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Abstract

We examine a supply chain with a single risk-averse manufacturer who purchases from vendors and sells to consumers. Within this context, we establish 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 vendors and thereby leads the manufacturer to endogenously diversify across vendors 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 enables improved consumer decision-making and thereby increases consumer welfare. The manufacturer responds optimally by increasing the consumer price which transfers a portion of the consumer's welfare gain to the manufacturer, enhancing manufacturer welfare and serving as a second channel to drive blockchain adoption by the manufacturer.

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

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1 Introduction

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 the entity that sells directly to consumers as the manufacturer. The manufacturer purchases goods (or raw materials) from vendors and sells to consumers. We assume that the manufacturer has the ability to set prices in her interactions with both consumers and vendors, and also that she sells a good sufficiently differentiated from all other goods so that she acts as a monopolist. Formally, the referenced assumptions ensure that the manufacturer possesses market power. In the described setting, we demonstrate that blockchain adoption always strictly improves manufacturer welfare if blockchain adoption involves no fixed cost of implementation. In turn, when the manufacturer bears the cost of blockchain adoption for the supply chain as a whole, we find that blockchain adoption arises in equilibrium so long as the adoption cost is sufficiently small.[1]

An important contribution of our work is that we clarify the economic channels that enhance manufacturer welfare and thereby drive blockchain adoption. In particular, we demonstrate that blockchain adoption arises due to two economic channels: manufacturer risk aversion and consumer information asymmetry. The first channel, manufacturer risk aversion, reflects our finding that blockchain adoption increases the manufacturer's welfare more so when she is risk averse as compared to if she were risk neutral. The second channel, consumer information asymmetry, reflects our finding 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. We clarify the intuition for each channel subsequently after describing our economic framework.

We consider a supply chain with three layers: an infinite number of vendors, a single manufacturer, and a unit measure of consumers.[2] 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

[1]Since the manufacturer possesses market power in our setting, she can shift costs to other supply chain participants endogenously. Thus, the specific assumption regarding who bears the adoption cost is not crucial; our formal analysis assumes the adoption cost is borne by the manufacturer.

[2]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.

manufacturer. While consumers do not know the manufacturer type, each consumer nonetheless receives an imperfect signal of the manufacturer's type.

Our economic analysis consists of four stages: two correspond to the consumer-manufacturer interaction, and two correspond to the manufacturer-vendor interaction. In the first stage, the manufacturer determines whether or not to adopt blockchain, and also sets a consumer price. In the second stage, each consumer reacts to the consumer price, deciding whether to purchase the manufacturer's good or else select an outside option. The outside option reflects the consumer's opportunity cost. In the third stage, the manufacturer selects a set of vendors from which to fill consumer orders and simultaneously selects a price to offer each selected vendor. In the final stage, each vendor who received an offer from the manufacturer reacts by either accepting or rejecting the offer. Each such vendor also simultaneously selects an effort level, and the effort level determines the likelihood that her batch of goods is defective. A defective batch must be recalled and all associated revenues forfeited.

The manufacturer receives all vendor goods subsequent to the fourth stage. At this point the manufacturer may find some of the goods to be defective. If the manufacturer can trace each such detected defect to the respective defective batch, then the manufacturer recalls only the defective batches. In that case, the manufacturer provides a refund to the associated consumers, and also requires that vendors who produced those defective batches refund the received payment. In contrast, if the manufacturer cannot trace detected defects and nonetheless discovers some defects, then the manufacturer recalls *all* goods because she cannot determine the specific batches that are defective. In this second case, the manufacturers provides a refund to all customers and receives a refund from all vendors. Any goods that are not recalled are released to consumers.

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 vendor causes a recall of *all* goods. Second, we assume that blockchain adoption improves the accuracy of consumer signals, which reflects the fact that a blockchain can store various relevant details of the manufacturing process, leading to a reduction in consumer information asymmetry regarding the manufacturer's type. Each of these corresponds to an economic channel that enhances manufacturer welfare, and therefore, also drives blockchain adoption. To reiterate, the two economic channels that we identify as driving blockchain adoption are manufacturer risk aversion and consumer information asymmetry.

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 because the manufacturer is risk averse. Without a blockchain, the risk-averse manufacturer sources from a single vendor because sourcing from multiple vendors only increases her expected number of recalls, since she must recall *all* goods if *any* vendor produces a defective batch. In contrast, the blockchain enables the manufacturer to trace defective goods to the vendor who supplied it, and conduct targeted recalls. Targeted recalls allow her to fully diversify away individual vendor recall risks in equilibrium by spreading her purchase order across a countably infinite set of vendors. Note that the manufacturer faces the same *expected* number of recalled goods with and without blockchain because vendors are homogeneous; nonetheless, blockchain adoption leads to a degenerate distribution of recalled goods because of the diversification across vendors, and thus, a lower *risk* of recalls.

Consumer information asymmetry drives blockchain adoption because the blockchain reduces that asymmetry, thereby improving consumer welfare; in turn, the manufacturer extracts some of the incremental consumer 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. The manufacturer rationally reacts by raising the price charged to the consumer, thereby extracting some of the increase in consumer surplus, and enhancing manufacturer welfare.

We also examine the effect of blockchain adoption upon vendor and consumer welfare. We find that blockchain adoption has an ambiguous effect upon vendor welfare because it has an ambiguous effect upon the price paid to vendors by the manufacturer. In contrast, blockchain adoption unambiguously increases consumer welfare because it improves the consumer information environment, thereby enabling improved decision-making.

Our paper contributes to the literature examining economic questions associated with blockchains. Most of that literature focuses on settings not applicable to business. 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, and Rosu and Saleh 2021) and decentralized finance platforms (e.g., Cong et al. 2021, Gan et al. 2021, and Mayer 2021). John et al. (2022) provide an overview of the literature examining Bitcoin and non-business alternatives. Our work differs from that literature in that we focus on a business setting, supply chain in particular.

The literature examining blockchain in a business setting is small but growing. Some notable papers in this literature include Cao et al. (2019), Chod et al. (2020), Babich and Hilary (2020), Cui et al. (2020a), Cui et al. (2020b), Dong et al. (2020), Chen et al. (2021), Iyengar et al. (2022), and Ma et al. (2022). Our paper is most closely related to Iyengar et al. (2022), which also focuses on the blockchain adoption decision. Our work differs from that paper though in that we consider a setting in which the manufacturer possesses market power, whereas Iyengar et al. (2022) study a setting in which the manufacturing sector is perfectly competitive.

Our paper proceeds as follows. Section 2 formally states our economic model. Section 3 provides our main results, clarifying that blockchain adoption arises for sufficiently small adoption costs and also demonstrating how manufacturer risk aversion and consumer information asymmetry drive adoption. Section 4 provides results regarding vendor and consumer welfare. Section 5 concludes.

2 Model

We consider a static model consisting of infinitely many vendors, one manufacturer, and a unit measure of consumers. At the outset of our model, the manufacturer selects whether or not to adopt blockchain. Thereafter, the manufacturer sets prices for consumers, and consumers make purchasing decisions. The manufacturer fulfills consumer demand by sourcing from vendors. In more detail, the manufacturer offers a chosen set of vendors a price per unit produced, and each such vendor subsequently accepts or rejects the manufacturer's offer. Any vendor who accepts a manufacturer's offer also selects an effort level with effort being costly and reducing the probability of the vendor's batch being defective.

We put forth our model primitives in Section 2.1. We then specify equilibrium conditions for the subgames arising from blockchain non-adoption and blockchain adoption in Sections 2.2 and 2.3, respectively. We specify those subgames separately to emphasize how blockchain's presence affects the economic environment. Section 2.4 provides model solutions.

2.1 Model Primitives

2.1.1 Manufacturer

There exists a single manufacturer who possesses a type q which is equally likely to be A or B. The manufacturer type impacts consumer utility, but it is unknown to consumers. Our assumptions reflect situations in which consumers are poorly informed regarding the specific type of a manufacturer (see, e.g., Poole and Baron 1996).

We assume that the manufacturer is risk averse and values her profits according to the utility function:

$$U(x) = \frac{x^{1-\gamma}}{1-\gamma} \tag{1}$$

where $\gamma \in (0,1)$ denotes the level of risk aversion of the manufacturer. Note that $U(x)$ is a Constant Relative Risk Aversion (CRRA) utility function and therefore satisfies the standard regularity conditions (i.e., $U'(x) \geq 0$, $U''(x) \leq 0$ and $U(0) = 0$). Moreover, $\lim_{\gamma \to 0^+} U(x) = x$ so that the manufacturers becomes risk-neutral as $\gamma \to 0^+$.

2.1.2 Consumers

There exists a unit mass of consumers $k \in [0,1]$. Each consumer k has a two-dimensional type $(v_k, t_k) \in [0,H] \times \{A,B\}$ where $0 < H \leq 1$. We assume that v_k is drawn uniformly from the interval $[0,H]$, and t_k is A or B with equal probability. Moreover, the utility V_k of a consumer of type (v_k, t_k) from consuming a good from the manufacturer is given by:

$$V_k = v_k \cdot \Big(\mathcal{I}\big(q = t_k\big) - \mathcal{I}\big(q \neq t_k\big)\Big), \tag{2}$$

where $\mathcal{I}(\cdot) \in \{0, 1\}$ is the indicator function that takes the value 1 if the argument is true. Note that consumer (v_k, t_k) earns positive utility $V_k \geq 0$ if her type matches that of the manufacturer (i.e., $q = t_k$) and negative utility otherwise. Our model thus reflects the heterogeneous preferences of consumers in practice (see, e.g., Yiridoe et al. 2005 and Moser et al. 2011).

Although consumers do not know the manufacturer's type, each consumer has access to a *signal* which provides information regarding the type of the manufacturer. Specifically, consumer $k \in [0, 1]$ receives a random signal $\tilde{q}_k \in \{A, B\}$. In the absence of blockchain, this signal is generated according to the following probability law:

$$\mathbb{P}(\tilde{q}_k = \tilde{q} \mid q) = \begin{cases} \alpha & \text{if } \tilde{q} = q \\ 1 - \alpha & \text{if } \tilde{q} \neq q \end{cases} \tag{3}$$

with $\alpha \in [\frac{1}{2}, 1)$ 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.

The presence of the blockchain changes the information environment of the consumer: if the manufacturer adopts the blockchain, then 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:

$$\mathbb{P}(\tilde{q}_k = \tilde{q} \mid q) = \begin{cases} \alpha + \delta & \text{if } \tilde{q} = q \\ 1 - \alpha - \delta & \text{if } \tilde{q} \neq q \end{cases} \tag{4}$$

with $\delta \in (0, 1 - \alpha]$ representing the extent to which blockchain improves the accuracy of consumer signals. This modeling choice reflects the fact that the blockchain stores all relevant aspects of the manufacturing process and provides such information not only to manufacturers but also to consumers.

We allow that each consumer may forgo purchasing from the manufacturer and instead avail herself of an outside option which provides value zero. This outside option captures the opportunity cost of purchasing from the manufacturer, and could reflect, for example, the utility from another manufacturer that we do not explicitly model.

2.1.3 Vendors

There exist countably infinite homogeneous vendors indexed by $j \in \mathbb{N}_+ = \{1, 2, \ldots\}$. Vendors receive orders from the manufacturer to fulfill consumer demand. In turn, each vendor decides whether to accept the order and a level of effort to exert if the order is accepted. Effort is costly for the vendor, but it determines the probability that the vendor's batch is *defective*. Defective batches must be recalled, and neither the vendor nor the manufacturer earn revenues from recalled batches.

More formally, the batch produced by vendor j is assumed to be defective with probability $\rho(e_j) \in [0, 1]$, where $e_j \in [0, 1]$ denotes vendor j's effort choice. We let $\rho(e_j) = 1 - \sqrt{e_j}$, implying $\rho(e_j) \in [0, 1]$ for all e_j and $\rho' < 0$ so that a higher vendor effort induces a lower defect probability. Exerting effort e_j results in a per unit cost $\frac{e_j}{2}$ to vendor j.

We assume that the manufacturer cannot expediently trace a defective unit to its batch in the absence of blockchain. As a consequence, when the manufacturer does not adopt blockchain, she recalls batches from all vendors if she discovers any defects. This action represents a precautionary measure taken in practice. However, if the manufacturer adopts the blockchain, every defective unit can be traced to the appropriate vendor(s); in turn, the manufacturer recalls *only* the defective vendor batches. Our assumptions are consistent with practice as blockchain has been shown to produce practically relevant reductions in tracing times.[3]

[3]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.

2.1.4 Timeline

Our model evolves over three periods indexed by $t = 0, 1, 2$. At the beginning of period 0, consumers and the manufacturer learn their own types, and immediately thereafter, the manufacturer decides whether to adopt the blockchain. In the middle of period 0, the manufacturer sets her price for consumers. At the end of period 0, each consumer observes a signal from the manufacturer and then decides whether to purchase from the manufacturer or choose the outside option instead. These decisions determine the demand of the manufacturer, $s \in [0, 1]$, where s represents the measure of consumers purchasing from the manufacturer and $1 - s$ represents the measure of consumers selecting the outside option.

At the beginning of period 1, the manufacturer observes the consumer demand and places orders with vendors to fulfill that demand. More precisely, the manufacturer selects a subset of vendors, equally divides the demand over the chosen subset, and offers each of the chosen vendors the same price. Since the vendors are homogeneous, choosing a subset of vendors is equivalent to choosing the number of vendors n, and we can, without loss of generality, assume that the set of vendors is $\{1, \ldots, n\}$. Thereafter, each vendor that receives an offer chooses whether to accept the offer, and then selects an effort level. Each vendor that receives and accepts the offer produces the goods and sends them to the manufacturer. This completes period 1.

We assume that defects, if present, are detected at the beginning of period 2. Recall though that defective units cannot be traced expediently in the absence of blockchain. As a consequence, all batches are recalled if there exists any defect in the absence of blockchain, whereas only defective batches are recalled if blockchain were adopted. Then, at the end of period 2, all units that are not recalled are released to consumers, and pay-offs realize. Any consumer not having her order filled due to a recall receives a full refund and incurs no utility. Moreover, vendors and the manufacturer earn revenue only on goods that were not recalled.

2.2 Subgame Arising from Blockchain Non-Adoption

Since vendors are homogeneous, we restrict ourselves to examining equilibria in which vendors act symmetrically. Accordingly, if the manufacturer makes vendor j an offer and vendor j accepts and exerts effort e_j then vendor j's per unit expected profit is given by:

$$\mathcal{V}(\Psi, n, e_j, e_{-j}) := \underbrace{(1-\rho(e_{-j}))^{n-1} \cdot (1-\rho(e_j)) \cdot \Psi}_{\text{Per Unit Expected Revenue}} - \underbrace{\frac{e_j}{2}}_{\text{Per Unit Cost}} \tag{5}$$

where $\Psi \geq 0$ denotes the price offered by the manufacturer, $n \in \mathbb{N}_+$ denotes the number of vendors that receive an offer from the manufacturer, and $e_{-j} \in [0,1]$ denotes the symmetric effort choice of all other vendors. Note that $(1-\rho(e_{-j}))^{n-1} \cdot (1-\rho(e_j))$ corresponds to the probability that vendor j's batch is not recalled. This follows because, in the absence of blockchain, the manufacturer cannot trace defects to the offending vendor and thus recalls all batches when any batch is defective.

We assume that a vendor receives zero pay-off if she rejects the manufacturer's offer. Since $\mathcal{V}(\Psi, n, 0, e_{-j}) = 0$ for all $e_{-j} \in [0,1]$, we can, without loss of generality, assume that each vendor receiving an offer from the manufacturer accepts that offer. Thus, the effort choice for each vendor $e_j^*(\Psi, n) = e^*(\Psi, n) \in [0,1]$ is given as the solution for the following fixed-point problem:

$$e^*(\Psi, n) := \underset{e_j \in [0,1]}{\arg\max}\ \mathcal{V}(\Psi, n, e_j, e^*(\Psi, n)) \tag{6}$$

The manufacturer anticipates vendor effort choices. Therefore, independence of vendor defects implies that the manufacturer's expected utility is given by:

$$\mathcal{M}(P, s, \Psi, n) = \underbrace{\Big(1-\rho(e^*(\Psi, n))\Big)^n}_{\text{No Defect Probability}} \times \underbrace{U\Big((P-\Psi)\cdot s\Big)}_{\text{Utility If No Defect}} \tag{7}$$

where $s \geq 0$ denotes consumer demand for the manufacturer and $U(x)$ is given by (1).

Recall that the manufacturer first sets the price P she charges consumers. Then, observing consumer demand, she selects the number of vendors n to transact with, and the price she offers those vendors. Therefore, the number of vendors $n^*(P)$ and the price $\Psi^*(P)$ she offers these vendors are given by:

$$(\Psi^*(P), n^*(P)) := \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}(P, s, \Psi, n) = \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}(P, 1, \Psi, n) \tag{8}$$

where her choices are optimal conditional on all relevant and available information and thus depend upon the price she previously set for the consumer, $P \geq 0$. The equality in (8) follows from the fact that for CRRA functions U we have that $\underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}(P, 1, \Psi, n) = \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}(P, s, \Psi, n)$ holds for all $s > 0$. Thus, it follows that optimal $(\Psi^*(P), n^*(P))$ are independent of the consumer demand s.

The consumer base size s is determined endogenously. Specifically, consumers make purchase decisions based on the manufacturer prices and observed signals. Recall that consumer $k \in [0, 1]$ receives utility V_k if she purchases from the manufacturer but her knowledge of V_k is imperfect and depends upon a signal, $\tilde{q}_k$ along with her own type, (v_k, t_k). Consequently, her expected pay-off for purchasing from the manufacturer is:

$$\mathcal{C}(P, v_k, t_k, \tilde{q}_k) = \underbrace{\Big(1 - \rho(e^*(P))\Big)^{n^*(P)}}_{\text{No Defect Probability}} \times \underbrace{\mathbb{E}[\ V_k - P \mid v_k, t_k, \tilde{q}_k\ ]}_{\text{Conditional Expected Utility If No Defect}} \tag{9}$$

where the expectation is taken over the manufacturer's type q and:

$$e^*(P) := e^*(\Psi^*(P), n^*(P)) \tag{10}$$

Recall that the consumer possesses an outside option which we normalize to zero. Consequently, consumer k purchases from the manufacturer if and only if $\mathcal{C}(P, v_k, t_k, \tilde{q}_k) > 0$, and thus the equilibrium consumer demand for the manufacturer, $s^*(P)$, is given by:

$$s^*(P) := \mu(\{k : \mathcal{C}(P, v_k, t_k, \tilde{q}_k) > 0\}) \tag{11}$$

with $\mu(S)$ denoting the measure of a set $S \subseteq [0, 1]$ of consumers.

Finally, the manufacturer anticipates all future actions and therefore sets her price for consumers, P^*, according to:

$$P^* = \underset{P \geq 0}{\arg\max}\ \mathcal{M}(P) \tag{12}$$

where

$$\mathcal{M}(P) := \mathcal{M}(P, s^*(P), \Psi^*(P), n^*(P)) \tag{13}$$

Note that (6), (8), (11) and (12) provide equilibrium conditions for optimal behavior conditional on arbitrary behavior beforehand. More formally, the solution to these equations correspond to a subgame perfect Nash equilibrium in which agents behave optimally in a subgame even if that subgame is not on the equilibrium path of play. To ease the discussion of our results in Section 3, we denote all actions on the equilibrium path of play when blockchain is not adopted as follows:

$$e^* := e^*(P^*) \qquad \Psi^* := \Psi^*(P^*) \qquad n^* := n^*(P^*) \qquad s^* := s^*(P^*) \tag{14}$$

2.3 Subgame Arising from Blockchain Adoption

Since the blockchain enables the manufacturer to trace defects to the offending vendor, a generic vendor's objective function is not given by (5) when adoption occurs. Rather, vendor j's per unit expected profit is given by:

$$\mathcal{V}^{\mathcal{B}}(\Psi, n, e_j, e_{-j}) = (1 - \rho(e_j)) \cdot \Psi - \frac{e_j}{2} \tag{15}$$

where $\rho(e_j)$ corresponds to both the probability that vendor j's batch is defective and the probability that vendor j's batch is recalled. Recall that blockchain enables the manufacturer to trace defects to the offending vendor so that vendor j's batch is recalled if and only if it is defective. In turn, the symmetric vendor effort choice, $e^{**}(\Psi, n) \in [0, 1]$, is given by:

$$e^{**}(\Psi, n) := \underset{e_j \in [0,1]}{\arg\max}\ \mathcal{V}^{\mathcal{B}}(\Psi, n, e_j, e^{**}(\Psi, n)) \tag{16}$$

Note that we use the superscript ** to denote choices in the subgame arising from blockchain being adopted. This distinguishes such choices from those in the subgame arising from blockchain not being adopted. Recall, from Section 2.2, that we designated the latter with a superscript *.

Blockchain adoption entails an implementation cost, $\chi > 0$. Accordingly, when blockchain is adopted, the manufacturer's expected utility is given by:

$$\mathcal{M}^{\mathcal{B}}(P, s, \Psi, n) = \mathbb{E}[\ U\Big((P - \Psi) \cdot \frac{s}{n} \cdot N_s\Big)\ ] - \chi \tag{17}$$

with N_s denoting the number of batches that were *not* defective. Note the random variable N_s that defines the demand when $a = 1$ satisfies $N_s \sim \text{Binomial}(n, 1 - \rho(e^{**}(\Psi)))$ with $e^{**}(\Psi) := e^{**}(\Psi, 1) = e^{**}(\Psi, n)$, where the equality follows from (16), and the definition of $\mathcal{V}^{\mathcal{B}}$ in (15).

In turn, the number of vendors $n^{**}(P)$ who receive an offer, and the offered price $\Psi^{**}(P)$ are given by:

$$(\Psi^{**}(P), n^{**}(P)) := \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}^{\mathcal{B}}(P, s, \Psi, n) = \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}^{\mathcal{B}}(P, 1, \Psi, n), \tag{18}$$

where the last equality follows for all s because the manufacturer utility U is CRRA.

Recall that blockchain adoption affects consumer demand by improving the accuracy of consumer signals (see (4)). Accordingly, consumer k's expected utility of purchasing from the manufacturer is:

$$\mathcal{C}^{\mathcal{B}}(P, v_k, t_k, \tilde{q}_k) = \Big(1 - \rho(e^{**}(P))\Big) \times \mathbb{E}[\ V_k - P \mid v_k, t_k, \tilde{q}_k\ ] \tag{19}$$

where the expectation is taken over the manufacturer's type q and:

$$e^{**}(P) := e^{**}(\Psi^{**}(P), n^{**}(P)) \tag{20}$$

Consumer k purchases from a manufacturer if and only if $\mathcal{C}^{\mathcal{B}}(P, v_k, t_k, \tilde{q}_k) > 0$. Consequently, consumer demand for the manufacturer, $s^{**}(P)$, is given by:

$$s^{**}(P) = \mu(\{k : \mathcal{C}^{\mathcal{B}}(P, v_k, t_k, \tilde{q}_k) > 0\}) \tag{21}$$

The manufacturer anticipates all future actions when setting her price for consumers and deciding whether to adopt blockchain. Consequently, the consumer price when blockchain is adopted,

P^{**} is given explicitly by:

$$P^{**} = \arg\max_{P \geq 0} \mathcal{M}^{\mathcal{B}}(P) \tag{22}$$

where

$$\mathcal{M}^{\mathcal{B}}(P) := \mathcal{M}^{\mathcal{B}}(P, s^{**}(P), \Psi^{**}(P), n^{**}(P)) \tag{23}$$

Note that (16), (18), (21) and (22) provide equilibrium conditions for optimal behavior conditional on arbitrary behavior beforehand. More formally, the solution to these equations correspond to a subgame perfect Nash equilibrium in which agents behave optimally in a subgame even if that subgame is not on the equilibrium path of play. To ease the discussion of our results in Section 3, we denote all actions on the equilibrium path of play if blockchain is adopted as follows:

$$e^{**} := e^{**}(P^{**}) \qquad \Psi^{**} := \Psi^{**}(P^{**}) \qquad n^{**} := n^{**}(P^{**}) \qquad s^{**} := s^{**}(P^{**}) \tag{24}$$

2.4 Model Solution

We solve for the subgame perfect Nash equilibrium both in the case that blockchain is not adopted (Proposition A.1) and in the case that blockchain is adopted (Proposition A.2). We then employ those results to derive the endogenous blockchain adoption decision (Proposition 2.3). For exposition, we state only solutions on the equilibrium path of play in this section (Corollaries 2.1 and 2.2) and relegate the exhaustive subgame perfect equilibrium solution to Appendix A (Propositions A.1 and A.2).

Corollary 2.1, which follows from Proposition A.1, provides solutions on the equilibrium path of play if blockchain is not adopted:

Corollary 2.1. ***Equilibrium Actions In The Absence Of Blockchain***

I. *Each vendor's effort choice is given by* $e^* = \left(\frac{(2\alpha-1)H}{3-2\gamma}\right)^2$.

II. *The number of vendors from which the manufacturer buys, and the price that she offers those vendors, are given by* $\Psi^* = \frac{(2\alpha-1)H}{3-2\gamma}$ *and* $n^* = 1$.

III. *Consumer demand for the manufacturer is given by* $s^* = \frac{1-\gamma}{6-4\gamma}$.

IV. The manufacturer price for consumers is given by $P^{*} = \frac{2-\gamma}{3-2\gamma}(2\alpha - 1)H$.

In contrast, Corollary 2.2, which follows from Proposition A.2, provides solutions on the equilibrium path of play when blockchain is adopted:

Corollary 2.2. ***Equilibrium Actions When Blockchain Is Adopted***

I. Each vendor's effort choice is given by $e^{**} = \left(\frac{(2(\alpha+\delta)-1)H}{3}\right)^{2}$.

II. The number of vendors from which the manufacturer buys, and the price that she offers those vendors, are given by $\Psi^{**} = \frac{(2(\alpha+\delta)-1)H}{3}$ *and* $n^{**} = \infty$.

III. Consumer demand for the manufacturer is given by $s^{**} = \frac{1}{6}$.

IV. The manufacturer price for consumers is given by $P^{**} = \frac{2}{3}(2(\alpha + \delta) - 1)H$.

The manufacturer anticipates outcomes arising from her adoption decision so that she adopts blockchain if and only if it enhances her overall utility:

$$\mathcal{M}^{\mathcal{B}}(P^{**}) \geq \mathcal{M}(P^{*}) \tag{25}$$

Let Π^{**} denote the profit of the manufacturer (excluding the adoption cost) when she adopts blockchain and Π^{*} denote the profit of the manufacturer when she does not adopt blockchain. Then, the latter condition is equivalent to requiring that the incremental utility $\Omega := \mathbb{E}[U(\Pi^{**})] - \mathbb{E}[U(\Pi^{*})]$ associated with manufacturer profits exceeds the manufacturer's adoption cost, χ. More formally, the following equivalence holds.

$$\mathcal{M}^{\mathcal{B}}(P^{**}) \geq \mathcal{M}(P^{*}) \Longleftrightarrow \Omega \geq \chi. \tag{26}$$

and thus, we have the following result.

Proposition 2.3. ***Endogenous Adoption Decision***

In equilibrium, the manufacturer adopts the blockchain if the incremental utility $\Omega := \mathbb{E}[U(\Pi^{**})] -$

$\mathbb{E}[U(\Pi^*)] \geq \chi$. *Moreover, Ω is given explicitly by*

$$\Omega = \frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{(1-\gamma)54^{1-\gamma}} - \frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma}$$

3 Blockchain Adoption and Manufacturer Welfare

Our first result establishes that blockchain adoption always increases manufacturer welfare when adoption costs are zero. As a consequence, blockchain adoption is generic for sufficiently small adoption costs:

Proposition 3.1. ***Blockchain Adoption in Equilibrium***
The manufacturer's incremental utility from blockchain adoption due to a change in profits, $\Omega := \mathbb{E}[U(\Pi^{**})] - \mathbb{E}[U(\Pi^*)]$, *is always strictly positive (i.e.,* $\Omega > 0$*). Consequently, blockchain adoption arises in equilibrium when* $0 < \chi \leq \Omega$.

We emphasize that the finding of Proposition 3.1, $\Omega > 0$, does not apply to arbitrary market settings. More precisely, Iyengar et al. (2022) demonstrate that $\Omega = 0$ when the manufacturing sector is competitive, and thus, blockchain adoption does not arise in equilibrium in that setting. To better understand how blockchain adoption arises in our setting, define

$$\Phi := U(\mathbb{E}[\Pi^{**}]) - U(\mathbb{E}[\Pi^*]) \tag{27}$$

Recall that Π^* denotes the manufacturer profit in the absence of blockchain and Π^{**} denotes the manufacturer profit (excluding the adoption cost) in the presence of blockchain. Thus, Φ corresponds to the incremental utility gain due to endogenous changes in the manufacturer's *expected* profit. In Section 3.2, we establish that $\Phi > 0$. Let

$$\Sigma := \Omega - \Phi. \tag{28}$$

Then, by definition, $\Phi + \Sigma = \Omega$, and Σ corresponds to incremental utility gain due to the reduction in the risk of the manufacturer's random profit. In Section 3.1 we establish that $\Sigma > 0$. Thus, establishing that the incremental gain Ω results from a strictly positive increase in the manufacturer's expected profit and a strictly positive reduction in the manufacturer's risk. We also discuss the underlying economic channels that generate Σ and Φ (i.e., manufacturer risk aversion and consumer information asymmetry).

3.1 Manufacturer Profit Risk Reduction Σ

The information on the blockchain results in the manufacturer endogenously diversifying across *all* vendors, and thereby, driving the variance of the profit to zero. Since the manufacturer is risk averse, the aforementioned reduced risk increases her utility and thereby enables blockchain adoption for sufficiently small adoption costs. We formalize this insight in the following result:

Proposition 3.2. ***Manufacturer Diversification Benefits***

Let $\Phi := U(\mathbb{E}[\Pi^{**}]) - U(\mathbb{E}[\Pi^{*}])$ *and* $\Sigma := \Omega - \Phi$. *Then the following results hold:*

1. *Blockchain Endogenously Generates Vendor Diversification*

   $n^{**} = \infty > n^{*} = 1.$

2. *Blockchain Endogenously Generates Reduction In Profit Variance*

   $Var[\Pi^{**}] = 0 < Var[\Pi^{*}]$

3. *Diversification Benefits Are Always Strictly Positive But Vanish Without Risk Aversion*

   $\Sigma > 0$ *but* $\lim_{\gamma \to 0^{+}} \Sigma = 0$

Proposition 3.2.1 establishes that the presence of the blockchain results in the manufacturer changing from purchasing from a single vendor (i.e., $n^{*} = 1$) to purchasing from infinitely many vendors (i.e., $n^{**} = \infty$). This effect arises endogenously because the blockchain enables the manufacturer to trace a defective item to the responsible vendor, thereby, allowing a targeted recall of only defective items. Without blockchain, the manufacturer cannot trace defective items and thus recalls all items whenever a single defect is detected. As a consequence, without blockchain, the manufacturer endogenously specializes to a single vendor ($n^* = 1$) in order to reduce the recall probability. In contrast, with blockchain, only defective items are recalled even when the manufacturer purchases from multiple vendors. Thus, since purchasing from many vendors does not increase recall probabilities but does reduce risk, the manufacturer optimally diversifies away all recall risks by splitting her order over infinitely many vendors (i.e., $n^{**} = \infty$).

Since consumers are infinitesimal, the manufacturer faces no aggregate risk from consumer demand. Rather, the manufacturer's profit variance arises entirely from the risk of vendor defects, which implies a distribution for the number of recalled goods, and thus, a distribution for profit. Since, the manufacturer splits her order over infinitely many vendors when blockchain is adopted, the distribution of defective goods received from vendors becomes degenerate, and thus, so too does the distribution of the number of recalled goods. In turn, in the presence of blockchain, the manufacturer profit also becomes degenerate, and she therefore incurs no profit variance (i.e., $Var[\Pi^{**}] = 0$). In contrast, without blockchain, the manufacturer orders from a single vendor, and she is, therefore, exposed to the risk that her chosen vendor sends her a defective batch (i.e., $Var[\Pi^*] > 0$). Proposition 3.2.2 formalizes this.

The manufacturer always gains from the discussed risk reduction (i.e., $\Sigma > 0$) because the manufacturer is risk averse (i.e., $\gamma > 0$). In fact, the manufacturer's gain due to risk reduction vanishes without risk aversion (i.e., $\lim_{\gamma \to 0^+} \Sigma = 0$), as demonstrated by Proposition 3.2.3.

3.2 Manufacturer Expected Profit Gains Φ

Blockchain adoption not only reduces the manufacturer's risk but also increases the manufacturer's expected profit. The increase in expected profits arises endogenously due to the manufacturer's risk aversion (i.e., $\gamma > 0$) and the blockchain's ability to ameliorate consumer information asymmetry (i.e., $\delta > 0$). We clarify these findings with our next result:

Proposition 3.3. ***Expected Profit Gains***

Let $\Phi := U(\mathbb{E}[\Pi^{**}]) - U(\mathbb{E}[\Pi^*])$*. Then, the following results hold:*

1. *Blockchain Endogenously Enhances Expected Profits*

   $\mathbb{E}[\Pi^{**}] > \mathbb{E}[\Pi^*]$ *and thus* $\Phi > 0$

2. *Expected Profit Gains Vanish Without Risk Aversion And Without Information Asymmetry Reduction*

$$\lim_{\gamma,\delta\to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^{*}]} = 1 \text{ and thus } \lim_{\gamma,\delta\to 0^+} \Phi = 0$$

3. *Expected Profit Gains Do Not Vanish With Risk Aversion But Without Information Asymmetry Reduction*

For fixed $\gamma > 0 : \lim_{\delta\to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^{*}]} > 1$ *and thus* $\lim_{\delta\to 0^+} \Phi > 0$

4. *Expected Profit Gains Do Not Vanish Without Risk Aversion But With Information Asymmetry Reduction*

For fixed $\delta > 0 : \lim_{\gamma\to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^{*}]} > 1$ *and thus* $\lim_{\gamma\to 0^+} \Phi > 0$

Proposition 3.3.1 establishes that the manufacturer's expected profit always increases with blockchain adoption so that $\Phi > 0$. This increase in expected profits under blockchain adoption arises due to two factors: the manufacturer's risk aversion (i.e., $\gamma > 0$), and the blockchain reducing information asymmetry (i.e., $\delta > 0$). Propositions 3.3.2 - 3.3.4 formalize that point, establishing that the two factors are jointly necessary and separately sufficient for blockchain adoption to generate increased expected profit for the manufacturer.

The following result further elaborates on how the manufacturer's risk aversion $\gamma > 0$, and the information asymmetry reduction $\delta > 0$ interact to generate increased expected profits from blockchain adoption.

Proposition 3.4. ***Determinants of Increased Expected Profits***

The manufacturer's expected profit in the presence of blockchain is given as follows:

$$\mathbb{E}[\Pi^{**}] = f_{\Pi}(\gamma) \cdot g_{\Pi}(\alpha, \delta) \cdot \mathbb{E}[\Pi^{*}]$$

where $f_{\Pi}(\gamma)$ *and* $g_{\Pi}(\alpha, \delta)$ *separate the effect of manufacturer risk aversion,* $\gamma > 0$*, from that of the information asymmetry reduction,* $\delta > 0$*. More explicitly:*

$$f_{\Pi}(\gamma) = \frac{1}{27}\frac{(3-2\gamma)^3}{(1-\gamma)^2}, \qquad g_{\Pi}(\alpha, \delta) = (1 + \frac{2\delta}{2\alpha-1})^2$$

Moreover, the following results hold:

1. *Manufacturer Risk Aversion Puts Upward Pressure On Expected Profits*

$f_{\Pi}(\gamma) > 1$ *and* $\frac{df_{\Pi}}{d\gamma} > 0$

2. *Information Asymmetry Reduction Puts Upward Pressure On Expected Profits*

$g_\Pi(\alpha, \delta) > 1$ *and* $\frac{\partial g_\Pi}{\partial \delta} > 0$

Proposition 3.4 establishes that the proportional change in the manufacturer's expected profits with and without blockchain, $\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^{*}]}$, decomposes into two multiplicative terms: $f_\Pi(\gamma)$ and $g_\Pi(\alpha, \delta)$. Those two multiplicative terms separate the effects of the manufacturer's risk aversion γ and the information asymmetry reduction δ. Note that $f_\Pi(\gamma) \cdot g_\Pi(\alpha, \delta) > 1$ is equivalent to $\mathbb{E}[\Pi^{**}] > \mathbb{E}[\Pi^{*}]$ so that $f_\Pi(\gamma) \cdot g_\Pi(\alpha, \delta) > 1$ implies that blockchain adoption increases expected profits. Next, we consider the study the effects of the manufacturer's risk aversion γ and the information asymmetry reduction δ separately. Since $f_\Pi(0) = g_\Pi(\alpha, 0) = 1$, $\mathbb{E}[\Pi^{**}] = f_\Pi(\gamma) \cdot \mathbb{E}[\Pi^{*}]$ when there is no information asymmetry reduction $\delta = 0$, and $\mathbb{E}[\Pi^{**}] = g_\Pi(\alpha, \delta) \cdot \mathbb{E}[\Pi^{*}]$ when the manufacturer is risk neutral i.e., $\gamma = 0$. Consequently, in examining each factor separately, we say that the manufacturer's risk aversion puts upward (downward) pressure on expected profits in the presence of blockchain if $f_\Pi(\gamma) > 1$ ($f_\Pi(\gamma) < 1$). Similarly, we say that the reduction in information asymmetry puts upward (downward) pressure on expected profits in the presence of blockchain if $g(\alpha, \delta) > 1$ ($g(\alpha, \delta) < 1$). In that context, Proposition 3.4 establishes that both the manufacturer's risk aversion, γ, and the reduction in information asymmetry, δ, put upward pressure on expected profits in the presence of blockchain. Additionally, this upward pressure augments as manufacturer risk aversion increases (i.e., $\frac{df_\Pi}{d\gamma} > 0$) and as information asymmetry reduction increases (i.e., $\frac{\partial g_\Pi}{\partial \delta} > 0$).

While the manufacturer's risk aversion and the reduction of information asymmetry both lead to higher expected profits for the manufacturer when blockchain is adopted, these channels operate in qualitatively different ways. We clarify that point with the following result:

Proposition 3.5. ***Consumer Demand and Consumer Prices***

Consumer demand in the presence of blockchain is given as follows:

$$s^{**} = f_s(\gamma) \cdot s^{*}, \quad \textit{with:} \quad f_s(\gamma) = \frac{3 - 2\gamma}{3 - 3\gamma}.$$

Additionally, the consumer price in the presence of blockchain is given as follows:

$$P^{**} = f_P(\gamma) \cdot g_P(\alpha, \delta) \cdot P^*.$$

where $f_P(\gamma)$ *and* $g_P(\alpha, \delta)$ *separate the effect of manufacturer risk aversion,* $\gamma > 0$*, from that of the information asymmetry reduction,* $\delta > 0$*. More explicitly:*

$$f_P(\gamma) = \frac{6 - 4\gamma}{6 - 3\gamma}, \qquad g_P(\alpha, \delta) = 1 + \frac{2\delta}{2\alpha - 1}.$$

Moreover, the following results hold:

1. *Blockchain Adoption Increases Demand But Has An Ambiguous Effect on Prices*

   For all $\gamma, \delta : s^{**} > s^*$ *but there exist* $\gamma, \delta : P^{**} < P^*$ *and there exist* $\gamma, \delta : P^{**} > P^*$*.*

2. *Risk Aversion Pressures Demand Upward But Prices Downward*

   $f_s(\gamma) > 1$ *and* $\frac{df_s}{d\gamma} > 0$*, but* $f_P(\gamma) < 1$ *and* $\frac{df_P}{d\gamma} < 0$*.*

3. *Information Asymmetry Reduction Pressures Prices Upward*

   For all $\alpha : g_P(\alpha, \delta) > 1$ *and* $\frac{\partial g_P}{\partial \delta} > 0$*, but* $\frac{s^{**}}{s^*}$ *is independent of* δ*.*

Proposition 3.5.1 establishes that blockchain adoption increases consumer demand (i.e., $s^{**} > s^*$) but has an ambiguous effect on the consumer price (i.e., there exist $\gamma, \delta : P^{**} < P^*$ yet there exist $\gamma, \delta : P^{**} > P^*$). Propositions 3.5.2 and 3.5.3 clarify these findings, explaining how the manufacturer's risk aversion and the information asymmetry reduction generate the results. In particular, the manufacturer's risk aversion puts upward pressure on consumer demand when blockchain is adopted (i.e., $f_s(\gamma) > 1$) while information asymmetry reduction does not affect consumer demand when blockchain is adopted (i.e., $\frac{s^{**}}{s^*}$ does not depend upon δ); thus, as noted, blockchain adoption unambiguously increases consumer demand. In contrast, manufacturer risk aversion and information asymmetry reduction have opposing effects on the consumer price, which explains the aforementioned ambiguous effect of blockchain adoption on the consumer price.

The impact of the risk aversion effect is mediated by the risk associated with a recall and, when the manufacturer is exposed to such risk, she compensates by selling to fewer consumers, which reduces her overall profit risk. Recall that, as discussed in Section 3.1, the manufacturer faces a recall risk only in the absence of blockchain because the blockchain enables the manufacturer to achieve zero profit variance. Consequently, by removing the recall risk, blockchain adoption leads the manufacturer to increase her sales volume, which equals consumer demand in equilibrium. Since the manufacturer has market power, the manufacturer's consumer price determines consumer demand. In turn, a higher consumer demand necessarily entails a lower consumer price. Thus, as per Proposition 3.5.2, risk aversion puts upward pressure on consumer demand but downward pressure on the consumer price.

The reduction in information asymmetry increases demand because it increases each consumer's utility from purchasing the manufacturer's good. The manufacturer reacts to this increased consumer utility by raising the consumer price to extract some of the consumer's increased utility. Note that, since the increased consumer utility results in an upward shift in the consumer demand curve, an increase in the consumer price need not accompany a decrease in consumer demand. More formally, from Proposition A.2, the endogenous consumer demand curve in the presence of blockchain is given as follows:

$$s^{**}(P) = \frac{1}{2}\Big(1 - \frac{P}{(2(\alpha+\delta)-1)H}\Big) \tag{29}$$

Note that a reduction in information asymmetry shifts the entire consumer demand curve upward (i.e., for all $P : \frac{\partial s^{**}}{\partial \delta} > 0$). Thus, it is possible for blockchain adoption to generate a higher consumer price without decreasing consumer demand. In fact, when blockchain is adopted, our results highlight that the partial effect of the information asymmetry reduction upon the manufacturer is that the manufacturer increases her consumer price to the exact level of consumer demand without blockchain (i.e., $\frac{s^{**}}{s^{*}}$ does not depend upon δ, but $g_P(\alpha, \delta) > 1$).

The described effects for the manufacturer's risk aversion and the reduction in information asymmetry become more pronounced if the manufacturer is more risk averse or if the reduction in information asymmetry is larger respectively. More formally, Proposition 3.5.2 demonstrates that higher risk aversion levels generate higher upward pressure on consumer demand when blockchain is adopted (i.e., $\frac{df_s}{d\gamma} > 0$) and higher downward pressure on the consumer price when blockchain is adopted (i.e., $\frac{df_P}{d\gamma} < 0$). Additionally, Proposition 3.5.3 establishes that a higher information asymmetry reduction leads to higher upward pressure on the consumer price when blockchain is adopted (i.e., $\frac{\partial g_P}{\partial \delta} > 0$).

4 Vendor and Consumer Welfare

Both vendors and consumers are affected by blockchain adoption. We discuss the welfare implications for each in Sections 4.1 and 4.2 respectively.

4.1 Vendor Welfare

We find that blockchain adoption has an ambiguous effect upon vendor welfare. More formally, we define W_V^* and W_V^{**} as follows:

$$W_V^* = \mathcal{V}(\Psi^*, n^*, e^*, e^*) \cdot s^*, \qquad W_V^{**} = \mathcal{V}^{\mathcal{B}}(\Psi^{**}, n^{**}, e^{**}, e^{**}) \cdot s^{**} \tag{30}$$

Recall that $\mathcal{V}$ corresponds to per unit vendor profit in the presence of blockchain, whereas $\mathcal{V}^{\mathcal{B}}$ corresponds to per unit vendor profit in the presence of blockchain. Then, since overall vendor sales equals consumer demand in equilibrium, W_V^* therefore denotes vendor welfare in the absence of blockchain and W_V^{**} denotes vendor welfare when blockchain is adopted. We relate W_V^* and W_V^{**} via the following result:

Proposition 4.1. ***Vendor Welfare***

Vendor welfare W_V depends on the price Ψ paid to vendors by manufacturers and consumer demand s as follows:

$$W_V^* = \frac{(\Psi^*)^2 \cdot s^*}{2}, \qquad W_V^{**} = \frac{(\Psi^{**})^2 \cdot s^{**}}{2}.$$

Consequently, vendor welfare in the presence of blockchain is given as follows:

$$W_V^{**} = \left(\frac{\Psi^{**}}{\Psi^*}\right)^2 \cdot \frac{s^{**}}{s^*} \cdot W_V^*.$$

and blockchain adoption has an ambiguous effect upon vendor welfare (i.e., there exist $\gamma, \delta : W_V^{**} < W_V^*$ *and there exist* $\gamma, \delta : W_V^{**} > W_V^*$*).*

Proposition 4.1 establishes that vendor welfare depends positively upon both the price Ψ paid to vendors and consumer demand s. As we discuss subsequently, the effect of blockchain adoption upon the vendor price is ambiguous because blockchain adoption can increase or decrease the vendor price; in turn, blockchain adoption has an ambiguous effect upon vendor welfare despite the fact that blockchain adoption unambiguously increases consumer demand (see Proposition 3.5).

The effect of blockchain adoption upon the vendor price is summarized by the following result:

Proposition 4.2. ***Vendor Price***

The vendor price in the presence of blockchain is given as follows:

$$\Psi^{**} = f_\Psi(\gamma) \cdot g_\Psi(\alpha, \delta) \cdot \Psi^*$$

where $f_\Psi(\gamma)$ *and* $g_\Psi(\alpha, \delta)$ *separate the effect of manufacturer risk aversion,* $\gamma > 0$*, from that of the information asymmetry reduction,* $\delta > 0$*. More explicitly:*

$$f_\Psi(\gamma) = \frac{3 - 2\gamma}{3}, \qquad g_\Psi(\alpha, \delta) = 1 + \frac{2\delta}{2\alpha - 1}$$

Moreover, the following results hold:

1. *Blockchain Adoption Has An Ambiguous Effect on Vendor Price*

   There exist $\gamma, \delta : \Psi^{**} < \Psi^*$ *and there exist* $\gamma, \delta : \Psi^{**} > \Psi^*$

2. *Risk Aversion Pressures Vendor Price Downward*

   $f_\Psi(\gamma) < 1$ *and* $\frac{df_\Psi}{d\gamma} < 0$

3. *Information Asymmetry Reduction Pressures Vendor Price Upward*

$g_\Psi(\alpha, \delta) > 1$ *and* $\frac{\partial g_\Psi}{\partial \delta} > 0$

Proposition 4.2.1 highlights that blockchain adoption has an ambiguous effect on the vendor price. This ambiguity arises because the manufacturer's risk aversion and information asymmetry reduction have opposing affects. In particular, Proposition 4.2.2 demonstrates that the former exerts downward pressure (i.e., $f_\Psi(\gamma) < 1$), whereas Proposition 4.2.3 demonstrates that the latter exerts upward pressure (i.e., $g_\Psi(\alpha, \delta) > 1$). Moreover, the referenced effects amplify as risk aversion and information asymmetry reduction increase respectively (i.e., $\frac{df_\Psi}{d\gamma} < 0$ and $\frac{\partial g_\Psi}{\partial \delta} > 0$).

The following result clarifies the impact of the manufacturer's risk aversion and the information asymmetry reduction on the vendor price:

Proposition 4.3. ***Vendor Price and Consumer Price***

The vendor price and consumer price are related as follows:

$$\Psi^* = h(\gamma) \cdot P^*, \qquad \Psi^{**} = h(0) \cdot P^{**}$$

whereas the vendor effort level is given as follows:

$$e^* = (\Psi^*)^2 = (h(\gamma) \cdot P^*)^2, \qquad e^{**} = (\Psi^{**})^2 = (h(0) \cdot P^{**})^2$$

where

$$h(\gamma) = \frac{1}{2 - \gamma}$$

Note that $\frac{dh}{d\gamma} > 0$ *so that* $0 < h(0) < h(\gamma) \leq 1$.

Proposition 4.3 establishes that the manufacturer passes through a positive fraction of the consumer price to the vendor (i.e., $\frac{\Psi^*}{P^*} = h(\gamma) \in [0, 1]$ and $\frac{\Psi^{**}}{P^{**}} = h(0) \in [0, 1]$). This relationship arises because the manufacturer's forfeited revenue due to a defect is proportional to the consumer price and thus an increase in the consumer price leads the manufacturer to increase her vendor price in order to increase vendor effort and reduce the probability of forfeiting the associated revenue.

Proposition 4.3 formalizes this, and shows that the vendor price increases in the consumer price and that optimal vendor effort also increases in the vendor price.

Note that the relative fraction which the manufacturer passes through to the vendor with and without blockchain is given by $\frac{h(0)}{h(\gamma)}$. Then, Proposition 3.5, together with Proposition 4.3, implies that the vendor price in the presence of blockchain can be written as follows:

$$\Psi^{**} = \frac{h(0)}{h(\gamma)} \cdot \frac{P^{**}}{P^{*}} \cdot \Psi^{*} = \underbrace{\frac{h(0)}{h(\gamma)} \cdot f_P(\gamma)}_{\text{Effect of } \gamma} \cdot \underbrace{g_P(\alpha, \delta)}_{\text{Effect of } \delta} \cdot \Psi^{*} \tag{31}$$

Thus, (31) shows that the impact of information asymmetry reduction on the vendor price due to blockchain adoption is mediated by its impact on consumer price. In particular, since information asymmetry reduction pressures the consumer price upward when blockchain is adopted (i.e. , $g_P(\alpha, \delta) > 1$), it also pressures the vendor price upward when blockchain is adopted.

The impact of the manufacturer's risk aversion on the vendor price arises for two reasons. First, manufacturer risk aversion puts downward pressure on the consumer price when blockchain is adopted (i.e., $f_P(\gamma) < 1$), and this effect is passed through to the vendor price. Second, manufacturer risk aversion reduces the relative fraction that the manufacturer passes through to the vendor from $h(\gamma)$ to $h(0)$ when the blockchain is adopted because the manufacturer does not face recall risk when blockchain is adopted, and thus, has a weaker incentive to induce higher vendor effort as compared to the case without blockchain. Since these effects both pressure the vendor price downward, the cumulative effect is that manufacturer risk aversion puts downward pressure on the vendor price when blockchain is adopted as per Proposition 4.2.2.

4.2 Consumer Welfare

We find that blockchain adoption unambiguously improves consumer welfare. More formally, we define W_C^* and W_C^{**} as follows:

$$W_C^* = \int_{k:\mathcal{C}_k^*>0} \mathcal{C}_k^* \, d\mu, \qquad W_C^{**} = \int_{k:\mathcal{C}_k^{**}>0} \mathcal{C}_k^{**} \, d\mu \tag{32}$$

where

$$C_k^* := \mathcal{C}(P^*, v_k, t_k, \tilde{q}_k), \qquad C_k^{**} := \mathcal{C}^{\mathcal{B}}(P^{**}, v_k, t_k, \tilde{q}_k) \tag{33}$$

so that C_k^* denotes the equilibrium utility of consumer k if she purchases from the manufacturer in the absence of blockchain and C_k^{**} denotes the equilibrium utility of consumer k if she purchases from the manufacturer when blockchain is adopted. In turn, since μ denotes the measure over consumers and since consumers have access to an outside option that gives utility zero, W_C^* therefore denotes consumer welfare in the absence of blockchain and W_C^{**} denotes consumer welfare when blockchain is adopted. We relate W_C^* and W_C^{**} via the following result:

Proposition 4.4. ***Consumer Welfare***

Consumer welfare, W_C, in the presence of blockchain is given as follows:

$$W_C^{**} = f_{W_C}(\gamma) \cdot g_{W_C}(\alpha, \delta) \cdot W_C^*,$$

where $f_{W_C}(\gamma)$ and $g_{W_C}(\alpha, \delta)$ separate the effect of manufacturer risk aversion, $\gamma > 0$, from that of the information asymmetry reduction, $\delta > 0$. More explicitly:

$$f_{W_C}(\gamma) = \frac{(3-2\gamma)^3}{27(1-\gamma)^2}, \qquad g_{W_C}(\alpha, \delta) = (1 + \frac{2\delta}{2\alpha - 1})^2$$

Moreover, the following results hold:

1. *Blockchain Adoption Increases Consumer Welfare*
   $W_C^{**} > W_C^*$

2. *Risk Aversion Pressures Consumer Welfare Upward*
   $f_{W_C}(\gamma) > 1$ *and* $\frac{df_{W_C}}{d\gamma} > 0$

3. *Information Asymmetry Reduction Pressures Consumer Welfare Upward*
   $g_{W_C}(\alpha, \delta) > 1$ *and* $\frac{\partial g_{W_C}}{\partial \delta} > 0$

Proposition 4.4 establishes that consumer welfare unambiguously increases with blockchain adoption because of both the manufacturer's risk aversion, γ, and the information asymmetry reduction, δ. In particular, as per Propositions 4.4.2 and 4.4.3, both the manufacturer's risk aversion and the information asymmetry reduction put upward pressure on consumer welfare when blockchain is adopted (i.e., $f_{W_C}(\gamma) > 1$ and $g_{W_C}(\alpha, \delta) > 1$). Moreover, those effects augment with the manufacturer's risk aversion and the information asymmetry reduction respectively (i.e., $\frac{df_{W_C}}{d\gamma} > 0$ and $\frac{\partial g_{W_C}}{\partial \delta}$).

Consumer welfare increases due to the manufacturer's risk aversion when blockchain is adopted because, as discussed in Proposition 3.5.2, blockchain adoption leads a risk-averse manufacturer to lower her consumer price. The lower consumer price, in turn, enhances consumer welfare.

The information asymmetry reduction enhances consumer welfare when blockchain is adopted because it improves endogenous consumer decision-making. More precisely, when blockchain is adopted, consumer signals regarding the manufacturer's type become more accurate. In turn, consumer decision-making improves and thus consumer welfare increases.

5 Conclusion

Our analysis establishes that blockchain adoption can arise in equilibrium when entities facing the cost of adoption possess market power. In particular, this is the case when the manufacturer has the power to adjust prices, and thereby extract gains accrued to other supply chain participants. In turn, the extracted gains render implementation of blockchain incentive compatible for sufficiently small adoption costs and consequently lead to blockchain adoption in equilibrium. Our main result contrasts with that of Iyengar et al. (2022), which establishes that blockchain adoption does not arise in equilibrium when the manufacturing sector is competitive. Our work thus highlights market power as a crucial determinant of whether blockchain adoption arises.

Our results also highlight which economic channels drive blockchain adoption by the manufacturer. More explicitly, we find that both manufacturer risk aversion and consumer information asymmetry drive blockchain adoption. With regard to the former, blockchain enables the manufacturer to diversify across vendors and thereby reduce risk. This risk reduction enhances the manufacturer's welfare only if she is risk averse and thus the manufacturer's risk aversion serves as an incentive for the manufacturer to adopt blockchain. With regard to the latter, blockchain ameliorates consumer information asymmetry thereby increasing consumer welfare. The manufacturer responds optimally to the increased consumer welfare by increasing the consumer price and thus consumer information asymmetry in the absence of blockchain enhances the manufacturer's welfare in the presence of blockchain and serves as a second incentive for the manufacturer to adopt blockchain.

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Appendices

A Model Solution

In this section, we state the subgame perfect Nash equilibrium solution both when blockchain is not adopted and also when blockchain is adopted. Proofs for these results are also given in this section, directly afterward the statement of the respective proposition.

Proposition A.1. ***Solution when Blockchain is not Adopted***

I. Each vendor's effort choice is given as follows:

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

II. The number of vendors from which the manufacturer buys, and the price that she offers those vendors, are given as follows:

- $\Psi^*(P) = \begin{cases} \frac{P}{2-\gamma} & \text{if } P < 2-\gamma \\ 1 & \text{if } P \geq 2-\gamma \end{cases}$
- $n^*(P) = 1$

III. Consumer demand for the manufacturer is given by:

$$s^*(P) = \begin{cases} \frac{1}{2}\left(1 - \frac{P}{(2\alpha-1)H}\right) & \text{if } 1 - \frac{P}{(2\alpha-1)H} \geq 0 \\ 0 & \text{if } 1 - \frac{P}{(2\alpha-1)H} < 0 \end{cases}$$

IV. The manufacturer price for consumers is given as follows:

$P^* = \frac{2-\gamma}{3-2\gamma}(2\alpha - 1)H$

Proof of Proposition A.1.

I. Given Ψ and n, defined in (5) and (6), the effort choice for each vendor, e^*, is a solution for the following fixed-point problem:

$$\begin{aligned} e^* &= \underset{e_j \in [0,1]}{\arg\max}\ \mathcal{V}(\Psi, n, e_j, e^*) \\ &= \underset{e_j \in [0,1]}{\arg\max}\ \big(1 - \rho(e^*)\big)^{n-1} \cdot \big(1 - \rho(e_j)\big) \cdot \Psi - \frac{e_j}{2} \\ &= \underset{e_j \in [0,1]}{\arg\max}\ (e^*)^{\frac{n-1}{2}} \cdot e_j^{\frac{1}{2}} \cdot \Psi - \frac{e_j}{2}. \end{aligned}$$

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

When $n = 1$, $e^* = \min\{\Psi^2, 1\}$. When $n = 2$, $e^* = \min\{e^* \cdot \Psi^2, 1\}$; if $\Psi < 1$, the only solution is $e^* = 0$, and if $\Psi \geq 1$, two solutions are $e^* = 1$ and $e^* = 0$. When $n > 2$, $e^* = \min\{(e^*)^{n-1} \cdot \Psi^2, 1\}$; if $\Psi < 1$, the only solution is $e^* = 0$, and if $\Psi \geq 1$, two solutions are $e^* = \Psi^{-\frac{2}{n-2}}$ and $e^* = 0$ coming from solving $e^* = (e^*)^{n-1} \cdot \Psi^2$ and the other solution is $e^* = 1$. To conclude, we have that

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

II. With P and s, defined in (7) and (8), the number of vendors n^* and the price Ψ^* the manufacturer offers the vendors are given by:

$$\begin{aligned}
(\Psi^*, n^*) &= \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}(P, s, \Psi, n) \\
&= \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ \Big(1 - \rho(e^*(\Psi, n))\Big)^n \cdot \frac{\big((P-\Psi)\cdot s\big)^{1-\gamma}}{1-\gamma} \\
&= \underset{\Psi \geq 0, n \in \overline{\mathbb{N}}_+}{\arg\max}\ (e^*(\Psi, n))^{\frac{n}{2}} \cdot \frac{(P-\Psi)^{1-\gamma}}{1-\gamma}.
\end{aligned}$$

The last equality indicates that Ψ^* and n^* do not depend upon the consumer demand s.

If the manufacturer chooses a $\Psi < 1$, then $e^*(\Psi, n) = 0$ for any $n > 1$. Thus, $n^* = 1$ and

$$\begin{aligned}
\Psi_1^* &:= \underset{\Psi \in [0,1)}{\arg\max}\ \frac{\Psi \cdot (P-\Psi)^{1-\gamma}}{1-\gamma} \\
&= \begin{cases} \frac{P}{2-\gamma} & \text{if } P < 2-\gamma \\ 1^- & \text{if } P \geq 2-\gamma \end{cases}.
\end{aligned}$$

If the manufacturer chooses a $\Psi \geq 1$, then the value of $e^*(\Psi, n)$ is ambiguous by the result of part I. However, there always exists a n such that $e^*(\Psi, n) = 1$ attains the maximum. The manufacturer will select such a n as her n^*. Consequently,

$$\begin{aligned}
\Psi_2^* &:= \underset{\Psi \geq 1}{\arg\max}\ \frac{(P-\Psi)^{1-\gamma}}{1-\gamma} \\
&= 1.
\end{aligned}$$

Finally, the manufacturer chooses between Ψ_1^* and Ψ_2^* to maximize her expected utility. If $P \geq 2-\gamma$, then $\Psi^* = \Psi_1^* = \Psi_2^* = 1$. If $P < 1$, choosing Ψ_2^* results in a negative expected utility, so $\Psi^* = \Psi_1^*$. If $1 \leq P < 2-\gamma$, by the definition of Ψ_1^* and Ψ_2^*,

$$\frac{\Psi_1^* \cdot (P-\Psi_1^*)^{1-\gamma}}{1-\gamma} > \frac{1 \cdot (P-1)^{1-\gamma}}{1-\gamma} = \frac{(P-\Psi_2^*)^{1-\gamma}}{1-\gamma}.$$

Hence, the expected utility of choosing Ψ_1^* is greater than that of choosing Ψ_2^*, meaning

$\Psi^* = \Psi_1^*$. To conclude, we have that

$$\Psi^*(P) = \begin{cases} \frac{P}{2-\gamma} & \text{if } P < 2-\gamma \\ 1 & \text{if } P \geq 2-\gamma \end{cases}$$

and

$$n^*(P) = \begin{cases} 1 & \text{if } P < 2-\gamma \\ \text{ambiguous} & \text{if } P \geq 2-\gamma \end{cases}.$$

In part IV, we will see that the equilibrium price for consumers, P^*, is less than $2-\gamma$, so we actually do not need to deal with the ambiguous case.

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

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

For P given by (9), consumer k's expected payoff for purchasing from the manufacturer is:

$$\begin{aligned} \mathcal{C}(P, v_k, t_k, \tilde{q}_k) &= \Big(1 - \rho(e^*(P))\Big)^{n^*(P)} \cdot \mathbb{E}[V_k - P \mid v_k, t_k, \tilde{q}_k] \\ &= (e^*(P))^{\frac{n^*(P)}{2}} \cdot (\mathbb{E}[V_k \mid v_k, t_k, \tilde{q}_k] - P)\,, \end{aligned}$$

where $e^*(P) = e^*(\Psi^*(P), n^*(P))$. Consumer k purchases from the manufacturer if and only if $\mathcal{C}(P, v_k, t_k, \tilde{q}_k) > 0$, which is equivalent to $\mathbb{E}[V_k \mid v_k, t_k, \tilde{q}_k] > P$. Note that when $\tilde{q}_k \neq t_k$, $\mathbb{E}[V_k \mid v_k, t_k, \tilde{q}_k] = -v_k \cdot (2\alpha - 1) \leq 0 \leq P$ and thus consumer k will take her outside option. Therefore, consumer k purchases from the manufacturer if and only if $\tilde{q}_k = t_k$ and $\mathbb{E}[V_k \mid v_k, t_k, \tilde{q}_k] = v_k \cdot (2\alpha - 1) > P$.

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

$$
\begin{aligned}
s^*(P) &= \underbrace{\frac{1}{2} \cdot \mathbb{P}(\tilde{q}_k = A \mid q) \cdot \mathbb{P}(v_k \cdot (2\alpha - 1) > P)}_{\text{Type } A \text{ Consumers' Demand}} + \underbrace{\frac{1}{2} \cdot \mathbb{P}(\tilde{q}_k = B \mid q) \cdot \mathbb{P}(v_k \cdot (2\alpha - 1) > P)}_{\text{Type } B \text{ Consumers' Demand}} \\
&= \frac{1}{2} \cdot \mathbb{P}(v_k \cdot (2\alpha - 1) > P) \\
&= \frac{1}{2} \cdot \max\Big\{1 - \frac{P}{(2\alpha - 1)H}, 0\Big\}.
\end{aligned}
$$

IV. By (12), the manufacturer anticipates all future actions and sets her price for consumers, P^*, such that:

$$
\begin{aligned}
P^* &= \underset{P \geq 0}{\arg\max}\ \mathcal{M}(P) \\
&= \underset{P \geq 0}{\arg\max}\ \mathcal{M}(P, s^*(P), \Psi^*(P), n^*(P)) \\
&= \underset{P \geq 0}{\arg\max}\ \Big(1 - \rho(e^*(P))\Big)^{n^*(P)} \cdot \frac{\Big((P - \Psi^*(P)) \cdot s^*(P)\Big)^{1-\gamma}}{1 - \gamma} \\
&= \underset{P \geq 0}{\arg\max}\ (e^*(P))^{\frac{n^*(P)}{2}} \cdot \frac{\Big((P - \Psi^*(P)) \cdot s^*(P)\Big)^{1-\gamma}}{1 - \gamma},
\end{aligned}
$$

where $e^*(P) = e^*(\Psi^*(P), n^*(P))$.

Define

$$
P_1^* := \underset{0 \leq P < 2-\gamma}{\arg\max}\ (e^*(P))^{\frac{n^*(P)}{2}} \cdot \frac{\Big((P - \Psi^*(P)) \cdot s^*(P)\Big)^{1-\gamma}}{1 - \gamma}
$$

and

$$
P_2^* := \underset{P \geq 2-\gamma}{\arg\max}\ (e^*(P))^{\frac{n^*(P)}{2}} \cdot \frac{\Big((P - \Psi^*(P)) \cdot s^*(P)\Big)^{1-\gamma}}{1 - \gamma}.
$$

If $P < 2 - \gamma$, then $\Psi^*(P) = \frac{P}{2-\gamma}, n^*(P) = 1$, and $e^*(P) = \left(\frac{P}{2-\gamma}\right)^2$ by part I and part II.

Hence,

$$P_1^* = \underset{0 \le P < 2-\gamma}{\arg\max} \ \frac{P}{2-\gamma} \cdot \frac{\left((P - \frac{P}{2-\gamma}) \cdot \frac{1}{2} \cdot \max\left\{1 - \frac{P}{(2\alpha-1)H}, 0\right\}\right)^{1-\gamma}}{1-\gamma}$$

$$= \underset{0 \le P < (2\alpha-1)H}{\arg\max} \ \frac{(1-\gamma)^{-\gamma}}{2^{1-\gamma}(2-\gamma)^{2-\gamma}} \cdot P^{2-\gamma} \cdot \left(1 - \frac{P}{(2\alpha-1)H}\right)^{1-\gamma}.$$

Note that the second line follows from the first because $(2\alpha - 1)H < 1 < 2 - \gamma$ and $\max\left\{1 - \frac{P}{(2\alpha-1)H}, 0\right\} = 0$ when $P \in [(2\alpha - 1)H, 2 - \gamma)$. The objective is a unimodal function and the corresponding first order condition tells us that its maximum is attained at $P = \frac{2-\gamma}{3-2\gamma}(2\alpha - 1)H$, which is in the interval $[0, (2\alpha - 1)H)$. Therefore, we can conclude that $P_1^* = \frac{2-\gamma}{3-2\gamma}(2\alpha - 1)H$ and the corresponding maximum is positive. If $P \ge 2 - \gamma$, then $\Psi^*(P) = 1$ and $(e^*(P))^{n^*(P)} = 1$ by part I and part II. Hence,

$$P_2^* = \underset{P \ge 2-\gamma}{\arg\max} \ \frac{\left((P-1) \cdot \frac{1}{2} \cdot \max\left\{1 - \frac{P}{(2\alpha-1)H}, 0\right\}\right)^{1-\gamma}}{1-\gamma}.$$

Note that $(2\alpha - 1)H < 1 < 2 - \gamma$ and $\max\left\{1 - \frac{P}{(2\alpha-1)H}, 0\right\} = 0$ when $P \ge 2 - \gamma$. Thus, the objective is always zero. In conclusion, the manufacturer chooses $P^* = P_1^* = \frac{2-\gamma}{3-2\gamma}(2\alpha - 1)H$.

□

Proposition A.2. ***Solution when Blockchain is Adopted***

I. Each vendor's effort choice is given as follows:

$$e^{**}(\Psi, n) = \begin{cases} \Psi^2 & \text{if } \Psi < 1 \\ 1 & \text{if } \Psi \ge 1 \end{cases}$$

II. The number of vendors from which the manufacturer buys and the price that she offers those vendors are given as follows:

- $\Psi^{**}(P) = \begin{cases} \frac{P}{2} & \textit{if } P < 2 \\ 1 & \textit{if } P \geq 2 \end{cases}$
- $n^{**}(P) = \infty$

III. Consumer demand for the manufacturer is given by:

$$s^{**}(P) = \begin{cases} \frac{1}{2}\left(1 - \frac{P}{(2(\alpha+\delta)-1)H}\right) & \textit{if } 1 - \frac{P}{(2(\alpha+\delta)-1)H} \geq 0 \\ 0 & \textit{if } 1 - \frac{P}{(2(\alpha+\delta)-1)H} < 0 \end{cases}$$

IV. The manufacturer price for consumers is given as follows:

$P^{**} = \frac{2}{3}(2(\alpha + \delta) - 1)H$

Proof of Proposition A.2.

I. When Ψ and n are given by (15) and (16), the vendor effort choice e^{**} solves:

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

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 $e^{**} = \min\{\Psi^2, 1\}$. To sum up, we have that

$$e^{**}(\Psi, n) = \begin{cases} \Psi^2 & \text{if } \Psi < 1 \\ 1 & \text{if } \Psi \geq 1 \end{cases}.$$

II. For P and s given by (17) and (18), the number of vendors n^{**} to whom the manufacturer makes an offer and the offer price Ψ^{**} are given by:

$$\begin{aligned}(\Psi^{**}, n^{**}) &= \underset{\Psi\geq 0, n\in\overline{\mathbb{N}}_+}{\arg\max}\ \mathcal{M}^{\mathcal{B}}(P, s, \Psi, n)\\ &= \underset{\Psi\geq 0, n\in\overline{\mathbb{N}}_+}{\arg\max}\ \mathbb{E}[U\Big((P-\Psi)\cdot\frac{s}{n}\cdot N_s\Big)] - \chi,\end{aligned}$$

where $N_s \sim \text{Binomial}(n, 1-\rho(e^{**}(\Psi)))$ with $e^{**}(\Psi) := e^{**}(\Psi, 1) = e^{**}(\Psi, n)$.

Define $X_n := (P-\Psi)\cdot\frac{s}{n}\cdot N_s$ and $c := \mathbb{E}[X_n] = (P-\Psi)\cdot s\cdot(e^{**}(\Psi))^{\frac{1}{2}}$. By strong law of large numbers, $X_\infty = c$. Since U is strictly concave on $\mathbb{R}_+$, for given Ψ and any finite n, $\mathbb{E}[U(X_n)] < U(\mathbb{E}[X_n]) = U(c) = \mathbb{E}[U(X_\infty)]$ holds by Jensen's inequality. Thus, $n=\infty$ is a dominant strategy and $n^{**}=\infty$, which is independent of Ψ. It follows that

$$\begin{aligned}\Psi^{**} &= \underset{\Psi\geq 0}{\arg\max}\ \mathbb{E}[U(X_\infty)] - \chi\\ &= \underset{\Psi\geq 0}{\arg\max}\ U\Big((P-\Psi)\cdot s\cdot(e^{**}(\Psi))^{\frac{1}{2}}\Big) - \chi\\ &= \underset{\Psi\geq 0}{\arg\max}\ (P-\Psi)\cdot(e^{**}(\Psi))^{\frac{1}{2}}\\ &= \underset{\Psi\geq 0}{\arg\max}\ (P-\Psi)\cdot\min\{\Psi, 1\}\\ &= \begin{cases}\frac{P}{2} & \text{if } P<2\\ 1 & \text{if } P\geq 2\end{cases}.\end{aligned}$$

Note that the third line follows from the second because U is strictly increasing, and the fourth line holds true due to the result of part I. To sum up, we have that

$$\begin{aligned}\Psi^{**}(P) &= \begin{cases}\frac{P}{2} & \text{if } P<2\\ 1 & \text{if } P\geq 2\end{cases},\\ n^{**}(P) &= \infty.\end{aligned}$$

III. The argument to get $s^{**}(P)$ is very similar to what we did in Proposition A.1 part III; the only difference here is that we need to replace α with $\alpha+\delta$ in the proof of Proposition A.1 part III. Consequently, we get that $s^{**}(P) = \frac{1}{2}\cdot \max\left\{1 - \frac{P}{(2(\alpha+\delta)-1)H}, 0\right\}$.

IV. By (22) and the results of part I, part II and part III,

$$\begin{aligned}
P^{**} &:= \arg\max_{P\geq 0} \mathcal{M}^{\mathcal{B}}(P) \\
&= \arg\max_{P\geq 0} \mathcal{M}^{\mathcal{B}}(P, s^{**}(P), \Psi^{**}(P), n^{**}(P)) \\
&= \arg\max_{P\geq 0} \mathbb{E}[U\Big((P-\Psi^{**}(P))\cdot \frac{s^{**}(P)}{n^{**}(P)}\cdot N_s\Big)] - \chi \\
&= \arg\max_{P\geq 0} U\Big((P-\Psi^{**}(P))\cdot s^{**}(P)\cdot (e^{**}(P))^{\frac{1}{2}}\Big) - \chi \\
&= \arg\max_{P\geq 0} (P-\Psi^{**}(P))\cdot s^{**}(P)\cdot (e^{**}(P))^{\frac{1}{2}} \\
&= \arg\max_{P\geq 0} \Big(P - \min\{\frac{P}{2}, 1\}\Big)\cdot \frac{1}{2}\cdot \max\Big\{1 - \frac{P}{(2(\alpha+\delta)-1)H}, 0\Big\}\cdot \min\{\frac{P}{2}, 1\},
\end{aligned}$$

where $N_s \sim \text{Binomial}(n^{**}(P), 1-\rho(e^{**}(P)))$ and $e^{**}(P) := e^{**}(\Psi^{**}(P)) = e^{**}(\Psi^{**}(P), 1)$. Note that if $P \geq 2$, then $1 - \frac{P}{(2(\alpha+\delta)-1)H} \leq 1 - \frac{2}{(2(\alpha+\delta)-1)H} \leq 1-2 < 0$ because $(2(\alpha+\delta)-1)H \leq 1$. Consequently, in this case, $\max\left\{1 - \frac{P}{(2(\alpha+\delta)-1)H}, 0\right\} = 0$ and the objective is always zero. It immediately follows that

$$\begin{aligned}
P^{**} &= \arg\max_{0\leq P<2} \Big(P - \min\{\frac{P}{2}, 1\}\Big)\cdot \frac{1}{2}\cdot \max\Big\{1 - \frac{P}{(2(\alpha+\delta)-1)H}, 0\Big\}\cdot \min\{\frac{P}{2}, 1\} \\
&= \arg\max_{0\leq P<2} \frac{P}{2}\cdot\frac{1}{2}\cdot\Big(1 - \frac{P}{(2(\alpha+\delta)-1)H}\Big)\cdot\frac{P}{2}.
\end{aligned}$$

The objective is a unimodal function and the corresponding first order condition tells us that its maximum is attained at $P = \frac{2}{3}(2(\alpha+\delta)-1)H$, which is in the interval $[0, 2)$. Therefore, $P^{**} = \frac{2}{3}(2(\alpha+\delta)-1)H$.

□

B Proofs

Proof of Corollary 2.1. By Proposition A.1, solutions for all equilibrium actions in the absence of blockchain are given by:

$$
\begin{aligned}
e^* &= e^*(P^*) = \Big(\frac{(2\alpha-1)H}{3-2\gamma}\Big)^2, \\
\Psi^* &= \Psi^*(P^*) = \frac{(2\alpha-1)H}{3-2\gamma}, \\
n^* &= n^*(P^*) = 1, \\
s^* &= s^*(P^*) = \frac{1-\gamma}{6-4\gamma}, \\
P^* &= \frac{2-\gamma}{3-2\gamma}(2\alpha-1)H.
\end{aligned}
$$

□

Proof of Corollary 2.2. By Proposition A.2, solutions for all equilibrium actions when blockchain is adopted are given by:

$$
\begin{aligned}
e^{**} &= e^{**}(P^{**}) = \Big(\frac{(2(\alpha+\delta)-1)H}{3}\Big)^2, \\
\Psi^{**} &= \Psi^{**}(P^{**}) = \frac{(2(\alpha+\delta)-1)H}{3}, \\
n^{**} &= n^{**}(P^{**}) = \infty, \\
s^{**} &= s^{**}(P^{**}) = \frac{1}{6}, \\
P^{**} &= \frac{2}{3}(2(\alpha+\delta)-1)H.
\end{aligned}
$$

□

Proof of Proposition 2.3. By Proposition A.1 part IV,

$$
\begin{aligned}
\mathcal{M}(P^*) &= \frac{(1-\gamma)^{-\gamma}}{2^{1-\gamma}(2-\gamma)^{2-\gamma}} \cdot P^{2-\gamma} \cdot \Big(1 - \frac{P}{(2\alpha-1)H}\Big)^{1-\gamma}\Big|_{P=P^*} \\
&= \frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma}.
\end{aligned}
$$

By Proposition A.2 part IV,

$$\begin{aligned}\mathcal{M}^{\mathcal{B}}(P^{**}) &= U\Big(\frac{P^2}{8}\cdot\Big(1-\frac{P}{(2(\alpha+\delta)-1)H}\Big)\Big)-\chi\Big|_{P=P^{**}}\\ &= \frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{(1-\gamma)54^{1-\gamma}}-\chi.\end{aligned}$$

Define

$$\begin{aligned}\Omega &:= \mathbb{E}[U(\Pi^{**})]-\mathbb{E}[U(\Pi^{*})]\\ &= (\mathcal{M}^{\mathcal{B}}(P^{**})+\chi)-\mathcal{M}(P^{*})\\ &= \frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{(1-\gamma)54^{1-\gamma}}-\frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma}.\end{aligned}$$

Then, the manufacturer adopts the blockchain, i.e., $a=1$, if and only if $\Omega \geq \chi$. In conclusion, $a=\mathcal{I}\Big(\Omega\geq\chi\Big)$. □

Proof of Proposition 3.1. By Proposition 2.3, $\Omega = \frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{(1-\gamma)54^{1-\gamma}} - \frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma}$. In order to show that $\Omega>0$, it suffices to show that the ratio of two terms is greater than 1, i.e.,

$$\frac{\frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{(1-\gamma)54^{1-\gamma}}}{\frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma}} = \frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{[(2\alpha-1)H]^{2-\gamma}}\cdot\frac{(3-2\gamma)^{3-2\gamma}}{27^{1-\gamma}(1-\gamma)^{2-2\gamma}} > 1.$$

Define an auxiliary function $l_1(\gamma) := \ln\left(\frac{(3-2\gamma)^{3-2\gamma}}{27^{1-\gamma}(1-\gamma)^{2-2\gamma}}\right) = (3-2\gamma)\ln(3-2\gamma)-(1-\gamma)\ln 27-(2-2\gamma)\ln(1-\gamma)$. Then, $l_1'(\gamma) = -2\ln(3-2\gamma)+2\ln(1-\gamma)+\ln 27 = 2\ln\left(\frac{1}{2}-\frac{1}{6-4\gamma}\right)+\ln 27$, which is decreasing in γ on $(0,1)$. Define $\gamma^* := \frac{21-3\sqrt{3}}{23}$. Then, $l_1'(\gamma)>0$ when $\gamma<\gamma^*$ and $l_1'(\gamma)<0$ when $\gamma>\gamma^*$. Hence, $l_1(\gamma)$ is strictly increasing on $(0,\gamma^*)$ and strictly decreasing on $(\gamma^*,1)$. As $\lim_{\gamma\to 0^+} l_1(\gamma) = \lim_{\gamma\to 1^-} l_1(\gamma) = 0$, $l_1(\gamma)$ is thereby positive on $(0,1)$. Combining all the above, we have that

$$\frac{[(2(\alpha+\delta)-1)H]^{2-2\gamma}}{[(2\alpha-1)H]^{2-\gamma}}\cdot\frac{(3-2\gamma)^{3-2\gamma}}{27^{1-\gamma}(1-\gamma)^{2-2\gamma}} = \Big(\frac{2(\alpha+\delta)-1}{2\alpha-1}\Big)^{2-2\gamma}\cdot\frac{1}{((2\alpha-1)H)^{\gamma}}\cdot e^{l_1(\gamma)} > 1\cdot 1\cdot e^0 = 1,$$

which completes the proof. □

Proof of Proposition 3.2. By Corollary 2.1,

$$\begin{aligned}\Pi^* &= (P^* - \Psi^*) \cdot s^* \cdot \prod_{j=1}^{n^*} I_j \\ &= \frac{(1-\gamma)^2}{2(3-2\gamma)^2}(2\alpha - 1)H \cdot I_1,\end{aligned}$$

where $I_j \sim \text{Bernoulli}(1 - \rho(e^*)) = \text{Bernoulli}\left(\frac{(2\alpha-1)H}{3-2\gamma}\right)$ are i.i.d. Bernoulli random variables. By Corollary 2.2,

$$\begin{aligned}\Pi^{**} &= (P^{**} - \Psi^{**}) \cdot s^{**} \cdot \frac{N_s}{n^{**}} \\ &= \frac{[(2(\alpha+\delta)-1)H]^2}{54}\end{aligned}$$

by strong law of large numbers, where $N_s \sim \text{Binomial}(n^{**}, 1-\rho(e^{**})) = \text{Binomial}\left(n^{**}, \frac{(2(\alpha+\delta)-1)H}{3}\right)$. Given the above results, we are ready to prove Proposition 3.2.

1. It is easy to see that $n^{**} = \infty > 1 = n^*$.

2. Π^{**} is a constant whereas Π^* is a nondegenerate random variable, so $Var[\Pi^{**}] = 0 < Var[\Pi^*]$.

3. Note that Π^{**} is a constant and $\Omega = \mathbb{E}[U(\Pi^{**})] - \mathbb{E}[U(\Pi^*)] = U(\Pi^{**}) - \mathbb{E}[U(\Pi^*)]$, so $\Sigma = \Omega - \Phi = U(\mathbb{E}[\Pi^*]) - \mathbb{E}[U(\Pi^*)]$. Since U is strictly concave, $\Sigma > 0$ holds by Jensen's inequality. Moreover,

$$\begin{aligned}\Sigma &= U(\mathbb{E}[\Pi^*]) - \mathbb{E}[U(\Pi^*)] \\ &= \frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-3\gamma}}[(2\alpha-1)H]^{2-2\gamma} - \frac{(1-\gamma)^{1-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-2\gamma}}[(2\alpha-1)H]^{2-\gamma} \\ &= \frac{(1-\gamma)^{1-2\gamma}[(2\alpha-1)H]^{2-2\gamma}}{2^{1-\gamma}(3-2\gamma)^{3-3\gamma}}\left(1 - \left(\frac{(2\alpha-1)H}{3-2\gamma}\right)^{\gamma}\right) \\ &\to 0\end{aligned}$$

as $\gamma \to 0^+$.

$\square$

Proof of Proposition 3.3. By the proof of Proposition 3.2, we know that $\Pi^* = \frac{(1-\gamma)^2}{2(3-2\gamma)^2}(2\alpha-1)H \cdot I_1$ and $\Pi^{**} = \frac{[2(\alpha+\delta)-1)H]^2}{54}$. Therefore, $\mathbb{E}[\Pi^*] = \frac{(1-\gamma)^2}{2(3-2\gamma)^3}[(2\alpha-1)H]^2$ and $\mathbb{E}[\Pi^{**}] = \frac{[(2(\alpha+\delta)-1)H]^2}{54}$.

1. Note that

$$\begin{aligned}\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} &= \left(\frac{2(\alpha+\delta)-1}{2\alpha-1}\right)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2} \\ &> \frac{(3-2\gamma)^3}{27(1-\gamma)^2} \\ &=: e^{l_2(\gamma)}.\end{aligned}$$

The auxiliary function $l_2(\gamma) = \ln\left(\frac{(3-2\gamma)^3}{27(1-\gamma)^2}\right) = 3\ln(3-2\gamma) - \ln 27 - 2\ln(1-\gamma)$. Then, $l_2'(\gamma) = \frac{2\gamma}{(1-\gamma)(3-2\gamma)} > 0$ and thus $l_2(\gamma)$ is strictly increasing in γ on $(0,1)$. As $\lim_{\gamma\to 0^+} l_2(\gamma) = 0$, $l_2(\gamma) > 0$ holds for all $\gamma \in (0,1)$. Consequently, $\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} > e^{l_2(\gamma)} > e^0 = 1$ and $\mathbb{E}[\Pi^{**}] > \mathbb{E}[\Pi^*]$. Since U is strictly increasing, $\Phi > 0$ follows.

2. We have that

$$\begin{aligned}\lim_{\gamma,\delta\to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} &= \lim_{\gamma,\delta\to 0^+} \left(\frac{2(\alpha+\delta)-1}{2\alpha-1}\right)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2} \\ &= \left(\frac{2\alpha-1}{2\alpha-1}\right)^2 \cdot \frac{3^3}{27\cdot 1^2} \\ &= 1.\end{aligned}$$

Thus,

$$\begin{aligned}\lim_{\gamma,\delta\to 0^+} \Phi &= \lim_{\gamma,\delta\to 0^+} \left(\frac{U(\mathbb{E}[\Pi^{**}])}{U(\mathbb{E}[\Pi^*])} - 1\right) U(\mathbb{E}[\Pi^*]) \\ &= \lim_{\gamma,\delta\to 0^+} \left(\left(\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]}\right)^{1-\gamma} - 1\right) U(\mathbb{E}[\Pi^*]) \\ &= \left(\lim_{\gamma,\delta\to 0^+} \left(\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]}\right)^{1-\gamma} - 1\right) \cdot \lim_{\gamma,\delta\to 0^+} U(\mathbb{E}[\Pi^*]) \\ &= 0.\end{aligned}$$

3. For fixed $\gamma > 0$,

$$\lim_{\delta \to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} = \lim_{\delta \to 0^+} \Big(\frac{2(\alpha+\delta)-1}{2\alpha-1}\Big)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2}$$
$$= \frac{(3-2\gamma)^3}{27(1-\gamma)^2}.$$

It has been shown in part 1 that $\frac{(3-2\gamma)^3}{27(1-\gamma)^2} > 1$ for all $\gamma \in (0,1)$. Thus, $\lim_{\delta \to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} > 1$.

4. For fixed $\delta > 0$,

$$\lim_{\gamma \to 0^+} \frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} = \lim_{\gamma \to 0^+} \Big(\frac{2(\alpha+\delta)-1}{2\alpha-1}\Big)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2}$$
$$= \Big(\frac{2(\alpha+\delta)-1}{2\alpha-1}\Big)^2$$
$$> 1.$$

$\square$

Proof of Proposition 3.4. By the proof of Proposition 3.3, we know that $\frac{\mathbb{E}[\Pi^{**}]}{\mathbb{E}[\Pi^*]} = \Big(\frac{2(\alpha+\delta)-1}{2\alpha-1}\Big)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2} = f_\Pi(\gamma) \cdot g_\Pi(\alpha, \delta)$.

1. That $f_\Pi(\gamma) > 1$ has been proved in the proof of Proposition 3.3. Moreover, $\frac{df_\Pi}{d\gamma} = \frac{2\gamma(3-2\gamma)^2}{27(1-\gamma)^3} > 0$.

2. It is easy to see that $g_\Pi(\alpha, \delta) > 1$. Moreover, $\frac{\partial g_\Pi}{\partial \delta} = \frac{4}{2\alpha-1}(1 + \frac{2\delta}{2\alpha-1}) > 0$.

$\square$

Proof of Proposition 3.5. By Corollaries 2.1 and 2.2,

$$\frac{s^{**}}{s^*} = \frac{3-2\gamma}{3-3\gamma} = f_s(\gamma),$$
$$\frac{P^{**}}{P^*} = \frac{2(\alpha+\delta)-1}{2\alpha-1} \cdot \frac{6-4\gamma}{6-3\gamma} = f_P(\gamma) \cdot g_P(\alpha, \delta).$$

1. For all $\gamma \in (0,1)$ and $\delta \in (0, 1-\alpha]$, $f_s(\gamma) > 1$ and thus $s^{**} > s^*$. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{64}$, $P^{**} < P^*$. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{4}$, $P^{**} > P^*$.

2. We have that $f_s(\gamma) > 1$ and $\frac{df_s}{d\gamma} = \frac{1}{3(1-\gamma)^2} > 0$, but $f_P(\gamma) < 1$ and $\frac{df_P}{d\gamma} = -\frac{2}{3(2-\gamma)^2} < 0$.

3. For all $\alpha \in [\frac{1}{2}, 1)$ and $\delta \in (0, 1-\alpha]$, it is easy to see that $g_P(\alpha, \delta) > 1$. Moreover, $\frac{\partial g_P}{\partial \delta} = \frac{2}{2\alpha - 1} > 0$.

□

Proof of Proposition 4.1. By (30) and Corollaries 2.1 and 2.2, we have that

$$\begin{aligned} W_V^* &= \left((1-\rho(e^*))^{n^*} \cdot \Psi^* - \frac{e^*}{2}\right) \cdot s^* \\ &= \frac{(\Psi^*)^2 \cdot s^*}{2} \\ &= \frac{1-\gamma}{4(3-2\gamma)^3}[(2\alpha-1)H]^2 \end{aligned}$$

and

$$\begin{aligned} W_V^{**} &= \left((1-\rho(e^{**})) \cdot \Psi^{**} - \frac{e^{**}}{2}\right) \cdot s^{**} \\ &= \frac{(\Psi^{**})^2 \cdot s^{**}}{2} \\ &= \frac{[(2(\alpha+\delta)-1)H]^2}{108}. \end{aligned}$$

Thus, $\frac{W_V^{**}}{W_V^*} = \left(\frac{2(\alpha+\delta)-1}{2\alpha-1}\right)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)}$. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{64}$, $W_V^{**} < W_V^*$. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{4}$, $W_V^{**} > W_V^*$.

□

Proof of Proposition 4.2. By Corollaries 2.1 and 2.2, $\frac{\Psi^{**}}{\Psi^*} = \frac{2(\alpha+\delta)-1}{2\alpha-1} \cdot \frac{3-2\gamma}{3} = f_\Psi(\gamma) \cdot g_\Psi(\alpha, \delta)$.

1. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{64}$, $\Psi^{**} < \Psi^*$. When $\alpha = \frac{3}{4}, \gamma = \frac{1}{2}, \delta = \frac{1}{4}$, $\Psi^{**} > \Psi^*$.

2. It is easy to see that $f_\Psi(\gamma) < 1$. Moreover, $\frac{\partial f_\Psi}{\partial \gamma} = -\frac{2}{3} < 0$.

3. It is easy to see that $g_\Psi(\alpha, \delta) > 1$. Moreover, $\frac{\partial g_\Psi}{\partial \delta} = \frac{2}{2\alpha-1} > 0$.

□

Proof of Proposition 4.3. By Corollaries 2.1 and 2.2, we have that

$$\frac{\Psi^*}{P^*} = \frac{1}{2-\gamma} = h(\gamma),$$
$$\frac{\Psi^{**}}{P^{**}} = \frac{1}{2} = h(0),$$
$$\frac{e^*}{(P^*)^2} = \left(\frac{\Psi^*}{P^*}\right)^2 = \frac{1}{(2-\gamma)^2} = (h(\gamma))^2,$$
$$\frac{e^{**}}{(P^{**})^2} = \left(\frac{\Psi^{**}}{P^{**}}\right)^2 = \frac{1}{4} = (h(0))^2.$$

Moreover, $\frac{dh}{d\gamma} = \frac{1}{(2-\gamma)^2} > 0$. □

Proof of Proposition 4.4. By (32) and Corollaries 2.1 and 2.2, we have that

$$\begin{aligned}
W_C^* &= (1-\rho(e^*))^{n^*} \cdot \frac{1}{2} \cdot \int_0^1 \mathbb{E}\big[\big(v_k \cdot (2\alpha-1) - P^*\big)\mathcal{I}\big(v_k \cdot (2\alpha-1) > P^*\big)\big]\ dk \\
&= \frac{\Psi^*}{2} \cdot \frac{\big((2\alpha-1)H - P^*\big)^2}{2(2\alpha-1)H} \\
&= \frac{(1-\gamma)^2}{4(3-2\gamma)^3}[(2\alpha-1)H]^2, \\
W_C^{**} &= (1-\rho(e^{**})) \cdot \frac{1}{2} \cdot \int_0^1 \mathbb{E}\big[\big(v_k \cdot (2(\alpha+\delta)-1) - P^{**}\big)\mathcal{I}\big(v_k \cdot (2(\alpha+\delta)-1) > P^{**}\big)\big]\ dk \\
&= \frac{\Psi^{**}}{2} \cdot \frac{\big((2(\alpha+\delta)-1)H - P^{**}\big)^2}{2(2(\alpha+\delta)-1)H} \\
&= \frac{[(2(\alpha+\delta)-1)H]^2}{108}.
\end{aligned}$$

Thus, $\frac{W_C^{**}}{W_C^*} = \left(\frac{2(\alpha+\delta)-1}{2\alpha-1}\right)^2 \cdot \frac{(3-2\gamma)^3}{27(1-\gamma)^2} = f_{W_C}(\gamma) \cdot g_{W_C}(\alpha,\delta)$.

1. That $f_{W_C}(\gamma) > 1$ has been proved in the proof of Proposition 3.3. It is obvious that $g_{W_C}(\alpha,\delta) > 1$. Consequently, $\frac{W_C^{**}}{W_C^*} > 1$ and thus $W_C^{**} > W_C^*$.
2. $\frac{df_{W_C}}{d\gamma} = \frac{2\gamma(3-2\gamma)^2}{27(1-\gamma)^3} > 0$.
3. $\frac{\partial g_{W_C}}{\partial\delta} = \frac{4}{2\alpha-1}(1 + \frac{2\delta}{2\alpha-1}) > 0$.

□