption. *Management Science* 66(10):4359–4919.

Cong LW, Li Y, Wang N (2021) Tokenomics: Dynamic adoption and valuation. *Review of Financial Studies* 34(3):1105–1155.

Cui Y, Gaur V, Liu J (2023a) Supply chain transparency and blockchain design. *Management Science* Forthcoming.

Cui Y, Hu M, Liu J (2023b) Value and design of traceability-driven blockchains. *Manufacturing & Service Operations Management* 25(3):1099–1116.

Dong L, Jiang P, Xu F (2023) Impact of traceability technology adoption in food supply chain networks. *Management Science* 69(3):1518–1535.

Easley D, O'Hara M, Basu S (2019) From mining to markets: The evolution of bitcoin transaction fees. *Journal of Financial Economics* 134(1):91–109, URL `http://dx.doi.org/10.1016/j.jfineco.2019.03`.

Gan J, Tsoukalas G, Netessine S (2021) Inventory, speculators, and initial coin offerings. *Management Science* 67:914 – 931.

Gan X, Sethi SP, Yan H (2004) Coordination of supply chains with risk-averse agents. *Production and Operations Management* 13(2):135–149, URL `http://dx.doi.org/https://doi.org/10.1111/j.1937-5956.2004.tb00150.x`.

Haber S, Stornetta WS (1991) How to time-stamp a digital document. *Journal of Cryptology* 3(2):99–111.

Hasbrouck J, Rivera T, Saleh F (2022) The need for fees at a dex: How increases in fees can increase dex trading volume. *Working Paper* .

Hinzen FJ, John K, Saleh F (2022) Bitcoin's limited adoption problem. *Journal of Financial Economics* 144(2):347–369, ISSN 0304-405X, URL `http://dx.doi.org/https://doi.org/10.1016/j.jfineco.2022.01.003`.

Huberman G, Leshno JD, Moallemi C (2021) Monopoly without a monopolist: An economic analysis of the bitcoin payment system. *The Review of Economic Studies* ISSN 0034-6527, URL http://dx.doi.org/10.1093/restud/rdab014.

Iyengar G, Saleh F, Sethuraman J, Wang W (2023) Economics of permissioned blockchain adoption. *Management Science* 69(6):3415–3436.

John K, Kogan L, Saleh F (2023) Smart contracts and decentalized finance. *Annual Review of Financial Economics* 15.

John K, O'Hara M, Saleh F (2022a) Bitcoin and beyond. *Annual Review of Financial Economics* 14:95–115.

John K, Rivera T, Saleh F (2022b) Equilibrium staking levels in a proof-of-stake blockchain. *Working Paper* .

Ma H, Xia Y, Yang B (2022) Blockchains, smart contracts, and supply chain efficiency. *Working Paper* .

Mayer S (2021) Token-based platforms and speculators. *Working Paper* .

Nakamoto S (2008) Bitcoin: A peer-to-peer electronic cash system. *https://bitcoin.org/bitcoin.pdf* .

Pagnotta ES (2022) Decentralizing money: Bitcoin prices and blockchain security. *The Review of Financial Studies* 35(2):866–907.

Rivera TJ, Saleh F, Vandeweyer Q (2023) Equilibrium in a defi lending market. *Available at SSRN 4389890* .

Rosu I, Saleh F (2021) Evolution of shares in a proof-of-stake cryptocurrency. *Management Science* 67:661–672.

Saleh F (2021) Blockchain without waste: Proof-of-stake. *Review of Financial Studies* 34:1156–1190.

Tomlin B (2006) On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science* 52(5):639–657, URL http://dx.doi.org/10.1287/mnsc.1060.0515.

# Appendices

## A Model Assumptions

While our main results hold for arbitrary $N$, the specific results Propositions 4.2.2, 4.3.1 and 4.4.2 are derived under the condition that the number of suppliers $N$ is sufficiently large. More formally, we impose the following assumption on $N$:

**Assumption 1.** *We assume that the number of suppliers $N$ satisfies $N > \frac{16}{(2\underline{\alpha}-1)^4}$.*

We impose Assumption 1 to highlight how blockchain's traceability affects the manufacturer's profit variance when blockchain is adopted. In more detail, although blockchain's traceability function always reduces the manufacturer's profit variance when blockchain is adopted, blockchain's ability to reduce consumer information asymmetry has a countervailing effect, increasing the manufacturer's profit variance when blockchain is adopted; Assumption 1 implies that the traceability effect dominates. Note that Assumption 1 is a sufficient condition and not a necessary condition; in particular, Propositions 4.2.2, 4.3.1 and 4.4.2 all hold without any restriction on $N$ when the consumer information asymmetry channel is absent, i.e., $\delta = 0$.

## B Proofs

*Proof of Proposition 3.1.*

**Equilibrium Solution when Blockchain is not Adopted**

1. $t = 2$: Consumer Demand

By Bayes' theorem, $\mathbb{P}_{\mathcal{NB}}(q = \tilde{q}_k \mid \tilde{q}_k) = \alpha$. It follows that

$$\begin{aligned}
\mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] &= \mathbb{E}_{\mathcal{NB}}[v_0 + v_\Delta \cdot \big(\mathcal{I}(q = t_k) - \mathcal{I}(q \neq t_k)\big) \mid t_k, \tilde{q}_k] \\
&= v_0 + v_\Delta \cdot \Big(2 \cdot \mathbb{P}_{\mathcal{NB}}(q = t_k \mid t_k, \tilde{q}_k) - 1\Big) \\
&= \begin{cases} v_0 + (2\alpha - 1) & \text{if } \tilde{q}_k = t_k \\ v_0 - (2\alpha - 1) & \text{if } \tilde{q}_k \neq t_k \end{cases}.
\end{aligned}$$

For a given consumer price $P$, consumer $k$'s expected utility from purchasing the manufacturer's good is $\mathcal{C}_{\mathcal{NB},k} = \mathbb{E}_{\mathcal{NB}}[V_k - P \mid t_k, \tilde{q}_k, P] = \mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] - P$. Consumer $k$ purchases from the manufacturer if and only if $\mathcal{C}_{\mathcal{NB},k} \geq v_0$, which is equivalent to $\mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] \geq v_0 + P$. Note that when $\tilde{q}_k \neq t_k$, $\mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] = v_0 - (2\alpha - 1) < v_0 + P$ as $2\alpha - 1 > 0$ and $P \geq 0$. Thus, consumer $k$ purchases from the manufacturer if and only if $\tilde{q}_k = t_k$ and $\mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] = v_0 + (2\alpha - 1) \geq v_0 + P$.

By the model setting, half of the consumers are of type $A$ and half of the consumers are of type $B$, and the manufacturer knows her type $q$. Thus, the consumer demand

$$\begin{aligned}
s^*_{\mathcal{NB}}(P) &= \int_0^1 \mathcal{I}(\mathcal{C}_{\mathcal{NB},k} \geq v_0)\ dk \\
&= \underbrace{\frac{1}{2} \cdot \mathbb{P}_{\mathcal{NB}}(\tilde{q}_k = A \mid q) \cdot \mathcal{I}\big(v_0 + (2\alpha - 1) \geq v_0 + P\big)}_{\text{Type } A \text{ Consumers' Demand}} \\
&\quad + \underbrace{\frac{1}{2} \cdot \mathbb{P}_{\mathcal{NB}}(\tilde{q}_k = B \mid q) \cdot \mathcal{I}\big(v_0 + (2\alpha - 1) \geq v_0 + P\big)}_{\text{Type } B \text{ Consumers' Demand}} \\
&= \frac{1}{2} \cdot \mathcal{I}\big(P \leq 2\alpha - 1\big).
\end{aligned}$$

2. <u>End of $t = 1$: Supplier Effort Decision</u>

   The manufacturer anticipates consumer demand $s = s^*_{\mathcal{NB}}(P)$ and splits her order evenly across suppliers when she selects multiple suppliers. Once the manufacturer determines the subset $\Xi$ of supplier(s) with which to place the order(s), the quantity of the order supplier $j$ receives is given by $Q_j = s/|\Xi|$. This holds for all $j \in \Xi$. Since all the suppliers are homogeneous and the quantities $Q_j, j \in \Xi$ are the same, we will focus on and look for symmetric equilibria where all supplier prices are the same, i.e., $\Psi_j = \Psi$ for all $j \in \Xi$.

The suppliers first solve a coordination game. Given $\Psi$, $s = s^*_{\mathcal{NB}}(P)$ and $\Xi \neq \varnothing$, the effort choice for each supplier in $\Xi$, $e^*_{\mathcal{NB}}$, is a solution to the following fixed-point problem:

$$\begin{aligned} e^*_{\mathcal{NB}} &= \arg\max_{e_j \in [0,1]} \pi_{\mathcal{NB}}(e_j, e^*_{\mathcal{NB}}) \cdot \Psi \cdot \frac{s}{|\Xi|} - \frac{e_j}{2} \cdot \frac{s}{|\Xi|} \\ &= \arg\max_{e_j \in [0,1]} \left(1 - \rho(e^*_{\mathcal{NB}})\right)^{|\Xi|-1} \cdot \left(1 - \rho(e_j)\right) \cdot \Psi - \frac{e_j}{2} \\ &= \arg\max_{e_j \in [0,1]} (e^*_{\mathcal{NB}})^{\frac{|\Xi|-1}{2}} \cdot e_j^{\frac{1}{2}} \cdot \Psi - \frac{e_j}{2}. \end{aligned}$$

Then, the suppliers' decisions to accept or reject the order are determined by

$$\begin{aligned} \theta^*_{\mathcal{NB}} &= \mathcal{I}\left(\pi_{\mathcal{NB}}(e^*_{\mathcal{NB}}, e^*_{\mathcal{NB}}) \cdot \Psi \cdot \frac{s}{|\Xi|} - \frac{e^*_{\mathcal{NB}}}{2} \cdot \frac{s}{|\Xi|} > 0\right) \\ &= \mathcal{I}\left((e^*_{\mathcal{NB}})^{\frac{|\Xi|}{2}} \cdot \Psi - \frac{e^*_{\mathcal{NB}}}{2} > 0\right). \end{aligned}$$

Note that the objective is a quadratic function in terms of $e_j^{\frac{1}{2}}$ (i.e., $(e^*_{\mathcal{NB}})^{\frac{|\Xi|-1}{2}} \cdot \Psi \cdot x - \frac{x^2}{2}$) and its unconstrained maximum is attained at $e_j^{\frac{1}{2}} = (e^*_{\mathcal{NB}})^{\frac{|\Xi|-1}{2}} \cdot \Psi$. Therefore, the effort choice $e^*_{\mathcal{NB}} = \min\{(e^*_{\mathcal{NB}})^{|\Xi|-1} \cdot \Psi^2, 1\}$.

When $|\Xi| = 1$, $e^*_{\mathcal{NB}} = \min\{\Psi^2, 1\}$. When $|\Xi| = 2$, $e^*_{\mathcal{NB}} = \min\{e^*_{\mathcal{NB}} \cdot \Psi^2, 1\}$; if $\Psi < 1$, the only solution is $e^*_{\mathcal{NB}} = 0$, and if $\Psi \geq 1$, two solutions are $e^*_{\mathcal{NB}} = 1$ and $e^*_{\mathcal{NB}} = 0$. When $|\Xi| > 2$, $e^*_{\mathcal{NB}} = \min\{(e^*_{\mathcal{NB}})^{|\Xi|-1} \cdot \Psi^2, 1\}$; if $\Psi < 1$, the only solution is $e^*_{\mathcal{NB}} = 0$, and if $\Psi \geq 1$, two solutions are $e^*_{\mathcal{NB}} = \Psi^{-\frac{2}{|\Xi|-2}}$ and $e^*_{\mathcal{NB}} = 0$ coming from solving the equation

$e^*_{\mathcal{NB}} = (e^*_{\mathcal{NB}})^{|\Xi|-1} \cdot \Psi^2$ and the other solution is $e^*_{\mathcal{NB}} = 1$. To conclude, we have that

$$e^*_{\mathcal{NB}}(\Psi, \Xi) = \begin{cases} \Psi^2 & \text{if } \Psi < 1 \text{ and } |\Xi| = 1 \\ 0 & \text{if } \Psi < 1 \text{ and } |\Xi| > 1 \\ 1 & \text{if } \Psi \geq 1 \text{ and } |\Xi| = 1 \\ 1 \text{ or } 0 & \text{if } \Psi \geq 1 \text{ and } |\Xi| = 2 \\ 1 \text{ or } \Psi^{-\frac{2}{|\Xi|-2}} \text{ or } 0 & \text{if } \Psi \geq 1 \text{ and } |\Xi| > 2 \end{cases} \cdot$$

In the following part, we will see that the manufacturer never chooses a consumer price $P$ such that no consumers purchase the manufacturer's good. Thus, $P$ is bounded by $v_\Delta = 1$ and $\Psi < P \leq 1$. The expression of $e^*_{\mathcal{NB}}(\Psi, \Xi)$ can be further simplified as

$$e^*_{\mathcal{NB}}(\Psi, \Xi) = \begin{cases} \min\{\Psi^2, 1\} & \text{if } |\Xi| = 1 \\ 0 & \text{if } |\Xi| > 1 \end{cases}.$$

The above result concerning $e^*_{\mathcal{NB}}$ indicates that

$$\theta^*_{\mathcal{NB}}(\Psi, \Xi) = \begin{cases} 1 & \text{if } |\Xi| = 1 \text{ and } \Psi > 0 \\ 0 & \text{otherwise} \end{cases}$$

for all $j \in \Xi$ and

$$\Gamma^*_{\mathcal{NB}}(\Psi, \Xi) = \{j \in \Xi : \theta^*_j = 1\} = \begin{cases} \Xi & \text{if } |\Xi| = 1 \text{ and } \Psi > 0 \\ \varnothing & \text{otherwise} \end{cases}.$$

3. Beginning of $t = 1$: Manufacturer Decisions

The manufacturer anticipates all consumers' and suppliers' future actions and sets her price for consumers, $P^*_{\mathcal{NB}}$, a subset of supplier(s), $\Xi^*_{\mathcal{NB}} \subseteq S$, and her price for supplier(s), $\Psi^*_{\mathcal{NB}}$, such that:

$$
\begin{aligned}
(P^*_{\mathcal{NB}}, \Psi^*_{\mathcal{NB}}, \Xi^*_{\mathcal{NB}}) &= \underset{P\geq 0, \Psi\geq 0, \Xi\subseteq S}{\arg\max}\ \mathcal{M}_{\mathcal{NB}} \\
&= \underset{P\geq 0, \Psi\geq 0, \Xi\subseteq S}{\arg\max}\ \mathbb{E}[\Pi_{\mathcal{NB}}] - \frac{\gamma}{2} Var[\Pi_{\mathcal{NB}}],
\end{aligned}
$$

where

$$
\Pi_{\mathcal{NB}} = \sum_{j: j\in\Gamma^*_{\mathcal{NB}}(\Psi,\Xi)} (P-\Psi)\cdot\frac{s^*_{\mathcal{NB}}(P)}{|\Xi|}\cdot\xi_{\mathcal{NB},j}
$$

and $\xi_{\mathcal{NB},j} \sim \text{Bernoulli}(\pi_{\mathcal{NB}}(e^*_{\mathcal{NB}}(\Psi,\Xi), e^*_{\mathcal{NB}}(\Psi,\Xi))) = \text{Bernoulli}((e^*_{\mathcal{NB}}(\Psi,\Xi))^{\frac{|\Gamma^*_{\mathcal{NB}}(\Psi,\Xi)|}{2}})$.

When $|\Xi| = 0$, simply $\mathcal{M}_{\mathcal{NB}} = 0$. When $|\Xi| > 1$ or $\Psi = 0$, $\Gamma^*_{\mathcal{NB}}(\Psi,\Xi) = \varnothing$ by the result of part 2 and thus $\Pi_{\mathcal{NB}} = 0, \mathcal{M}_{\mathcal{NB}} = 0$. When $|\Xi| = 1$ and $\Psi > 0$, $\Gamma^*_{\mathcal{NB}}(\Psi,\Xi) = \Xi$ and $e^*_{\mathcal{NB}}(\Psi,\Xi) = \min\{\Psi^2, 1\}$ by the result of part 2. Consequently, $\xi_{\mathcal{NB},j} \sim \text{Bernoulli}(\min\{\Psi, 1\})$ and $\Pi_{\mathcal{NB}} = (P-\Psi)\cdot s^*_{\mathcal{NB}}(P)\cdot\xi_{\mathcal{NB},j}$ where $j$ is the only element in $\Xi$. It follows that

$$
\begin{aligned}
\mathcal{M}_{\mathcal{NB}} &= \mathbb{E}[\Pi_{\mathcal{NB}}] - \frac{\gamma}{2} Var[\Pi_{\mathcal{NB}}] \\
&= \frac{1}{2}\cdot\mathcal{I}\big(P\leq 2\alpha-1\big)\cdot(P-\Psi)\cdot\min\{\Psi,1\} \\
&\quad - \frac{\gamma}{2}\cdot\Big(\frac{1}{2}\cdot\mathcal{I}\big(P\leq 2\alpha-1\big)\cdot(P-\Psi)\Big)^2\cdot\min\{\Psi,1\}\cdot(1-\min\{\Psi,1\}).
\end{aligned}
$$

If $P > 2\alpha - 1$ or $\Psi \geq P$, then $\mathcal{M}_{\mathcal{NB}}$ is at most zero. Under the condition that $\Psi < P \leq 2\alpha - 1 < 1$, the expression of $\mathcal{M}_{\mathcal{NB}}$ can be further simplified as

$$
\mathcal{M}_{\mathcal{NB}} = \frac{1}{2}(P-\Psi)\Psi - \frac{\gamma}{8}(P-\Psi)^2\Psi(1-\Psi).
$$

Hence, under the constraint that $|\Xi| = 1$ and $0 < \Psi < P \leq 2\alpha - 1$, the manufacturer is solving the following optimization problem:

$$
\begin{aligned}
(P^*, \Psi^*) &= \operatorname*{arg\,max}_{0 \le P \le 2\alpha - 1, 0 < \Psi < P} \frac{1}{2}(P - \Psi)\Psi - \frac{\gamma}{8}(P - \Psi)^2 \Psi(1 - \Psi) \\
&=: \operatorname*{arg\,max}_{0 \le P \le 2\alpha - 1, 0 < \Psi < P} f(P, \Psi; \gamma). \qquad (15)
\end{aligned}
$$

Note that

$$
\begin{aligned}
\frac{\partial f(P, \Psi; \gamma)}{\partial P} &= \frac{\Psi}{2} \cdot \Big(1 - \frac{\gamma}{2}(1 - \Psi)(P - \Psi)\Big) \\
&\ge \frac{\Psi}{2} \cdot \Big(1 - \frac{\gamma}{2}\Big) \\
&> 0
\end{aligned}
$$

over the given domain as $0 < \gamma < 1$. This implies that $P^* = 2\alpha - 1$ and $\Psi^* = \operatorname*{arg\,max}_{0 < \Psi < P^*} f(P^*, \Psi; \gamma)$. We can further obtain that

$$
\begin{aligned}
\frac{\partial^2 f(P, \Psi; \gamma)}{\partial \Psi^2}\bigg|_{P = P^*} &= -1 + \frac{\gamma}{4} \cdot \big(6\Psi^2 - (6P^* + 3)\Psi + (P^* + 2)P^*\big) \\
&\le -1 + \frac{\gamma}{4} \cdot \max\big\{(P^* + 2)P^*, 6(P^*)^2 - (6P^* + 3)P^* + (P^* + 2)P^*\big\} \\
&= -1 + \frac{\gamma}{4} \cdot \max\big\{(P^*)^2 + 2P^*, (P^*)^2 - P^*\big\} \\
&\overset{(a)}{\le} -1 + \frac{3\gamma}{4} \\
&< 0
\end{aligned}
$$

for all $\Psi \in [0, P^*]$, where $(a)$ follows from $P^* = 2\alpha - 1 < 1$ and $0 < \gamma < 1$. It immediately follows that $f(P^*, \Psi; \gamma)$ as a function of $\Psi$ is strictly concave and thus has the unique maximum over $[0, P^*]$. Since $f(P^*, \Psi; \gamma)$ is strictly concave over $[0, P^*]$ and $f(P^*, 0; \gamma) = f(P^*, P^*; \gamma) = 0$, the maximum must be achieved at $\Psi^*$ in the interior of $[0, P^*]$ and $f(P^*, \Psi^*; \gamma) > 0$. Recall that in all aforementioned cases we discussed ($|\Xi| = 0$, $|\Xi| > 1$ or $\Psi = 0$, or $|\Xi| = 1$ but $P > 2\alpha - 1$ or $\Psi \ge P$), $\mathcal{M}_{\mathcal{NB}} \le 0$. Therefore, the manufacturer will go for $|\Xi^*| = 1, 0 < \Psi^* < P^* = 2\alpha - 1$ such that $\mathcal{M}^*_{\mathcal{NB}} = f(P^*, \Psi^*; \gamma) > 0$.

In conclusion, the manufacturer chooses $|\Xi^*_{\mathcal{NB}}| = 1, \Psi^*_{\mathcal{NB}} \in (0, P^*_{\mathcal{NB}})$, and $P^*_{\mathcal{NB}} = 2\alpha - 1$ to maximize her utility, where $\Psi^*_{\mathcal{NB}}$ is determined by the unique solution to the equation $\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\Big|_{P=P^*_{\mathcal{NB}}} = 0$, i.e.,

$$\frac{1}{2} \cdot (P^*_{\mathcal{NB}} - 2\Psi) - \frac{\gamma}{8} \cdot (P^*_{\mathcal{NB}} - \Psi) \cdot \big(4\Psi^2 - (2P^*_{\mathcal{NB}} + 3)\Psi + P^*_{\mathcal{NB}}\big) = 0.$$

**Equilibrium Solution when Blockchain is Adopted**

1. $t = 2$: Consumer Demand

   The argument to get $s^*_{\mathcal{B}}(P)$ is very similar to what we used in part 1 of the proof for the case in which blockchain is not adopted; the only difference is that we need to replace $\alpha$ with $\alpha + \delta \cdot (1 - \alpha)$ and the subscript $\mathcal{NB}$ with $\mathcal{B}$ in the proof. Consequently, we obtain that

$$s^*_{\mathcal{B}}(P) = \frac{1}{2} \cdot \mathcal{I}\big(P \le 2(\alpha + \delta \cdot (1 - \alpha)) - 1\big).$$

2. End of $t = 1$: Supplier Effort Decision

   Similar to the proof for the case in which blockchain is not adopted, we will focus on and look for symmetric equilibria where all supplier prices are the same, i.e., $\Psi_j = \Psi$ for all $j \in \Xi$.

   The suppliers first solve a coordination game. Given $\Psi$, $s = s^*_{\mathcal{B}}(P)$ and $\Xi \neq \varnothing$, the effort choice for each supplier in $\Xi$, $e^*_{\mathcal{B}}$, is a solution to the following fixed-point problem:

$$\begin{aligned} e^*_{\mathcal{B}} &= \arg\max_{e_j \in [0,1]} \pi_{\mathcal{B}}(e_j, e^*_{\mathcal{B}}) \cdot \Psi \cdot \frac{s}{|\Xi|} - \frac{e_j}{2} \cdot \frac{s}{|\Xi|} \\ &= \arg\max_{e_j \in [0,1]} \big(1 - \rho(e_j)\big) \cdot \Psi - \frac{e_j}{2} \\ &= \arg\max_{e_j \in [0,1]} e_j^{\frac{1}{2}} \cdot \Psi - \frac{e_j}{2}. \end{aligned}$$

Then, the suppliers' decisions to accept or reject the order are determined by

$$\theta^*_{\mathcal{B}} = \mathcal{I}\left(\pi_{\mathcal{B}}(e^*_{\mathcal{B}}, e^*_{\mathcal{B}}) \cdot \Psi \cdot \frac{s}{|\Xi|} - \frac{e^*_{\mathcal{B}}}{2} \cdot \frac{s}{|\Xi|} > 0\right)$$
$$= \mathcal{I}\left((e^*_{\mathcal{B}})^{\frac{1}{2}} \cdot \Psi - \frac{e^*_{\mathcal{B}}}{2} > 0\right).$$

Note that the objective is a quadratic function in terms of $e_j^{\frac{1}{2}}$ (i.e., $\Psi x - \frac{x^2}{2}$). The constrained maximum is attained at $e_j^{\frac{1}{2}} = \min\{\Psi, 1\}$, so the effort choice

$$e^*_{\mathcal{B}}(\Psi, \Xi) = \min\{\Psi^2, 1\}.$$

This implies that

$$\theta^*_{\mathcal{B}}(\Psi, \Xi) = \begin{cases} 1 & \text{if } \Psi > 0 \\ 0 & \text{otherwise} \end{cases}$$

for all $j \in \Xi$ and

$$\Gamma^*_{\mathcal{B}}(\Psi, \Xi) = \{j \in \Xi : \theta^*_j = 1\} = \begin{cases} \Xi & \text{if } \Psi > 0 \\ \varnothing & \text{otherwise.} \end{cases}$$

3. Beginning of $t = 1$: Manufacturer Decisions

   The manufacturer anticipates all consumers' and suppliers' future actions and sets her price for consumers, $P^*_{\mathcal{B}}$, a subset of supplier(s), $\Xi^*_{\mathcal{B}} \subseteq S$, and her price for supplier(s), $\Psi^*_{\mathcal{B}}$, such that:

$$(P^*_{\mathcal{B}}, \Psi^*_{\mathcal{B}}, \Xi^*_{\mathcal{B}}) = \underset{P \geq 0, \Psi \geq 0, \Xi \subseteq S}{\arg\max} \; \mathcal{M}_{\mathcal{B}}$$
$$= \underset{P \geq 0, \Psi \geq 0, \Xi \subseteq S}{\arg\max} \; \mathbb{E}[\Pi_{\mathcal{B}}] - \frac{\gamma}{2} Var[\Pi_{\mathcal{B}}],$$

   where

$$\Pi_{\mathcal{B}} = \sum_{j: j \in \Gamma^*_{\mathcal{B}}(\Psi, \Xi)} (P - \Psi) \cdot \frac{s^*_{\mathcal{B}}(P)}{|\Xi|} \cdot \xi_{\mathcal{B},j}$$

and $\xi_{\mathcal{B},j} \sim \text{Bernoulli}(\pi_{\mathcal{B}}\big(e^*_{\mathcal{B}}(\Psi,\Xi), e^*_{\mathcal{B}}(\Psi,\Xi)\big)) = \text{Bernoulli}(\big(e^*_{\mathcal{B}}(\Psi,\Xi)\big)^{\frac{1}{2}}) = \text{Bernoulli}(\min\{\Psi,1\})$ by the result of part 2.

When $|\Xi| = 0$, simply $\mathcal{M}_{\mathcal{B}} = 0$. When $\Psi = 0$, $\Gamma^*_{\mathcal{B}}(\Psi,\Xi) = \varnothing$ by the result of part 2 and thus $\Pi_{\mathcal{B}} = 0, \mathcal{M}_{\mathcal{B}} = 0$. When $|\Xi| > 0$ and $\Psi > 0$, $\Gamma^*_{\mathcal{B}}(\Psi,\Xi) = \Xi$ and thus

$$\begin{aligned}
\mathcal{M}_{\mathcal{B}} &= \mathbb{E}[\Pi_{\mathcal{B}}] - \frac{\gamma}{2} Var[\Pi_{\mathcal{B}}] \\
&= \frac{1}{2} \cdot \mathcal{I}\big(P \le 2(\alpha + \delta \cdot (1-\alpha)) - 1\big) \cdot (P - \Psi) \cdot \min\{\Psi, 1\} \\
&\quad - \frac{\gamma}{2} \cdot \Big(\frac{1}{2} \cdot \mathcal{I}\big(P \le 2(\alpha + \delta \cdot (1-\alpha)) - 1\big) \cdot (P - \Psi)\Big)^2 \cdot \frac{1}{|\Xi|} \cdot \min\{\Psi, 1\} \cdot (1 - \min\{\Psi, 1\}).
\end{aligned}$$

If $P > 2(\alpha + \delta \cdot (1-\alpha)) - 1$ or $\Psi \ge P$, then $\mathcal{M}_{\mathcal{B}}$ is at most zero. Under the condition that $\Psi < P \le 2(\alpha + \delta \cdot (1-\alpha)) - 1 \le 1$, the expression of $\mathcal{M}_{\mathcal{B}}$ can be further simplified as

$$\mathcal{M}_{\mathcal{B}} = \frac{1}{2}(P - \Psi)\Psi - \frac{\gamma}{8|\Xi|}(P - \Psi)^2 \Psi (1 - \Psi).$$

Hence, under the constraint that $|\Xi| > 0$ and $0 < \Psi < P \le 2(\alpha + \delta \cdot (1-\alpha)) - 1$, the manufacturer is solving the following optimization problem:

$$(P^*, \Psi^*, \Xi^*) = \underset{0 \le P \le 2(\alpha+\delta\cdot(1-\alpha))-1, 0<\Psi<P, |\Xi|>0}{\arg\max} \frac{1}{2}(P - \Psi)\Psi - \frac{\gamma}{8|\Xi|}(P - \Psi)^2 \Psi (1 - \Psi).$$

It is easy to see that the objective is increasing in $|\Xi|$ as the variance term is decreasing in $|\Xi|$. The manufacturer will pick $\Xi^*$ to be the set of all suppliers to minimize the variance term, i.e., $\Xi^* = S$. Her optimization problem is accordingly reduced to

$$\begin{aligned}
(P^*, \Psi^*) &= \underset{0 \le P \le 2(\alpha+\delta\cdot(1-\alpha))-1, 0<\Psi<P}{\arg\max} \frac{1}{2}(P - \Psi)\Psi - \frac{\gamma}{8|\Xi^*|}(P - \Psi)^2 \Psi (1 - \Psi) \\
&= \underset{0 \le P \le 2(\alpha+\delta\cdot(1-\alpha))-1, 0<\Psi<P}{\arg\max} f(P, \Psi; \frac{\gamma}{N}),
\end{aligned}$$

where $f$ was defined in (15).

Note that

$$\frac{\partial f(P,\Psi;\frac{\gamma}{N})}{\partial P} = \frac{\Psi}{2}\cdot\Big(1-\frac{\gamma}{2N}(1-\Psi)(P-\Psi)\Big)$$
$$\geq \frac{\Psi}{2}\cdot\Big(1-\frac{\gamma}{2N}\Big)$$
$$> 0$$

over the given domain as $0<\gamma<1$. This implies that $P^* = 2(\alpha+\delta\cdot(1-\alpha))-1$ and $\Psi^* = \underset{0<\Psi<P^*}{\arg\max}\, f(P^*,\Psi;\frac{\gamma}{N})$. By the same technique we used in part 3 of the proof for the case in which blockchain is not adopted, we can show that

$$\left.\frac{\partial^2 f(P,\Psi;\frac{\gamma}{N})}{\partial \Psi^2}\right|_{P=P^*} < 0$$

for all $\Psi \in [0,P^*]$, so $f(P^*,\Psi;\frac{\gamma}{N})$ as a function of $\Psi$ is strictly concave over $[0,P^*]$. Since $f(P^*,0;\frac{\gamma}{N}) = f(P^*,P^*;\frac{\gamma}{N}) = 0$, the unique maximum of $f(P^*,\Psi;\frac{\gamma}{N})$ must be achieved at $\Psi^*$ in the interior of $[0,P^*]$ and $f(P^*,\Psi^*;\frac{\gamma}{N})>0$. Recall that in all aforementioned cases we discussed ($|\Xi|=0$, $\Psi=0$, or $|\Xi|>0$ but $P>2(\alpha+\delta\cdot(1-\alpha))-1$ or $\Psi\geq P$), $\mathcal{M}_{\mathcal{B}}\leq 0$. Therefore, the manufacturer will go for $|\Xi^*|=N, 0<\Psi^*<P^*=2(\alpha+\delta\cdot(1-\alpha))-1$ such that $\mathcal{M}^*_{\mathcal{B}} = f(P^*,\Psi^*;\frac{\gamma}{|\Xi^*|})>0$.

In conclusion, the manufacturer chooses $\Xi^*_{\mathcal{B}} = S$, $\Psi^*_{\mathcal{B}}\in(0,P^*_{\mathcal{B}})$, and $P^*_{\mathcal{B}} = 2(\alpha+\delta\cdot(1-\alpha))-1$ to maximize her utility, where $\Psi^*_{\mathcal{B}}$ is determined by the unique solution to the equation $\left.\frac{\partial f(P,\Psi;\frac{\gamma}{|\Xi^*_{\mathcal{B}}|})}{\partial\Psi}\right|_{P=P^*_{\mathcal{B}}} = 0$, i.e.,

$$\frac{1}{2}\cdot(P^*_{\mathcal{B}}-2\Psi)-\frac{\gamma}{8N}\cdot(P^*_{\mathcal{B}}-\Psi)\cdot\big(4\Psi^2-(2P^*_{\mathcal{B}}+3)\Psi+P^*_{\mathcal{B}}\big)=0.$$

**$t=0$: Blockchain Adoption Decision**

Blockchain is adopted in equilibrium if and only if the manufacturer's incremental welfare in equilibrium

$$\begin{aligned}\Omega^* &= \mathcal{M}_{\mathcal{B}}^* - \mathcal{M}_{\mathcal{NB}}^* \\ &= f(P_{\mathcal{B}}^*, \Psi_{\mathcal{B}}^*; \frac{\gamma}{|\Xi_{\mathcal{B}}^*|}) - f(P_{\mathcal{NB}}^*, \Psi_{\mathcal{NB}}^*; \gamma)\end{aligned}$$

exceeds her implementation cost $\chi$, i.e., $\Omega^* \geq \chi$. □

*Proof of Proposition 4.1.* By the proof of Proposition 3.1, $\Omega^*$ is independent of $\chi$ and we have that

$$\begin{aligned}f(P_{\mathcal{NB}}^*, \Psi_{\mathcal{NB}}^*; \gamma) &\overset{(a)}{<} f(P_{\mathcal{B}}^*, \Psi_{\mathcal{NB}}^*; \gamma) \\ &\overset{(b)}{\leq} f(P_{\mathcal{B}}^*, \Psi_{\mathcal{NB}}^*; \frac{\gamma}{N}) \\ &\overset{(c)}{\leq} f(P_{\mathcal{B}}^*, \Psi_{\mathcal{B}}^*; \frac{\gamma}{N}) \\ &= f(P_{\mathcal{B}}^*, \Psi_{\mathcal{B}}^*; \frac{\gamma}{|\Xi_{\mathcal{B}}^*|}),\end{aligned}$$

where $(a)$ follows from $\Psi_{\mathcal{NB}}^* > 0$, $f(P, \Psi_{\mathcal{NB}}^*; \gamma)$ is strictly increasing in $P$, and $P_{\mathcal{NB}}^* = 2\alpha - 1 < 2(\alpha + \delta \cdot (1-\alpha)) - 1 = P_{\mathcal{B}}^*$, $(b)$ follows from $f(P, \Psi; \gamma)$ is decreasing in terms of the parameter $\gamma$ over $[0, +\infty)$, and $(c)$ follows from the definition of $\Psi_{\mathcal{B}}^*$. Hence,

$$\Omega^* = f(P_{\mathcal{B}}^*, \Psi_{\mathcal{B}}^*; \frac{\gamma}{|\Xi_{\mathcal{B}}^*|}) - f(P_{\mathcal{NB}}^*, \Psi_{\mathcal{NB}}^*; \gamma) > 0.$$

When the blockchain adoption cost $\chi > 0$ is sufficiently small such that $\chi \leq \Omega^*$, blockchain adoption arises in equilibrium for the manufacturer and all suppliers according to Proposition 3.1. □

Before going to the remaining proofs, we show a lemma that will be frequently invoked:

**Lemma B.1.** *Supplier pass-throughs without and with blockchain adoption, $\Psi_{\mathcal{NB}}^*/P_{\mathcal{NB}}^*$ and $\Psi_{\mathcal{B}}^*/P_{\mathcal{B}}^*$, satisfy*

$$\frac{1}{2} < \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}, \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} < \frac{3}{4}.$$

*Equivalently, $\frac{1}{2}P_{\mathcal{NB}}^* < \Psi_{\mathcal{NB}}^* < \frac{3}{4}P_{\mathcal{NB}}^*$ and $\frac{1}{2}P_{\mathcal{B}}^* < \Psi_{\mathcal{B}}^* < \frac{3}{4}P_{\mathcal{B}}^*$.*

*Proof.* By the proof of Proposition 3.1, $f(P^*_{\mathcal{NB}}, \Psi; \gamma)$ is strictly concave in $\Psi$ over $[0, P^*_{\mathcal{NB}}]$, and $\Psi^*_{\mathcal{NB}} \in (0, P^*_{\mathcal{NB}})$ is determined by the unique solution to the equation $\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\Big|_{P=P^*_{\mathcal{NB}}} = 0$, i.e.,

$$\frac{1}{2} \cdot (P^*_{\mathcal{NB}} - 2\Psi) - \frac{\gamma}{8} \cdot (P^*_{\mathcal{NB}} - \Psi) \cdot \big(4\Psi^2 - (2P^*_{\mathcal{NB}} + 3)\Psi + P^*_{\mathcal{NB}}\big) = 0.$$

Thus, $\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\Big|_{P=P^*_{\mathcal{NB}}} > 0$ for all $\Psi \in [0, \Psi^*_{\mathcal{NB}})$ and $\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\Big|_{P=P^*_{\mathcal{NB}}} < 0$ for all $\Psi \in (\Psi^*_{\mathcal{NB}}, P^*_{\mathcal{NB}}]$. Notice that

$$\begin{aligned} \frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\bigg|_{P=P^*_{\mathcal{NB}}, \Psi=\frac{3}{4}P^*_{\mathcal{NB}}} &= -\frac{1}{4}P^*_{\mathcal{NB}} + \frac{\gamma}{128}(P^*_{\mathcal{NB}})^2(5 - 3P^*_{\mathcal{NB}}) \\ &= \frac{P^*_{\mathcal{NB}}}{4} \cdot \Big( -1 + \frac{\gamma}{32} \cdot P^*_{\mathcal{NB}} \cdot (5 - 3P^*_{\mathcal{NB}}) \Big) \\ &\le \frac{P^*_{\mathcal{NB}}}{4} \cdot \Big( -1 + \frac{5\gamma}{32} \Big) \\ &< 0, \end{aligned}$$

where the last two inequalities follow from $P^*_{\mathcal{NB}} = 2\alpha - 1 \in (0,1)$ and $0 < \gamma < 1$, so it must be the case that $\Psi^*_{\mathcal{NB}} < \frac{3}{4}P^*_{\mathcal{NB}}$. In addition, we have that

$$\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\bigg|_{P=P^*_{\mathcal{NB}}, \Psi=\frac{1}{2}P^*_{\mathcal{NB}}} = \frac{\gamma}{32}(P^*_{\mathcal{NB}})^2 > 0,$$

so it must be the case that $\Psi^*_{\mathcal{NB}} > \frac{1}{2}P^*_{\mathcal{NB}}$. Two inequalities combined lead to $\frac{1}{2}P^*_{\mathcal{NB}} < \Psi^*_{\mathcal{NB}} < \frac{3}{4}P^*_{\mathcal{NB}}$, or $\frac{1}{2} < \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}} < \frac{3}{4}$. The other result, $\frac{1}{2} < \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} < \frac{3}{4}$, follows from the same technique. □

*Proof of Proposition 4.2.*

1. This result immediately follows from Proposition 3.1.

2. Following the proof of Proposition 3.1, we can derive the expression for $\Sigma^*$ and show that

$$\begin{aligned}
\Sigma^* &= \frac{\gamma}{2} \cdot \Big( Var[\Pi^*_{\mathcal{NB}}] - Var[\Pi^*_{\mathcal{B}}] \Big) \\
&= \frac{\gamma}{2} \Big( \frac{1}{4} (P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})^2 \Psi^*_{\mathcal{NB}} (1 - \Psi^*_{\mathcal{NB}}) - \frac{1}{4N} (P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}} (1 - \Psi^*_{\mathcal{B}}) \Big) \\
&= \frac{\gamma}{8} \Big( (P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})^2 \Psi^*_{\mathcal{NB}} (1 - \Psi^*_{\mathcal{NB}}) - \frac{1}{N} (P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}} (1 - \Psi^*_{\mathcal{B}}) \Big) \\
&\overset{(a)}{>} \frac{\gamma}{8} \Big( (P^*_{\mathcal{NB}} - \frac{3}{4} P^*_{\mathcal{NB}})^3 \cdot \frac{1}{2} P^*_{\mathcal{NB}} - \frac{1}{N} (P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}} (1 - \Psi^*_{\mathcal{B}}) \Big) \\
&\overset{(b)}{\geq} \frac{\gamma}{8} \Big( \frac{(P^*_{\mathcal{NB}})^4}{128} - \frac{1}{N} (1 - \Psi^*_{\mathcal{B}})^3 \Psi^*_{\mathcal{B}} \Big) \\
&\overset{(c)}{\geq} \frac{\gamma}{8} \Big( \frac{(P^*_{\mathcal{NB}})^4}{128} - \frac{27}{256N} \Big) \\
&\overset{(d)}{>} 0
\end{aligned}$$

for all $\gamma, \delta \in (0,1)$, where $(a)$ follows from $P^*_{\mathcal{NB}} < 1$ and Lemma B.1, $(b)$ follows from $P^*_{\mathcal{B}} \leq 1$, $(c)$ follows from $0 < \Psi^*_{\mathcal{B}} < P^*_{\mathcal{B}} \leq 1$ and $(1-x)^3 x \leq 27/256$ for all $x \in [0,1]$, and $(d)$ follows from Assumption 1 and

$$N > \frac{16}{(2\underline{\alpha} - 1)^4} \geq \frac{27}{2(2\alpha - 1)^4} = \frac{27}{2(P^*_{\mathcal{NB}})^4}.$$

3. Since $0 < \Psi^*_{\mathcal{NB}} < P^*_{\mathcal{NB}} = 2\alpha - 1 < 1$ and $0 < \Psi^*_{\mathcal{B}} < P^*_{\mathcal{B}} = 2(\alpha + \delta \cdot (1 - \alpha)) - 1 \leq 1$, $(P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})^2 \Psi^*_{\mathcal{NB}} (1 - \Psi^*_{\mathcal{NB}}) - \frac{1}{N} (P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}} (1 - \Psi^*_{\mathcal{B}})$ is bounded and thus

$$\Sigma^* = \frac{\gamma}{8} \Big( (P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})^2 \Psi^*_{\mathcal{NB}} (1 - \Psi^*_{\mathcal{NB}}) - \frac{1}{N} (P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}} (1 - \Psi^*_{\mathcal{B}}) \Big) \to 0$$

as $\gamma \to 0^+$.

□

The proof of Proposition 4.3 relies on intermediate results in the proof of Proposition 4.4, so we will show the proof for Proposition 4.4 first.

*Proof of Proposition 4.4.*

1. By Proposition 3.1, $P^*_{\mathcal{NB}} = 2\alpha - 1$ and $P^*_{\mathcal{B}} = 2(\alpha + \delta \cdot (1-\alpha)) - 1$. Therefore, it is straightforward to get that $P^*_{\mathcal{NB}} = 2\alpha - 1 < 2(\alpha + \delta \cdot (1-\alpha)) - 1 = P^*_{\mathcal{B}}$ for all $\gamma, \delta \in (0,1)$ as $1/2 < \alpha < 1$, and

$$\lim_{\delta \to 0^+} \frac{P^*_{\mathcal{B}}}{P^*_{\mathcal{NB}}} = \lim_{\delta \to 0^+} \frac{2(\alpha + \delta \cdot (1-\alpha)) - 1}{2\alpha - 1} = 1$$

for all $\gamma \in (0,1)$.

2. By Proposition 3.1, two equations $\frac{\partial f(P,\Psi;\gamma)}{\partial \Psi}\Big|_{P=P^*_{\mathcal{NB}}} = 0$ and $\frac{\partial f(P,\Psi;\frac{\gamma}{|\Xi^*_{\mathcal{B}}|})}{\partial \Psi}\Big|_{P=P^*_{\mathcal{B}}} = 0$ characterize $\Psi^*_{\mathcal{NB}}$ and $\Psi^*_{\mathcal{B}}$, respectively, where

$$f(P,\Psi;\gamma) = \frac{1}{2}(P-\Psi)\Psi - \frac{\gamma}{8}(P-\Psi)^2\Psi(1-\Psi)$$

is defined on $\{(P,\Psi) | 0 \leq \Psi \leq P \leq 1\}$. It has been shown in the proof of Proposition 3.1 that $f(P,\Psi;\gamma)$ is strictly concave in $\Psi$ over $[0,P]$ for any $P \in (0,1]$. To analyze $\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}$ and $\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}$, we first introduce an auxiliary function

$$g(x;P,\gamma) := \frac{1}{2}P^2(1-x)x - \frac{\gamma}{8}P^3(1-x)^2 x(1-Px) \tag{16}$$

defined on $[0,1]$, where $P$ and $\gamma$ are treated as two parameters. The connection between $f$ and $g$ is $g(\frac{\Psi}{P};P,\gamma) = f(P,\Psi;\gamma)$ or $g(x;P,\gamma) = f(P,Px;\gamma)$ through $x = \Psi/P$. Accordingly, we have that

$$\begin{aligned}
\frac{\partial g(x;P,\gamma)}{\partial x} &= \frac{\partial f}{\partial \Psi} \cdot \frac{\partial \Psi}{\partial x} \\
&= P \cdot \frac{\partial f}{\partial \Psi} \\
&= \frac{1}{2}P^2(1-2x) - \frac{\gamma}{8}P^3(1-x)\big(4Px^2 - (2P+3)x + 1\big)
\end{aligned}$$

and

$$\begin{aligned}\frac{\partial^2 g(x;P,\gamma)}{\partial x^2} &= \frac{\partial\big(P\cdot\frac{\partial f}{\partial \Psi}\big)}{\partial x}\\ &= P^2\cdot\frac{\partial^2 f}{\partial \Psi^2}.\end{aligned}$$

In particular, the following hold: $\frac{\partial^2 g(x;P,\gamma)}{\partial x^2} = P^2\cdot\frac{\partial^2 f}{\partial\Psi^2} < 0$ for all $x\in[0,1]$ and any $P\in(0,1]$, and

$$\begin{aligned}\frac{\partial g(x;P^*_{\mathcal{NB}},\gamma)}{\partial x}\bigg|_{x=\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}} &= \left(P\cdot\frac{\partial f(P,\Psi;\gamma)}{\partial\Psi}\bigg|_{\Psi=Px}\right)\bigg|_{P=P^*_{\mathcal{NB}},x=\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}}\\ &= P^*_{\mathcal{NB}}\cdot\frac{\partial f(P,\Psi;\gamma)}{\partial\Psi}\bigg|_{P=P^*_{\mathcal{NB}},\Psi=\Psi^*_{\mathcal{NB}}}\\ &= 0\end{aligned}$$

by the definition of $\Psi^*_{\mathcal{NB}}$. Using a similar argument, we can also establish that $\frac{\partial g(x;P^*_{\mathcal{B}},\frac{\gamma}{N})}{\partial x}\Big|_{x=\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}} = 0$. To sum up, we obtain the following properties about $g$:

a. $g(x;P,\gamma)$ is strictly concave in $x$ over $[0,1]$ for any $P\in(0,1]$.

b. $\frac{\partial g(x;P^*_{\mathcal{NB}},\gamma)}{\partial x} > 0$ for all $x\in[0,\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}})$ and $\frac{\partial g(x;P^*_{\mathcal{NB}},\gamma)}{\partial x} < 0$ for all $x\in(\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}},1]$.

To prove $\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} < \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}$, it suffices to show that $\frac{\partial g(x;P^*_{\mathcal{NB}},\gamma)}{\partial x}\Big|_{x=\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}} > 0$.

Note that

$$\begin{aligned}4Px^2-(2P+3)x+1 &\le \max\left\{4Px^2-(2P+3)x+1\Big|_{x=\frac{1}{2}},\, 4Px^2-(2P+3)x+1\Big|_{x=\frac{3}{4}}\right\}\\ &= \max\left\{-\frac{1}{2},\frac{3P-5}{4}\right\}\\ &= -\frac{1}{2}\end{aligned}$$

and

$$
\begin{aligned}
4Px^2 - (2P+3)x + 1 &\geq -(2P+3)x + 1 \\
&\geq -(2 \cdot 1 + 3) \cdot 1 + 1 \\
&= -4
\end{aligned}
$$

for all $x \in [\frac{1}{2}, \frac{3}{4}]$ and any $P \in (0, 1]$. Hence, we have that

$$
\frac{(P_{\mathcal{B}}^*)^3(1-x)\big(-4P_{\mathcal{B}}^*x^2 + (2P_{\mathcal{B}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}}}{(P_{\mathcal{NB}}^*)^3(1-x)\big(-4P_{\mathcal{NB}}^*x^2 + (2P_{\mathcal{NB}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}}} \overset{(a)}{\leq} \frac{(P_{\mathcal{B}}^*)^3 \cdot \Big(1 - \frac{1}{2}\Big) \cdot 4}{(P_{\mathcal{NB}}^*)^3 \cdot \Big(1 - \frac{3}{4}\Big) \cdot \frac{1}{2}} \overset{(b)}{\leq} \frac{16}{(2\alpha - 1)^3}, \tag{17}
$$

where $(a)$ follows from Lemma B.1 and $\frac{1}{2} \leq -4Px^2 + (2P+3)x - 1 \leq 4$ for all $x \in [\frac{1}{2}, \frac{3}{4}]$ and any $P \in (0, 1]$, and $(b)$ follows from $0 < P_{\mathcal{B}}^* = 2(\alpha + \delta \cdot (1-\alpha)) - 1 \leq 1$ and $P_{\mathcal{NB}}^* = 2\alpha - 1$. Putting everything together, we can get that

$$
\begin{aligned}
\frac{\partial g(x; P_{\mathcal{NB}}^*, \gamma)}{\partial x}\bigg|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} &= \frac{1}{2}(P_{\mathcal{NB}}^*)^2(1-2x) - \frac{\gamma}{8}(P_{\mathcal{NB}}^*)^3(1-x)\big(4P_{\mathcal{NB}}^*x^2 - (2P_{\mathcal{NB}}^*+3)x + 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \\
&= -\frac{1}{2}(P_{\mathcal{NB}}^*)^2(2x-1) + \frac{\gamma}{8}(P_{\mathcal{NB}}^*)^3(1-x)\big(-4P_{\mathcal{NB}}^*x^2 + (2P_{\mathcal{NB}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \\
&\overset{(a)}{>} -\frac{1}{2}(P_{\mathcal{B}}^*)^2(2x-1) + \frac{\gamma}{8}(P_{\mathcal{NB}}^*)^3(1-x)\big(-4P_{\mathcal{NB}}^*x^2 + (2P_{\mathcal{NB}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \\
&\overset{(b)}{\geq} -\frac{1}{2}(P_{\mathcal{B}}^*)^2(2x-1) + \frac{\gamma}{8}(P_{\mathcal{B}}^*)^3(1-x)\big(-4P_{\mathcal{B}}^*x^2 + (2P_{\mathcal{B}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \cdot \frac{(2\alpha-1)^3}{16} \\
&\overset{(c)}{>} -\frac{1}{2}(P_{\mathcal{B}}^*)^2(2x-1) + \frac{\gamma}{8N}(P_{\mathcal{B}}^*)^3(1-x)\big(-4P_{\mathcal{B}}^*x^2 + (2P_{\mathcal{B}}^*+3)x - 1\big)\Big|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \\
&= \frac{\partial g(x; P_{\mathcal{B}}^*, \frac{\gamma}{N})}{\partial x}\bigg|_{x=\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}} \\
&= 0,
\end{aligned}
$$

where $(a)$ follows from $0 < P_{\mathcal{NB}}^* < P_{\mathcal{B}}^*$ and $\frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} > \frac{1}{2}$, $(b)$ follows from Inequality (17), and $(c)$

follows from

$$N > \frac{16}{(2\underline{\alpha}-1)^4} \geq \frac{16}{(2\alpha-1)^3}$$

by Assumption 1. From this, we can conclude that $\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} < \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}$ for all $\gamma, \delta \in (0,1)$. Uniting this result and Lemma B.1, a stronger result, $\frac{1}{2} < \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} < \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}} < \frac{3}{4}$ for all $\gamma, \delta \in (0,1)$, follows.

Finally, since $\Psi^*_{\mathcal{NB}}$ and $\Psi^*_{\mathcal{B}}$ are determined by two equations

$$\frac{1}{2} \cdot (P^*_{\mathcal{NB}} - 2\Psi) - \frac{\gamma}{8} \cdot (P^*_{\mathcal{NB}} - \Psi) \cdot \left(4\Psi^2 - (2P^*_{\mathcal{NB}} + 3)\Psi + P^*_{\mathcal{NB}}\right) = 0$$

and

$$\frac{1}{2} \cdot (P^*_{\mathcal{B}} - 2\Psi) - \frac{\gamma}{8N} \cdot (P^*_{\mathcal{B}} - \Psi) \cdot \left(4\Psi^2 - (2P^*_{\mathcal{B}} + 3)\Psi + P^*_{\mathcal{B}}\right) = 0,$$

respectively, it is not difficult to see that $\Psi^*_{\mathcal{NB}} \to P^*_{\mathcal{NB}}/2$ and $\Psi^*_{\mathcal{B}} \to P^*_{\mathcal{B}}/2$ as $\gamma \to 0^+$. Therefore, $\lim_{\gamma \to 0^+} \frac{\Psi^*_{\mathcal{B}}/P^*_{\mathcal{B}}}{\Psi^*_{\mathcal{NB}}/P^*_{\mathcal{NB}}} = 1$ for all $\delta \in (0,1)$.

□

*Proof of Proposition 4.3.* Following the proof of Proposition 3.1, the expression of $\Phi^*$ is given by

$$\begin{aligned}
\Phi^* &= \mathbb{E}[\Pi^*_{\mathcal{B}}] - \mathbb{E}[\Pi^*_{\mathcal{NB}}] \\
&= \frac{1}{2}(P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})\Psi^*_{\mathcal{B}} - \frac{1}{2}(P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})\Psi^*_{\mathcal{NB}} \\
&= \frac{1}{2}(P^*_{\mathcal{B}})^2 \cdot \left(1 - \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}\right) \cdot \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} - \frac{1}{2}(P^*_{\mathcal{NB}})^2 \cdot \left(1 - \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}\right) \cdot \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}.
\end{aligned}$$

By the proof of Proposition 4.4, we have that $0 < P^*_{\mathcal{NB}} < P^*_{\mathcal{B}} \leq 1$ for all $\gamma, \delta \in (0,1)$, $\lim_{\delta \to 0^+} P^*_{\mathcal{B}} = P^*_{\mathcal{NB}}$, $\frac{1}{2} < \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} < \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}} < \frac{3}{4}$ for all $\gamma, \delta \in (0,1)$, and $\lim_{\gamma \to 0^+} \frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}} = \lim_{\gamma \to 0^+} \frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}} = \frac{1}{2}$. Now we show the proofs as follows:

1.

$$\begin{aligned}
\Phi^* &= \frac{1}{2}(P_{\mathcal{B}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}\right) \cdot \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} \\
&> \frac{1}{2}(P_{\mathcal{B}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} \\
&> \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} \\
&= 0
\end{aligned}$$

for all $\gamma, \delta \in (0,1)$.

2.

$$\begin{aligned}
\lim_{\gamma,\delta\to 0^+} \Phi^* &= \lim_{\gamma,\delta\to 0^+} \left(\frac{1}{2}(P_{\mathcal{B}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}\right) \cdot \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \\
&= \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{1}{2}\right) \cdot \frac{1}{2} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{1}{2}\right) \cdot \frac{1}{2} \\
&= 0.
\end{aligned}$$

3.

$$\begin{aligned}
\lim_{\delta\to 0^+} \Phi^* &= \lim_{\delta\to 0^+} \left(\frac{1}{2}(P_{\mathcal{B}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}\right) \cdot \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \\
&= \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \lim_{\delta\to 0^+} \left(\left(1 - \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}\right) \cdot \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*}\right) - \frac{1}{2}(P_{\mathcal{NB}}^*)^2 \cdot \left(1 - \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*}\right) \cdot \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} \\
&> 0
\end{aligned}$$

for all $\gamma \in (0,1)$, where the last inequality follows from $P_{\mathcal{NB}}^* > 0$ and $\frac{1}{2} < \frac{\Psi_{\mathcal{B}}^*}{P_{\mathcal{B}}^*} < \frac{\Psi_{\mathcal{NB}}^*}{P_{\mathcal{NB}}^*} < \frac{3}{4}$ as long as $\gamma > 0$.

4.

$$
\begin{aligned}
\lim_{\gamma\to 0^+}\Phi^* &= \lim_{\gamma\to 0^+}\frac{1}{2}(P^*_{\mathcal{B}})^2\cdot\Big(1-\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}\Big)\cdot\frac{\Psi^*_{\mathcal{B}}}{P^*_{\mathcal{B}}}-\frac{1}{2}(P^*_{\mathcal{NB}})^2\cdot\Big(1-\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}\Big)\cdot\frac{\Psi^*_{\mathcal{NB}}}{P^*_{\mathcal{NB}}}\\
&=\frac{1}{2}(P^*_{\mathcal{B}})^2\cdot\Big(1-\frac{1}{2}\Big)\cdot\frac{1}{2}-\frac{1}{2}(P^*_{\mathcal{NB}})^2\cdot\Big(1-\frac{1}{2}\Big)\cdot\frac{1}{2}\\
&=\frac{1}{8}\big((P^*_{\mathcal{B}})^2-(P^*_{\mathcal{NB}})^2\big)\\
&>0
\end{aligned}
$$

for all $\delta\in(0,1)$.

□

*Proof of Proposition 5.1.* With the expected profit function $\mathcal{S}_{\mathcal{B}}$ for suppliers being modified, the equilibrium solution when blockchain is not adopted is unchanged, and we need to re-derive the equilibrium solution when blockchain is adopted. Note that $\theta_j = 1 \iff \mathcal{S}_{\mathcal{B}}|_{\theta_j=1}\geq\kappa$. By the definition of $\mathcal{S}_{\mathcal{B},\kappa}$, given $\Psi$, $s=s^*_{\mathcal{B}}(P)$ and $\Xi\neq\varnothing$, the effort choice for each supplier in $\Xi$, $e^*_{\mathcal{B}}$, is a solution to the following fixed-point problem:

$$
\begin{aligned}
e^*_{\mathcal{B}} &= \arg\max_{e_j\in[0,1]}\pi_{\mathcal{B}}(e_j,e^*_{\mathcal{B}})\cdot\Psi\cdot\frac{s}{|\Xi|}-\frac{e_j}{2}\cdot\frac{s}{|\Xi|}-\mathcal{I}(\mathcal{S}_{\mathcal{B}}|_{\theta_j=1}\geq\kappa)\cdot\kappa\\
&=\arg\max_{e_j\in[0,1]}\Big(e_j^{\frac{1}{2}}\cdot\Psi-\frac{e_j}{2}\Big)\cdot\frac{s}{|\Xi|}-\mathcal{I}(\mathcal{S}_{\mathcal{B}}|_{\theta_j=1}\geq\kappa)\cdot\kappa\\
&=\begin{cases}\min\{\Psi^2,1\} & \text{if }\Psi>0\text{ and }\big(\min\{\Psi^2,\Psi\}-\frac{1}{2}\cdot\min\{\Psi^2,1\}\big)\cdot\frac{s}{|\Xi|}-\kappa\geq 0\\ 0 & \text{otherwise}\end{cases}.
\end{aligned}
$$

If $\Psi>0$ and $\big(\min\{\Psi^2,\Psi\}-\frac{1}{2}\cdot\min\{\Psi^2,1\}\big)\cdot\frac{s}{|\Xi|}-\kappa\geq 0$ (the first case), the optimization problems the consumers and manufacturer face are the same as before, so by the proof of Proposition 3.1 we can obtain that the solution is

$$
\Xi^*=S=\Xi^*_{\mathcal{B}},\Psi^*=\Psi^*_{\mathcal{B}},P^*=2(\alpha+\delta\cdot(1-\alpha))-1=P^*_{\mathcal{B}},s^*=\frac{1}{2}\cdot\mathcal{I}\big(P^*\leq 2(\alpha+\delta\cdot(1-\alpha))-1\big)=\frac{1}{2}=s^*_{\mathcal{B}};
$$

in this case, $\mathcal{M}_{\mathcal{B}} > 0$. Otherwise (the second case), $\Pi_{\mathcal{B}} = \mathcal{M}_{\mathcal{B}} = 0$. Whenever

$$\begin{aligned}\mathcal{S}_{\mathcal{B}}^* &= \theta_{\mathcal{B}}^* \cdot \frac{(\Psi_{\mathcal{B}}^*)^2}{2} \cdot \frac{s_{\mathcal{B}}^*}{|\Xi_{\mathcal{B}}^*|} \\ &= \left(\min\{\Psi^2, \Psi\} - \frac{1}{2}\cdot\min\{\Psi^2, 1\}\right) \cdot \frac{s}{|\Xi|}\Big|_{\Xi=\Xi^*, \Psi=\Psi^*, s=s^*} \\ &\geq \kappa,\end{aligned}$$

the first case is feasible to the manufacturer and the manufacturer will definitely go for it to get a positive $\mathcal{M}_{\mathcal{B}}$.

In conclusion, whenever $\kappa \leq \mathcal{S}_{\mathcal{B}}^*$, the equilibrium solution when blockchain is adopted under the new setting is the same as that from the baseline model solved in Proposition 3.1. Thus, by Proposition 4.1, we can conclude that blockchain adoption arises in equilibrium for the manufacturer and all suppliers whenever the manufacturer implementation cost $0 < \chi \leq \Omega^*$ and the supplier implementation cost $\kappa \leq \mathcal{S}_{\mathcal{B}}^*$. □

The following lemma identifies the set of manufacturer blockchain implementation costs $\chi > 0$ and supplier blockchain implementation costs $\kappa > 0$ that ensure blockchain adoption arises in equilibrium, and the aggregate welfare increases/decreases relative to the case without blockchain.

**Lemma B.2.** *Define*

$$\begin{aligned}Z_{inc} &:= \Big\{(\chi,\kappa):\ 0<\chi\leq\Omega^*, 0<N\kappa\leq\frac{1}{4}(\Psi_{\mathcal{B}}^*)^2, \chi+N\kappa<\Omega^*+\frac{1}{4}\big((\Psi_{\mathcal{B}}^*)^2-(\Psi_{\mathcal{NB}}^*)^2\big)\Big\}, \\ Z_{dec} &:= \Big\{(\chi,\kappa):\ 0<\chi\leq\Omega^*, 0<N\kappa\leq\frac{1}{4}(\Psi_{\mathcal{B}}^*)^2, \chi+N\kappa>\Omega^*+\frac{1}{4}\big((\Psi_{\mathcal{B}}^*)^2-(\Psi_{\mathcal{NB}}^*)^2\big)\Big\}.\end{aligned}$$

*Then for all $(\chi,\kappa) \in Z_{inc}$ (resp. $Z_{dec}$) blockchain adoption arises in equilibrium and the aggregate welfare increases (resp. decreases) relative to the case without blockchain.*

*Proof.* By Proposition 3.1, we have that

$$e_{\mathcal{NB}}^* = (\Psi_{\mathcal{NB}}^*)^2, \quad \theta_{\mathcal{NB}}^* = 1, \quad s_{\mathcal{NB}}^* = \frac{1}{2}, \quad |\Xi_{\mathcal{NB}}^*| = 1, \quad P_{\mathcal{NB}}^* = 2\alpha - 1,$$

where $\Psi^*_{\mathcal{NB}} \in (0, P^*_{\mathcal{NB}})$ is the unique solution to the equation

$$\frac{1}{2} \cdot (P^*_{\mathcal{NB}} - 2\Psi) - \frac{\gamma}{8} \cdot (P^*_{\mathcal{NB}} - \Psi) \cdot \left(4\Psi^2 - (2P^*_{\mathcal{NB}} + 3)\Psi + P^*_{\mathcal{NB}}\right) = 0,$$

and

$$e^*_{\mathcal{B}} = (\Psi^*_{\mathcal{B}})^2, \quad \theta^*_{\mathcal{B}} = 1, \quad s^*_{\mathcal{B}} = \frac{1}{2}, \quad \Xi^*_{\mathcal{B}} = S, \quad P^*_{\mathcal{B}} = 2(\alpha + \delta \cdot (1 - \alpha)) - 1,$$

where $\Psi^*_{\mathcal{B}} \in (0, P^*_{\mathcal{B}})$ is the unique solution to the equation

$$\frac{1}{2} \cdot (P^*_{\mathcal{B}} - 2\Psi) - \frac{\gamma}{8N} \cdot (P^*_{\mathcal{B}} - \Psi) \cdot \left(4\Psi^2 - (2P^*_{\mathcal{B}} + 3)\Psi + P^*_{\mathcal{B}}\right) = 0.$$

In the proofs of Propositions 3.1 and 5.1, it was established that the supplier welfare without blockchain adoption $W^*_{\mathcal{NB},S}$ and with blockchain adoption $W^*_{\mathcal{B},S}$ are given by

$$\begin{aligned} W^*_{\mathcal{NB},S} &= |\Xi^*_{\mathcal{NB}}| \cdot \theta^*_{\mathcal{NB}} \cdot \frac{(\Psi^*_{\mathcal{NB}})^2}{2} \cdot \frac{s^*_{\mathcal{NB}}}{|\Xi^*_{\mathcal{NB}}|} = \frac{(\Psi^*_{\mathcal{NB}})^2}{4}, \\ W^*_{\mathcal{B},S} &= |\Xi^*_{\mathcal{B}}| \cdot \theta^*_{\mathcal{B}} \cdot \left(\frac{(\Psi^*_{\mathcal{B}})^2}{2} \cdot \frac{s^*_{\mathcal{B}}}{|\Xi^*_{\mathcal{B}}|} - \kappa\right) = \frac{(\Psi^*_{\mathcal{B}})^2}{4} - N\kappa, \end{aligned}$$

whereas the manufacturer welfare without blockchain adoption $W^*_{\mathcal{NB},M}$ is given by

$$W^*_{\mathcal{NB},M} = \mathcal{M}^*_{\mathcal{NB}} = \frac{1}{2}(P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})\Psi^*_{\mathcal{NB}} - \frac{\gamma}{8}(P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})^2 \Psi^*_{\mathcal{NB}}(1 - \Psi^*_{\mathcal{NB}}),$$

and the manufacturer welfare with blockchain adoption $W^*_{\mathcal{B},M}$ is given by

$$W^*_{\mathcal{B},M} = \mathcal{M}^*_{\mathcal{B}} - \chi = \frac{1}{2}(P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})\Psi^*_{\mathcal{B}} - \frac{\gamma}{8N}(P^*_{\mathcal{B}} - \Psi^*_{\mathcal{B}})^2 \Psi^*_{\mathcal{B}}(1 - \Psi^*_{\mathcal{B}}) - \chi.$$

Note that $\Omega^* = \mathcal{M}^*_{\mathcal{B}} - \mathcal{M}^*_{\mathcal{NB}}$ by the definition in (12), so $W^*_{\mathcal{B},M} - W^*_{\mathcal{NB},M} = \Omega^* - \chi$. Finally, the consumer welfare with blockchain adoption $W^\star_{\mathcal{B},C}$ and without blockchain adoption $W^\star_{\mathcal{NB},C}$ are given as follows: $W^\star_{\mathcal{B},C} = W^\star_{\mathcal{NB},C} = v_0$ (see proof of Proposition 6.3 for details).

Then, the difference between the two aggregate welfares is given as follows:

$$\begin{aligned}
&(W^\star_{\mathcal{B},S} + W^\star_{\mathcal{B},C} + W^\star_{\mathcal{B},M}) - (W^\star_{\mathcal{NB},S} + W^\star_{\mathcal{NB},C} + W^\star_{\mathcal{NB},M}) \\
&\quad = (W^\star_{\mathcal{B},S} - W^\star_{\mathcal{NB},S}) + (W^\star_{\mathcal{B},C} - W^\star_{\mathcal{NB},C}) + (W^\star_{\mathcal{B},M} - W^\star_{\mathcal{NB},M}) \\
&\quad = \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2 - (\Psi^*_{\mathcal{NB}})^2}{4} - \chi - N\kappa.
\end{aligned}$$

From Proposition 5.1, we have that blockchain adoption arises in equilibrium when $W^*_{\mathcal{B},M} \geq W^*_{\mathcal{NB},M}$ (or equivalently, $\Omega^* \geq \chi$) and $W^*_{\mathcal{B},S} \geq 0$ (or equivalently, $N\kappa \leq (\Psi^*_{\mathcal{B}})^2/4$). Thus, if $0 < \chi \leq \Omega^*, 0 < N\kappa \leq \frac{(\Psi^*_{\mathcal{B}})^2}{4}, \chi + N\kappa < \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2 - (\Psi^*_{\mathcal{NB}})^2}{4}$, then blockchain adoption arises in equilibrium and aggregate welfare increases, and if $0 < \chi \leq \Omega^*, 0 < N\kappa \leq \frac{(\Psi^*_{\mathcal{B}})^2}{4}, \chi + N\kappa > \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2 - (\Psi^*_{\mathcal{NB}})^2}{4}$, then blockchain adoption arises in equilibrium and yet aggregate welfare decreases. This completes the proof.

As a side note, $Z_{dec}$ is always non-empty whereas $Z_{inc}$ could be an empty set. When $\alpha = \overline{\alpha} \to 1, \delta \to 0, \gamma \to 1, N \to \infty$, then $\Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2 - (\Psi^*_{\mathcal{NB}})^2}{4} < 0$ so $Z_{inc}$ is an empty set. □

*Proof of Proposition 6.1.* Set $\overline{\gamma} = 1$ to be a trivial bound. For any $\gamma \in (0, \overline{\gamma})$, let $\varepsilon > 0$ be sufficiently small such that $\varepsilon < \min\left\{\Omega^*, \frac{(\Psi^*_{\mathcal{B}})^2}{4}, \frac{(\Psi^*_{\mathcal{NB}})^2}{8}\right\}$. Set $\chi = \Omega^* - \varepsilon$ and $\kappa = \frac{(\Psi^*_{\mathcal{B}})^2}{4N} - \frac{\varepsilon}{N}$; then, we have that $0 < \chi \leq \Omega^*$, $0 < N\kappa = \frac{(\Psi^*_{\mathcal{B}})^2}{4} - \varepsilon \leq \frac{(\Psi^*_{\mathcal{B}})^2}{4}$, and $\chi + N\kappa = \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2}{4} - 2\varepsilon > \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2 - (\Psi^*_{\mathcal{NB}})^2}{4}$. Thus, $(\chi, \kappa) \in Z_{dec}$ by Lemma B.2 and we see blockchain adoption arises in equilibrium, and yet aggregate welfare is lower than that in the case without blockchain. □

*Proof of Proposition 6.2.* Set $\overline{\gamma} = \frac{2\delta(1-\alpha)}{5}$. For any $\gamma \in (0, \overline{\gamma})$, recall that $0 < P^*_{\mathcal{NB}} \leq 1$ and $\Psi^*_{\mathcal{NB}} \in (0, P^*_{\mathcal{NB}})$ satisfies

$$\frac{1}{2} \cdot (P^*_{\mathcal{NB}} - 2\Psi^*_{\mathcal{NB}}) - \frac{\gamma}{8} \cdot (P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}}) \cdot \left(4(\Psi^*_{\mathcal{NB}})^2 - (2P^*_{\mathcal{NB}} + 3)\Psi^*_{\mathcal{NB}} + P^*_{\mathcal{NB}}\right) = 0,$$

so

$$\begin{aligned}\left|\Psi^*_{\mathcal{NB}} - \frac{P^*_{\mathcal{NB}}}{2}\right| &= \left|\frac{\gamma}{8}\cdot(P^*_{\mathcal{NB}} - \Psi^*_{\mathcal{NB}})\cdot\left(4(\Psi^*_{\mathcal{NB}})^2 - (2P^*_{\mathcal{NB}}+3)\Psi^*_{\mathcal{NB}} + P^*_{\mathcal{NB}}\right)\right| \\ &< \frac{\overline{\gamma}}{8}\cdot 1\cdot(4+5+1) \\ &= \frac{\delta\cdot(1-\alpha)}{2}.\end{aligned}$$

Similarly, we can get that $\left|\Psi^*_{\mathcal{B}} - \frac{P^*_{\mathcal{B}}}{2}\right| < \frac{\delta\cdot(1-\alpha)}{2}$. It follows that

$$\Psi^*_{\mathcal{NB}} < \frac{P^*_{\mathcal{NB}}}{2} + \frac{\delta\cdot(1-\alpha)}{2} = \frac{2\alpha-1+\delta\cdot(1-\alpha)}{2} = \frac{P^*_{\mathcal{B}}}{2} - \frac{\delta\cdot(1-\alpha)}{2} < \Psi^*_{\mathcal{B}}.$$

Note that $\Omega^* > 0$ by Proposition 4.1; thus, $\Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2-(\Psi^*_{\mathcal{NB}})^2}{4} > 0$.

Now let $\varepsilon > 0$ be sufficiently small such that $\varepsilon < \min\left\{\Omega^*, \frac{(\Psi^*_{\mathcal{B}})^2}{4}, \frac{\Omega^*}{2} + \frac{(\Psi^*_{\mathcal{B}})^2-(\Psi^*_{\mathcal{NB}})^2}{8}\right\}$. Set $\chi = \varepsilon$ and $\kappa = \frac{\varepsilon}{N}$; then, we have that $0 < \chi \leq \Omega^*$, $0 < N\kappa = \varepsilon \leq \frac{(\Psi^*_{\mathcal{B}})^2}{4}$, and $\chi + N\kappa = 2\varepsilon < \Omega^* + \frac{(\Psi^*_{\mathcal{B}})^2-(\Psi^*_{\mathcal{NB}})^2}{4}$. Thus, $(\chi,\kappa) \in Z_{inc}$ by Lemma B.2 and we see blockchain adoption arises in equilibrium, and aggregate welfare is higher than that in the case without blockchain. □

*Proof of Proposition 6.3.* In the equilibrium when blockchain is not adopted, by the proof of Proposition 3.1, a generic consumer $k$'s expected utility from purchasing the manufacturer's good is given by

$$\begin{aligned}\mathcal{C}_{\mathcal{NB},k} &= \mathbb{E}_{\mathcal{NB}}[V_k \mid t_k, \tilde{q}_k] - P^*_{\mathcal{NB}} \\ &= \begin{cases} v_0 & \text{if } \tilde{q}_k = t_k \\ v_0 - 2\cdot(2\alpha-1) & \text{if } \tilde{q}_k \neq t_k \end{cases}.\end{aligned}$$

Therefore, consumer $k$ will purchase from the manufacturer if $\tilde{q}_k = t_k$ or avail herself of her outside option if $\tilde{q}_k \neq t_k$. In either case, the expected utility consumer $k$ obtains is $v_0$. In the situation where consumer $k$ eventually does not receive her good due to a recall, she can go for her outside option and still get $v_0$. Thus, consumer $k$'s expected utility in the equilibrium is always $v_0$, and the total consumer welfare without blockchain adoption $W_{\mathcal{NB},C} = 1\cdot v_0 = v_0$.

Applying a similar argument to the case when blockchain is adopted, we can get that the total consumer welfare with blockchain adoption $W_{\mathcal{B},C} = 1 \cdot v_0 = v_0$. $W_{\mathcal{NB},C} = W_{\mathcal{B},C}$, so the total consumer welfare without blockchain adoption equals the total consumer welfare with blockchain adoption. $\square$