Blockchains, Smart Contracts, and Supply Chain Efficiency*

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ABSTRACT

This paper examines how real-time visibility of information on blockchain can mitigate supply chain uncertainty and increase its efficiency. We model a supply chain with two suppliers and one manufacturer, where the manufacturer needs intermediate goods from both suppliers for producing the finished product, and one supplier has an imperfect technology that generates non-defective products with a random yield. Supply chain inefficiencies arise due to potential production surpluses and deficits in the intermediate products. We show that a blockchain that shares verifiable real-time production information among suppliers and the manufacturer can improve supply chain efficiency. The benefit of blockchain is non-monotonic in the random yield of intermediate products and profit margin of the final product. Furthermore, we demonstrate that, in the decentralized setting, the optimal contracts are "smart contracts" contingent on information on the blockchain. We also show that smart contracts with varying price schedules can implement the first-best solution for the supply chain, in which all members are better off than in the case without blockchain. In an extension of the model, we consider two imperfect-technology suppliers who compete with partially substitutable products and show that blockchain continues to improve supply chain efficiency with competition. Interestingly, the benefit of blockchain decreases with product substitutability.

Key Words: Supply Chain Uncertainty, Blockchain, Smart Contracts, FinTech, Real-Time Data, Random Yield, Supply Chain Efficiency, Product Competition, Product Substitutability

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1. Introduction

With the evolution of specialization and decentralization, manufacturers and retailers have had to operate within increasingly complex environments. Globalization further increases the length of supply chains from raw material suppliers to retailers, creating many supply chain inefficiencies that range from extra work-in-process and inventory or shortage, to long transportation time, to uncertain production quantities due to disruption or random yields (Wurst 2019). These inefficiencies have generated substantial negative impacts, including unsatisfactory customer experiences and higher firm operation costs. For example, supply chain inefficiencies have been estimated to cost about $2 billion in the UK (Lopez 2018), and about $65 billion in India (Cornish 2020). In the automobile industry, unexpected global chip shortages in 2021 have caused huge production disruptions and massive profit loss.[1]

Researchers and practitioners have made significant progress towards supply chain efficiency improvement through optimization and contracts design (see, e.g., the survey in Cachon 2003). Supply chain coordination, defined as mechanisms to achieve the optimal supply chain profits in decentralized firm decisions, have been very successful within various contexts. However, when multiple firms in either the upstream or downstream of the channel are involved, coordination proves to be difficult. One main reason for such difficulty is the visibility of the supply chain, as firms may be unwilling to share their operating details, or cannot verifiably share them. In this paper, we provide a way to achieve supply chain coordination involving multiple suppliers by utilizing the newly developed blockchain technology.

Although blockchain technology began with financial applications such as payments and cryptocurrencies (Nakamoto 2008), it has since outgrown its roots and found a diverse range of real business applications, among which supply chain optimization is regarded as a key

[1] "Auto makers warn chip shortage will continue to impact vehicle production," Nick Kostov, August 3, 2021, *The Wall Street Journal*.

growth area (Deloitte 2020). Some of the key features of blockchains include transparency and immutability of data. In other words, blockchains allow supply chain participants to share operations data, such as production and inventory information, in a timely and verifiable way. As we show in the model, the availability of such data is important for the coordination of decisions across the supply chain. Importantly, the blockchain architecture allows "smart contracts" to be written in terms of information on the blockchain, which can greatly expand the space of feasible contracts among supply chain participants.

For enterprise blockchain applications, business considerations often require the use of a permissioned blockchain (e.g., the Walmart-IBM food safety blockchain) operated by authorized parties, as opposed to a public or permissionless blockchain (e.g., Bitcoin or Ethereum), which can involve any individual or entity in its operations. Permissioned blockchains provide a distributed, decentralized solution that maintains the immutability of data and offers superior performance and security. We, therefore, consider permissioned blockchains to be the appropriate technology for the implementation of our model.[2]

In this paper, we consider a supply chain with two competing suppliers in the upstream and one manufacturer in the downstream. The manufacturer needs components from both suppliers for producing its products. Between the two suppliers, one has a production uncertainty in the form of random yield, and the other supplier is reliable. The manufacturer orders from the two suppliers simultaneously and makes the final production decision after receiving components from each of them. The manufacturer then sells the final products to consumers.

The uncertainty in supplier 1's production technology can generate excess or deficit supply of components and lead to inefficiencies in the supply chain. If the supply chain is equipped with a blockchain system, then the suppliers can receive real-time, verifiable information about their production statuses, which can help them make more efficient decisions.

We first solve the social planner's centralized problem in the benchmark case where there

[2] In Appendix A, we discuss more details and examples of blockchain technology, smart contracts, and public and permissioned blockchains. See also Section 7 for detailed discussions of blockchain implementation.

are no blockchain systems and thus the social planner cannot observe or verify the state of real-time production. The social planner can achieve the maximum possible supply chain surplus under the constraint of no real-time visibility. This surplus is also achievable in a decentralized system with contracts between the suppliers and the manufacturer.

We then consider the centralized system with a blockchain, wherein the social planner can coordinate the production decisions of both suppliers, thus increasing efficiency and leading to a higher surplus. We calculate the blockchain surplus as the difference between the total supply chain profits in the blockchain case and in the benchmark case minus the costs of blockchain adoption. We show that the blockchain surplus is generally non-monotone in both the random yield and the profit margin of the final product. Intuitively, when the random yield is very low, increasing it will enhance the overall profits of the supply chain and hence the associated benefit of the blockchain system (sustenance effect). When the random yield is high, increasing it further will reduce the uncertainty in production and hence decreases the blockchain system's benefit (uncertainty effect). The intuition for profit margin is as follows: when profit margin is very low, the sustenance effect again kicks in and blockchain's benefit increases with profit margin; when profit margin is already high, supplier 1 always has strong incentives to produce and thus the benefit offered by blockchain adoption is limited (production incentive effect). Interestingly, when the final product is a "luxury good," i.e., when the profit margin is very high, the blockchain system's surplus is monotonically decreasing in the random yield and profit margin. This is because the uncertainty effect and production incentive effect discussed above dominate the sustenance effects for luxury goods.

The natural question thus becomes whether the centralized policy with blockchain adoption is implementable in a decentralized supply chain. To further increase efficiency, the supply chain counterparties need to resort to smart contracts whose terms are contingent on real-time information on the blockchain. The optimal contracts also depend on what kind of information is available and verifiable/contractable on the blockchain. We first consider the case where both production input and output information from the suppliers is available (and contractable) on the blockchain. In this case, we show that the supply chain can be optimized by standard wholesale contracts with orders contingent upon the blockchain's states, coordinated with lump-sum payments.

The second case, which may be more realistic, is when blockchain adoption only offers contractability for the suppliers' output information. We demonstrate that it is still possible to implement the supply chain's first-best solution in this case. The optimal contracts between the suppliers and manufacturer involve varying unit prices that are dependent on the output quantity of components as well as order size contingent on blockchain information. Furthermore, since the blockchain surplus is mostly captured by the manufacturer, payments have to be made to the suppliers so that all parties are better off than in the case without blockchain adoption. Overall, we show that real-time visibility and contractability offered by the combined implementation of blockchain technology and smart contracts can substantially improve supply chain efficiency.

Finally, we consider an extension of our model that incorporates competition among suppliers. In particular, we consider a third supplier who competes with the imperfect-technology supplier. The third supplier produces components that are partially substitutable with supplier 1's components. The manufacturer processes these intermediate products to provide consumers in the market with two partially substitutable products. We show that blockchain continues to improve the efficiency of the supply chain with competition. Interestingly, the benefit of blockchain adoption decreases with product substitutability. Intuitively, when the two intermediate goods are less substitutable, the idiosyncratic shocks in their production cannot be diversified away, generating more inefficiency in the supply chain and thus higher potential benefits from blockchain utilization.

Our paper is related to the quickly growing literature on blockchains and FinTech. Early work on blockchain technologies discuss digital currencies (Harvey 2016) and blockchain's potential impacts on corporate governance (Yermack 2017). Many studies (Halaburda and

Sarvary 2016; Malinova and Park 2018; Biais et al. 2019; Alsabah and Capponi 2019; Easley et al. 2019; Li and Mann 2019; Lyandres et al. 2019; Catalini and Gans 2020; Tsoukalas and Falk 2020; Gan et al. 2020; Lehar and Parlour 2020; Chod and Lyandres 2021; Cong et al. 2021a,b; John et al. 2021; Halaburda et al. 2021; Saleh 2021; Halaburda et al. 2022) focus on public blockchains, crypocurrencies, and tokens (such as initial coin offerings). Recently, permissioned blockchains have begun to receive more attention from researchers. Cong and He (2019) study information distribution in generating decentralized consensus that could be permission-based. Cao et al. (2019) consider the application of permissioned blockchains in financial reporting to achieve privacy preservation and automatic reconciliation of transaction accounts, and discuss the economic implications for the auditing industry. Hinzen et al. (2020) discuss overcoming scalability limitations using a permissioned blockchain system.

There is an emerging stream of theoretical research on the applications of blockchain technology in supply chains. Babich and Hilary (2020) provide an overview of the strengths and weaknesses of blockchains, as well as the relevant research questions related to supply chains and operations management. Chod et al. (2020) demonstrate that the verifiability of transactions offered by blockchain technology can enhance transparency and thereby finance operations more efficiently. Cui et al. (2020a) examine the opportunities introduced to supply chains resulting from network visibility or the awareness of existence of other parties on blockchains. Cui et al. (2020b) model the traceability of goods in supply chains and study its benefits to supply chain quality. Iyengar et al. (2020) investigate the equilibrium decisions arising from the adoption of blockchain technology in supply chains and show that adoption failure is possible. Iyengar et al. (2022) consider the benefits of traceability and information offered by blockchain implementation for supply chains with a risk-averse manufacturer. Hastig and Sodhi (2020) discuss the implementation of supply chain traceability systems and point out business requirements and factors critical to successful implementation. Wang et al. (2021) design and implement a blockchain-enabled data-sharing marketplace for a stylized supply chain with one supplier and independent retailers under a newsvendor setting. Shen et al. (2022) study how to use a permissioned blockchain technology (PBT) platform to combat copycats in the supply chain, as well as how blockchain technology can benefit brand name companies. In a similar vein, Pun et al. (2021) discuss how blockchain technology can be used to detect deceptive counterfeits under a setting with one manufacturer, one counterfeiter, and the government as a third party, which can provide incentives for blockchain technology adoption.

Our paper complements the existing studies by examining real-time visibility of production processes offered by blockchain adoption, smart contracts utilizing such information, and subsequent supply-chain efficiency gains. We also study how blockchains interact with supply chain competition and product substitutability. Furthermore, we discuss practical considerations in blockchain implementation for supply chains when collaborators and competitors are in the group.

In the remainder of the paper, we consider the main model's setup in Section 2 and solve the benchmark case where a social planner makes decisions without the real-time information offered by a blockchain in Section 3. We then consider the centralized problem with blockchain. The comparison of these two cases allows us to analyze the potential benefit of blockchain adoption in Section 4. Next, we investigate how to implement the optimal supply chain coordination through decentralized contracts among the three members of the supply chain in Section 5. We demonstrate the value of blockchain technology when there is supply competition by adding a third supplier whose products partially substitute the imperfect supplier in Section 6. Section 7 discusses the various implementation details related to supply chain blockchain. Finally, we offer concluding remarks and point out future research directions in Section 8.

2. Model Setup

We consider a supply chain that consists of two suppliers and a manufacturer. The manufacturer procures intermediate product (e.g., processed raw material, parts, or components) of type i from supplier $i \in \{1, 2\}$ respectively to produce an end product with a one-time market demand, e.g., small electronics with short lifecycles. Without loss of generality, one unit of end product requires one unit of each type of intermediate product to produce. Given a potentially long lead time for procurement, the manufacturer must order in advance. Since the focus of this study is on the supply uncertainties among the suppliers and the manufacturer, we assume that the aggregate consumer demand d of the end product is deterministic (e.g., Tang and Kouvelis 2014). Each unit of the end product sells for a fixed price p.

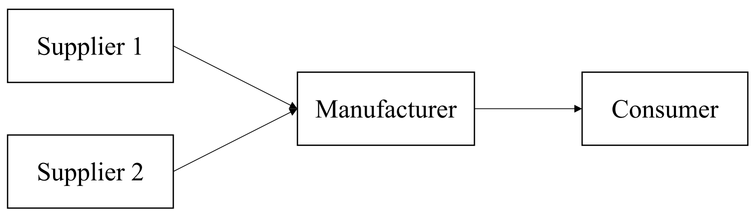


Figure 1: The product flow of the supply chain

At the beginning of the period, the manufacturer places an order o_i to each supplier i. These orders are manufactured simultaneously due to significant lead time in producing and procuring the intermediate products. After receiving the order, each supplier i decides on the production quantity q_i. The production technology of supplier 1 is imperfect and is associated with a random yield (e.g., in semiconductor and electronics industries). In particular, for a planned production quantity q_1, supplier 1 would generate q_1 units of non-defective type 1 components with probability 0.5, and αq_1 (non-defective) units of type 1 components with probability 0.5. The yield parameter $\alpha \in (0, 1]$ is exogenously determined and independent of the production quantity q_1. In contrast, supplier 2 has access to a perfect production technology which always yields the desired production quantity.[3] To better illustrate our setup, supplier 1 can produce components with a fast-evolving technology while supplier 2 supplies well-established complementary products; or supplier 1 can be in the farming industry where outputs and yield depend heavily on weather, while supplier 2 is not subject

[3]We make this assumption for simplicity of analysis. The results and intuition carry through if supplier 2 also has an imperfect production technology.

to unexpected weather conditions such as coldness or extreme heat. Each supplier incurs a unit production cost $c \in (0, \frac{p}{2})$, regardless of whether or not the output is defective.

The manufacturer takes one unit of each type of component and assembles/produces one unit of the final product. Without loss of generality, we assume all other costs incurred in assembly or production have already been incorporated into price p of the end product. We assume that the economic environment, including the production technologies, the production cost, and the end product price, are common knowledge to all participants in the supply chain. In the traditional case without blockchains, the two suppliers are unaware of each other's production status and thus make production decisions independently. Blockchain implementation would allow real-time sharing of production-related information between the suppliers and the manufacturer.

In our model, we assume that the information on a blockchain involving supplier 1 can generate a signal s_1 about supplier 1's yield when it starts the production. The signal can depend on different types of real-time information on the blockchain, e.g., information about supplier 1's inventory, the reliability and speed of its suppliers, the states of its machines and employees, and other factors that can affect supplier 1's production process. For example, supplier 1 in the farming industry can provide its plants' conditions such as growing health with or without disease. Since the blockchain can record an auditable trail of immutable information, the signal it provides is reliable and verifiable, contrary to the case when a signal is voluntarily provided by the supplier, which can be subject to manipulation. For simplicity, we assume that the signal s_1 perfectly predicts the random yield of supplier 1, i.e., the signal allows supplier 2 to learn of the final output of supplier 1.[4] Therefore, with the blockchain, supplier 2 can make the production decision with knowledge of supplier 1's production decision as well as its output. This can potentially make the supply chain more efficient and reduce costs from waste or inventory due to the random fluctuations of supplier 1.

[4]Our results and intuition hold when s_1 is positively but not perfectly correlated with the random yield. The results are available upon request from the authors.

3. Benchmark Model: Supply Chain without Blockchain

In this section, we consider the case where a social planner determines the production input quantities of two suppliers according to the market demand d, in order to achieve the maximum profits of the entire supply chain. Since there is no blockchain in use, we assume the social planner cannot use real-time information in production and thus needs to decide the input quantities for suppliers 1 and 2 simultaneously at the beginning of the time period.

The input quantity of supplier 1 is $q_1 \in \left[0, \frac{d}{\alpha}\right]$, since producing more than $\frac{d}{\alpha}$ would guarantee an output $> d$ and be wasteful. We note that it is possible for supplier 1 to have a production input greater than the market demand d since the random yield α can be less than 1. Given q_1, the input quantity of supplier 2 must satisfy $q_2 \in [\alpha q_1, \min\{q_1, d\}]$ to avoid under- or oversupply of component 2 to the manufacturer. Given (q_1, q_2), if the (non-defective) output quantity of component 1 is q_1, then the supply chain's profit is $pq_2 - cq_1 - cq_2$; if the output quantity of component 1 is αq_1, the supply chain's profit is $p\alpha q_1 - cq_1 - cq_2$. Therefore, the supply chain's expected profit is

$$C_{SC} = \frac{pq_2 + p\alpha q_1}{2} - cq_1 - cq_2 = \left(\frac{p\alpha}{2} - c\right) q_1 + \left(\frac{p}{2} - c\right) q_2. \tag{1}$$

In the following proposition, we derive the optimal input quantities of two suppliers, q_1^*, q_2^*, and the maximum expected profit of supply chain, C_{SC}^*. The proofs of all propositions are provided in Appendix B.

Proposition 1. *The optimal solution to the social planner's problem without blockchain adoption can be characterized as follows.*

(1) If $0 \le \alpha \le \max\left\{\frac{4c-p}{p}, 0\right\}$, *then* $q_1^* = 0, q_2^* = 0, C_{SC}^* = 0$.

(2) If $\max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \le \frac{2c}{p}$, *then* $q_1^* = d, q_2^* = d, C_{SC}^* = \left[\frac{(1+\alpha)p}{2} - 2c\right] d$.

(3) If $\frac{2c}{p} < \alpha \le 1$, *then* $q_1^* = \frac{d}{\alpha}, q_2^* = d, C_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$.

The proposition shows that the higher the random yield, the higher the optimal input quantities for both suppliers, and the greater the supply chain profit. Intuitively, a higher random yield provider increases the expected profit per unit and thus incentivizes supplier 1 to produce more. Supplier 2 also produces more to better match the expected output quantity of supplier 1, given the manufacturer needs one unit of each component to make the final product.

4. Blockchain and Supply Chain Efficiency

4.1. Centralized supply chain with blockchain

This section considers the central planner's problem for the supply chain equipped with blockchain technology, which provides real-time visibility of the suppliers' operations. The information derived from the blockchain allows the central planner to coordinate the productions of the two suppliers and increase efficiency.

In this case, supplier 1 first decides the production input quantity of component 1 according to the market demand d. If the output quantity of non-defective component 1 is greater than d, those that exceed the market demand will be abandoned, without any cost or residual value. With the blockchain, supplier 2 can observe the production status of supplier 1 in real time. Therefore, supplier 2 decides the production quantity of component 2 when he receives a signal about the output quantity of component 1.

Assume the input quantity of supplier 1 is $q_1 \in \left[0, \frac{d}{\alpha}\right]$. If the output quantity of non-defective component 1 is q_1, the optimal production quantity for supplier 2 is then $q_2 = \min\{q_1, d\}$ and the supply chain's profit is $p \min\{q_1, d\} - cq_1 - c \min\{q_1, d\}$. If the output quantity of non-defective component 1 is αq_1, then the optimal production quantity for supplier 2 is $q_2 = \alpha q_1$ and the supply chain's profit is $p\alpha q_1 - cq_1 - c\alpha q_1$. Therefore, the supply chain's expected profit is

$$B_{SC} = \frac{p \min\{q_1, d\} - c \min\{q_1, d\} + (p - c)\alpha q_1}{2} - cq_1. \tag{2}$$

The following proposition describes the optimal input quantity of supplier 1, q_1^*, and the maximum expected profit of supply chain, B_{SC}^*. Note that q_2^* is determined by the output of supplier 1 as above.

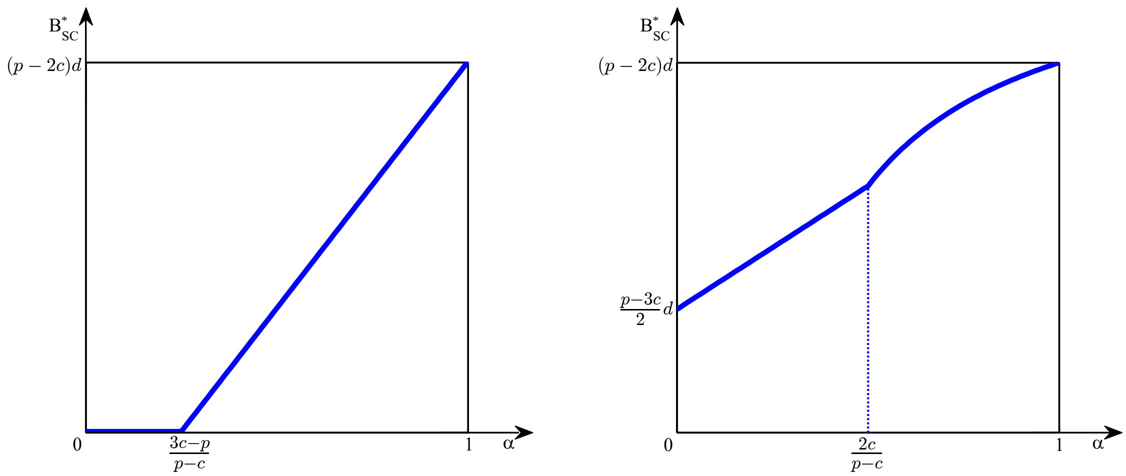
Proposition 2. *The optimal policies and expected supply chain profit for the centralized supply chain with blockchain are as follows.*

(1) If $0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$*, then* $q_1^* = 0$ *and* $B_{SC}^* = 0$.

(2) If $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$*, then* $q_1^* = d$ *and* $B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2}d$.

(3) If $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$*, then* $q_1^* = \frac{d}{\alpha}$ *and* $B_{SC}^* = \left(p - c - \frac{c}{\alpha}\right)d$.

To illustrate the results in Proposition 2, we fix the values of p, c and plot the maximum expected supply chain profit as a function of the random yield α in $(0, 1]$ in Figure 2. We illustrate the results for $2c < p \leq 3c$ and $p > 3c$ in Panels (a) and (b), respectively. For $2c < p \leq 3c$, B_{SC}^* always equals to 0 when $\alpha < \frac{3c-p}{p-c}$, and is linearly increasing for greater values of α. The intuition is that when the random yield is sufficiently low and profit margin not very high, the supply chain as a whole is not profitable. For $p > 3c$, B_{SC}^* is monotonically increasing in $(0, 1]$, but the increasing pattern is first linear and then concave as α increases. The concave function is due to the fact that the optimal input quantity for supplier 1 becomes d/α once α is large enough. This quantity is decreasing in α, because when α is already high, increasing α further reduces the uncertainty faced by supplier 1. In addition, Proposition 2 also implies that for fixed α, the optimal input quantity of supplier 1 is weakly increasing in the profit margin p/c, consistent with the notion that higher profit margin incentivizes more production, holding the risk (random yield) constant.



(a) $2c < p \leq 3c$

(b) $p > 3c$

Figure 2: Illustration of the relationship between α and B^*_{SC}

4.2. Comparison of supply chains without and with blockchain

In Proposition 1 and Proposition 2, we derive the optimal production input quantities and the maximum expected profit for the supply chains without and with blockchain, respectively. In this subsection, we compare the two cases and investigate the effects of blockchain adoption on the optimal policy and profit of the supply chain.

To facilitate the comparison, we summarize the results of Proposition 1 and Proposition 2 in Table 1. We also plot the five cases in Table 1 as five regions of parameter values for the random yield α and the profit margin p/c in Figure 3. Table 1 shows that, in the cases I and V, the optimal policies and maximum supply chain profits are identical without and with blockchains. Therefore, the comparison is nontrivial only in cases II, III and IV. We denote the difference between the maximum expected profit of the supply chains with blockchain and without blockchain by $\Delta_{BC} = B^*_{SC} - C^*_{SC}$.

Proposition 3. *The benefit of blockchain to the supply chain is always non-negative, i.e.,* $\Delta_{BC} \geq 0$*.*

Proposition 3 proves that the maximum expected profit of the supply chain utilizing

Table 1: Comparison between supply chain with blockchain and without blockchain

	Supply chain with blockchain		Supply chain without blockchain	
	Optimal input quantity	Maximum expected profit	Optimal input quantity	Maximum expected profit
$I: 0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$	$q_1^* = 0$	$B_{SC}^* = 0$	$q_1^* = 0, q_2^* = 0$	$C_{SC}^* = 0$
$II: \max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \max\left\{\frac{4c-p}{p}, 0\right\}$	$q_1^* = d$	$B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2} d$	$q_1^* = 0, q_2^* = 0$	$C_{SC}^* = 0$
$III: \max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \leq \frac{2c}{p}$	$q_1^* = d$	$B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2} d$	$q_1^* = d, q_2^* = d$	$C_{SC}^* = \left[\frac{(1+\alpha)p}{2} - 2c\right] d$
$IV: \frac{2c}{p} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$	$q_1^* = d$	$B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2} d$	$q_1^* = \frac{d}{\alpha}, q_2^* = d$	$C_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$
$V: \min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$	$q_1^* = \frac{d}{\alpha}$	$B_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$	$q_1^* = \frac{d}{\alpha}, q_2^* = d$	$C_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$

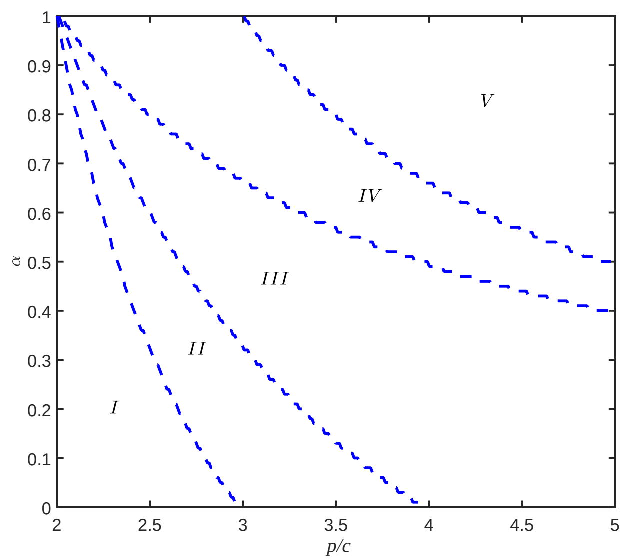


Figure 3: Different comparison cases as regions of model parameters

blockchain is always greater than or equal to that of the supply chain without blockchain. The benefit of blockchain utilization is two-fold: (1) the real-time visibility of production information enables supplier 2 to better coordinate its production with supplier 1; (2) such coordination also enables supplier 1 to choose a more optimal production quantity.

The following proposition studies how the benefit of blockchain adoption depends on the key model parameters: random yield and profit margin.

Proposition 4. *(1) When $p \leq 4c$, Δ_{BC} is increasing in the random yield α for $\alpha \leq \frac{4c-p}{p}$ and decreasing in α for $\alpha > \frac{4c-p}{p}$; furthermore, Δ_{BC} is increasing in the profit margin p/c for $p/c \leq \frac{4}{1+\alpha}$ and decreasing in p/c for $p/c > \frac{4}{1+\alpha}$.*
(2) When $p > 4c$, Δ_{BC} is decreasing in α and p/c, and achieves the maximum when $\alpha = 0$.

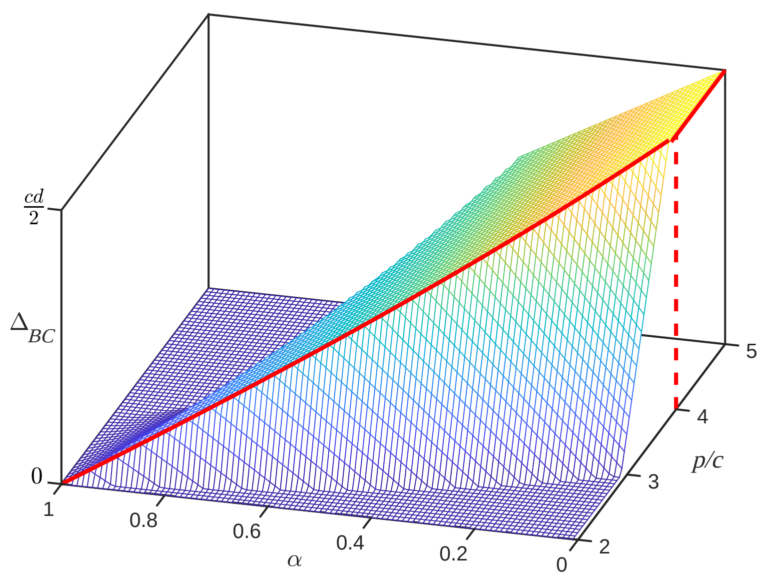


Figure 4: The benefit of blockchain Δ_{BC} and model parameters

We plot the blockchain's benefit on the supply chain as a function of model parameters in Figure 4. The figure and the proposition show that, when the profit margin is not too high ($p \leq 4c$), or when the final product is an "ordinary good," the blockchain surplus is non-monotone in the random yield and the profit margin of the final product. Intuitively, when the random yield is very low, increasing it will enhance the overall profits of the supply chain and thus the associated benefit of blockchain as well (sustenance effect). When the random yield is high, increasing it further will reduce the uncertainty in production and decrease the benefit from blockchain adoption (uncertainty effect). The intuition regarding the non-monotone dependence of blockchain's benefit on profit margin is as follows. When profit margin is very low, the sustenance effect kicks in and the benefit from blockchain adoption increases with profit margin; when profit margin is already high, supplier 1 always has strong incentives to produce and thus the benefit offered by blockchain is limited (production incentive effect). Interestingly, when the final product is a "luxury good," i.e., when its profit margin is very high ($p > 4c$), the blockchain surplus is monotonically decreasing in the random yield and profit margin. This is because the uncertainty effect and production incentive effect previously discussed dominate the sustenance effects for luxury goods.

5. Decentralized Supply Chain with Blockchain

5.1. Decentralized supply chain with wholesale contracts

We now consider a decentralized system where the manufacturer first determines the order quantity for each supplier, and then the two suppliers select the production quantities that are best for them. The trades between the manufacturer and the suppliers are based on wholesale contracts. For tractability purposes, we assume the wholesale prices of two suppliers are exogenous and the same, $w \in (c, \frac{p}{2})$ (Dong and Rudi 2004; Ang et al. 2017). Note that such a setting applies to a wide variety of business transactions wherein the downstream retailer/wholesaler is the dominant player. For example, Walmart and Costco have been notoriously known to impose wholesale prices on their suppliers. We further assume common knowledge, in that each supplier knows the other's costs and yield distributions.

The sequence of events is as follows. (1) The manufacturer places orders to supplier 1 with the quantity $o_1 \in \left[0, \frac{d}{\alpha}\right]$ and to supplier 2 with the quantity $o_2 \in [0, \min\{o_1, d\}]$. It should be noted that due to the yield uncertainty of supplier 1, the manufacturer's order quantity for supplier 1 must be greater than or equal to that of supplier 2, so as to stimulate supplier 1 to produce more components, even though both components are required in equal quantity for the manufacturer's production. (2) The two suppliers simultaneously decide their production quantities q_1, q_2, based solely on maximizing their individual profits. This is a Stackelberg game where the leader is the manufacturer and the followers are the two suppliers. (3) The output quantities of two suppliers are realized. The manufacturer pays for and receives all components produced by two suppliers, as long as they do not exceed the order quantities o_1, o_2. Supplier 1 will not deliver more than what is ordered by the manufacturer and excess products are discarded. This is a reasonable assumption since the manufacturer's demand is known in the model.

Under such wholesale contracts, for a given order quantity o_2, supplier 2 would always select the production quantity of component 2 to be equal to the order quantity o_2, that is, its optimal input quantity is $q_2^* = o_2$. The corresponding profit of supplier 2 is $D_{S_2}^* = (w-c)o_2$. For a given order quantity o_1, supplier 1's production quantity satisfies $q_1 \in \left[0, \frac{o_1}{\alpha}\right]$. Supplier 1's expected profit is

$$D_{S_1} = \frac{1}{2} w \min\{q_1, o_1\} + \frac{1}{2} w\alpha q_1 - cq_1. \tag{3}$$

The following proposition describes supplier 1's optimal input quantity q_1^* and the maximum expected profit $D_{S_1}^*$.

Proposition 5. *For a given order quantity o_1,*
(1) If $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0\right\}$, then $q_1^* = 0$ and $D_{S_1}^* = 0$.
(2) If $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, then $q_1^* = o_1$ and $D_{S_1}^* = \left[\frac{1}{2} w(1+\alpha) - c\right] o_1$.
(3) If $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, then $q_1^* = \frac{o_1}{\alpha}$ and $D_{S_1}^* = \left(w - \frac{c}{\alpha}\right) o_1$.

Next, using the optimal policies of the suppliers, we determine the optimal ordering decision for the manufacturer. Given supplier 1 and supplier 2's optimal production quantities q_1^*, q_2^*, the manufacturer's expected profit function is

$$D_M = -wo_2 + \frac{1}{2}\left[p \min\{q_1^*, o_2\} - w \min\{q_1^*, o_1\}\right] + \frac{1}{2}\left[p \min\{\alpha q_1^*, o_2\} - w\alpha q_1^*\right]. \tag{4}$$

From Equation (4) and Proposition 5, we obtain the manufacturer's optimal ordering decisions o_1^*, o_2^* and maximum expected profit D_M^* in the following proposition.

Proposition 6. *The optimal ordering policy of the manufacturer is as follows.*

(1) When $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\}$, $o_1^* = o_2^* = 0$ *and* $D_M^* = 0$.

(2) When $\max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\}$, $o_1^* = o_2^* = d$ *and* $D_M^* = \left[\frac{1}{2}p + \frac{1}{2}p\alpha - \frac{1}{2}(3+\alpha)w\right] d$.

(3) When $\min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, $o_1^* = \frac{d}{\alpha}, o_2^* = d$ *and* $D_M^* = \left[p - \frac{(1+3\alpha)w}{2\alpha}\right] d$.

(4) When $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, $o_1^* = o_2^* = d$ *and* $D_M^* = (p - 2w)d$.

From Proposition 5 and Proposition 6, we derive the complete solution of the decentralized supply chain, including the optimal policies and maximum expected profits of each party in the supply chain, and summarize them in Table 2.

Table 2: The optimal input quantities and profits for the decentralized supply chain

	Optimal input quantity	Maximum expected profit
$0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\}$	$q_1^* = q_2^* = 0$	$D_M^* = D_{S_1}^* = D_{S_2}^* = D_{SC}^* = 0$
$\max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\}$	$q_1^* = q_2^* = d$	$D_M^* = \left[\frac{1}{2}p + \frac{1}{2}p\alpha - \frac{1}{2}(3+\alpha)w\right] d$, $D_{S_1}^* = \left[\frac{1}{2}w(1+\alpha) - c\right] d, D_{S_2}^* = (w-c)d$, $D_{SC}^* = \left[\frac{(1+\alpha)p}{2} - 2c\right] d$
$\min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$	$q_1^* = \frac{d}{\alpha}, q_2^* = d$	$D_M^* = \left[p - \frac{(1+3\alpha)w}{2\alpha}\right] d$, $D_{S_1}^* = \left[\frac{1}{2}w(1+\alpha) - c\right] \frac{d}{\alpha}$, $D_{S_2}^* = (w-c)d$, $D_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$
$\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$	$q_1^* = \frac{d}{\alpha}, q_2^* = d$	$D_M^* = (p-2w)d$, $D_{S_1}^* = (w - \frac{c}{\alpha})d$, $D_{S_2}^* = (w-c)d$, $D_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$

5.2. *Supply chain coordination with decentralized contracts*

Due to the lack of coordination among parties, the traditional decentralized supply chain with wholesale contracts, in general, cannot achieve optimal profit for the supply chain without blockchain adoption (the benchmark case in Section 3), let alone for the centralized supply chain with blockchain adoption. In addition, the extent of information available and verifiable on the blockchain is also important. We consider two possible scenarios: (1) a "high-level" blockchain in which both inputs and outputs of suppliers are observable and verifiable, and (2) a "low-level" blockchain in which only outputs of suppliers are verifiable.

The following proposition shows it is possible to design "smart contracts" with revenue sharing to achieve coordination of the decentralized supply chain with blockchain. In other words, all parties are better off than in the case without blockchain and the optimal supply chain profit (as in the centralized case with blockchain) is achieved.[5]

Proposition 7. *a) When both production input and output information are verifiable on the blockchain, the supply chain with the blockchain can achieve coordination by revenue sharing and "smart" wholesale contracts with contingent quantities.*

b) When only the production output information are verifiable on the blockchain, the supply chain with the blockchain can achieve coordination by revenue sharing and "smart" contracts with varying price schedules.

We explain the intuition of the proposition below and leave the details of the proof to the Appendix. Our solutions regarding the decentralized supply chain with wholesale contracts (Table 2) and the centralized supply chain with blockchain adoption (Table 1) reveal that there are three non-trivial cases for the supply chain coordination, corresponding to regions with different forms of optimal policies with and without blockchains, which we summarize in Table 3. By adopting blockchain, the maximum expected profit of the entire supply chain will be increased, but some party's expected profit may decline. We denote the profits of suppliers 1 and 2 and the manufacturer with blockchain by $B^*_{S_1}$, $B^*_{S_2}$, and B^*_M, respectively, assuming that the suppliers take their production quantity to be the same as the optimal production quantities in the centralized supply chain with blockchain adoption and all parties trade with wholesale contracts as before. Recall that $D^*_{S_1}$, $D^*_{S_2}$, and D^*_M

[5] For simplicity, we abstract away from the adoption costs of blockchain. When there are adoption costs, supply chain coordination is achievable as long as the total supply chain profit gain due to blockchain is greater than the costs.

represent the profits of the suppliers and manufacturer in the decentralized supply chain without blockchain. Table 3 compares the companies' profits with and without blockchain for each case.[6]

Table 3: The coordination of the decentralized supply chain with blockchain

	Optimal input quantity for supply chain with blockchain	Optimal input quantity for decentralized supply chain without blockchain	$B^*_{S_1} - D^*_{S_1}$	$B^*_{S_2} - D^*_{S_2}$	$B^*_M - D^*_M$
Case 1	$q_1^* = d$	$q_1^* = q_2^* = d$	$= 0$	< 0	> 0
Case 2	$q_1^* = d$	$q_1^* = \frac{d}{\alpha}, q_2^* = d$	< 0	< 0	> 0
Case 3	$q_1^* = \frac{d}{\alpha}$	$q_1^* = q_2^* = d$	< 0	$= 0$	> 0

In each of the three cases, proper decentralized contracts, given blockchain adoption, need to be designed to achieve supply chain efficiency. For example, in Case 2, the optimal production quantity for supplier 1 without blockchain is $q_1^* = \frac{d}{\alpha}$, greater than the optimal quantity d with blockchain. With the high-level blockchain, the manufacturer can write a wholesale contract and directly specify the input quantity $q_1 = d$ since it is verifiable and contractable via the blockchain. With the low-level blockchain, the manufacturer can only observe the output quantity $\hat{q}_1$ of supplier 1 where $\hat{q}_1 = q_1$ or αq_1. In order to induce supplier 1 to select the desired input quantity $q_1 = d$, the manufacturer needs to design an output-based wholesale contract, in which its payment P depends on supplier 1's output quantity $\hat{q}_1$. One such contract is as follows,

$$P = \begin{cases} (\frac{w}{\alpha} - \varepsilon)\hat{q}_1, & \text{if } 0 \le \hat{q}_1 < \alpha d, \\ (\frac{w}{\alpha} - \varepsilon)\alpha d + \frac{\alpha\varepsilon}{1-\alpha}(\hat{q}_1 - \alpha d), & \text{if } \alpha d < \hat{q}_1 \le d, \\ wd, & \text{if } d < \hat{q}_1 \le \frac{d}{\alpha}, \end{cases}$$

in which $\varepsilon > 0$ is sufficiently small.

Furthermore, in Case 2, both suppliers' profits, given blockchain adoption, are smaller

[6]Detailed derivations are in the proof of Proposition 7 in the Appendix.

than those without blockchain when wholesale contracts are used, while the manufacturer's profit is greater. Therefore, the manufacturer needs to share profits with suppliers 1 and 2 in order for all parties to be willing to adopt blockchain technology. The other cases can be similarly analyzed. In sum, the manufacturer can write smart contracts with revenue sharing provisions to achieve supply chain coordination.

6. Competitive Suppliers that Produce Partially Substitutable Products

In this section, we generalize our main model in Section 2 by considering a supply chain that consists of three suppliers and a manufacturer. The manufacturer procures intermediate product (e.g., processed raw material, parts, or components) of type i from supplier $i \in \{1, 2, 3\}$ respectively to produce two end products with a one-time market demand. Intermediate products 1 and 3 can be assembled into the end product 1, while intermediate products 2 and 3 can be assembled into the end product 2, as shown in Figure 5. Without loss of generality, one unit of end product 1 (2) requires one unit of intermediate product 1 (2) and one unit of intermediate product 3 to produce. End products 1 and 2 are partially substitutable for the market demand. Therefore, suppliers 1 and 2 imperfectly compete with each other.

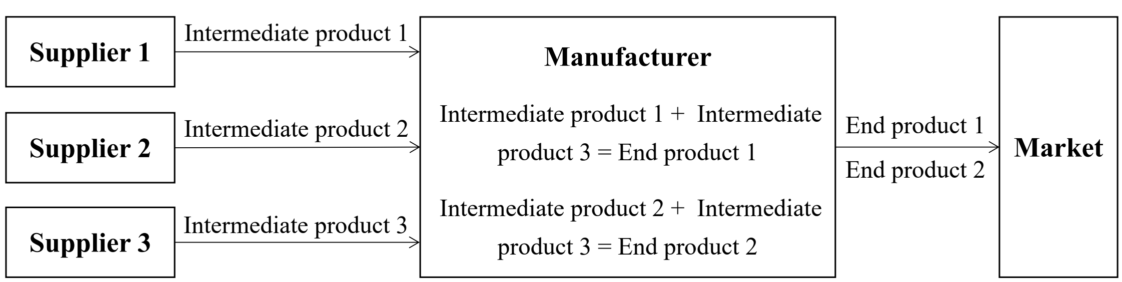


Figure 5: The product flow of the supply chain

We assume that a is the price cap of the end products ($a > c$); each unit of end product i sells at price p_i; the production quantity for end product i is d_i; and $\gamma \in [0, 1)$ captures the cross-substitutability effect of end product j on end product i, $i, j = 1, 2, j \neq i$. In other words, we have the following inverse demand function for product i,

$$p_i = a - d_i - \gamma d_j,\ \ i, j = 1, 2,\ \ j \neq i. \tag{5}$$

Note that, similar to supplier 1, supplier 2 has random yield. Without loss of generality, for a planned production quantity q_2, supplier 2 would generate q_2 units of non-defective type 2 components with probability 0.5, and αq_2 (non-defective) units of type 2 components with probability 0.5. At the beginning of the period, due to the long lead time, the manufacturer places an order o_i to each supplier i for $i = 1, 2$. These orders are manufactured simultaneously due to significant lead time in producing and procuring the intermediate products. After receiving the order, each supplier i decides on the production quantity q_i[7]. In contrast, supplier 3 has access to perfect production technology which always yields the desired production quantity.[8] The manufacturer takes one unit of each type of component and assembles/produces one unit of final product. Without loss of generality, we assume all other costs incurred in assembly or production have already been incorporated into the price of the end product.

6.1. Supply chain without blockchain

When there is no blockchain, the social planner cannot use real-time information in production and thus needs to decide the input quantities for three suppliers simultaneously at the beginning of the time period. The input quantities of the three suppliers are q_1, q_2 and q_3, respectively for suppliers 1, 2, and 3. The optimal input quantities of suppliers must satisfy $\alpha q_1 + \alpha q_2 \leq q_3 \leq q_1 + q_2$. Let $\hat{q}_1$ and $\hat{q}_2$ represent the realized outputs of intermediate product 1 and intermediate product 2 (therefore, $\hat{q}_i = q_i$ or αq_i). To maximize the supply chain's

[7]Both suppliers have imperfect production technology as described earlier

[8]We make this assumption for simplicity of analysis. The results and intuition carry through if supplier 3 also has imperfect production technology.

profit, the manufacturer's production should solve the following programming problem.

$$\begin{aligned} \max_{d_1,d_2} \quad & C_{SC} = (a - d_1 - \gamma d_2)d_1 + (a - d_2 - \gamma d_1)d_2 - c(q_1 + q_2 + q_3) \\ s.t. \quad & 0 \le d_1 \le \hat{q}_1,\ 0 \le d_2 \le \hat{q}_2,\ d_1 + d_2 \le q_3. \end{aligned} \tag{6}$$

We can solve the manufacturer's optimal output decisions, $d_1^* = d_1^*(q_1, q_2, q_3, \hat{q}_1, \hat{q}_2)$ and $d_2^* = d_2^*(q_1, q_2, q_3, \hat{q}_1, \hat{q}_2)$, as closed-form, continuous functions.[9] Finally, the social planner's problem becomes the following,

$$\max_{q_1,q_2,q_3} \quad E[C_{SC}] = E_{\hat{q}_1,\hat{q}_2}[(a - d_1^* - \gamma d_2^*)d_1^* + (a - d_2^* - \gamma d_1^*)d_2^* - c(q_1 + q_2 + q_3)], \tag{7}$$

where the expectation is taken with respect to the realizations of $\hat{q}_1$ and $\hat{q}_2$ given q_1 and q_2. Given that the feasible range of (q_1, q_2, q_3) is closed and bounded, and the objective function is continuous, we have the following proposition.

Proposition 8. *There exists a set of optimal input decisions by the suppliers (q_1^*, q_2^*, q_3^*) that maximize the expected profit of the supply chain without blockchain adoption. The manufacturer's optimal production decisions (d_1^*, d_2^*) are determined as in (6).*

6.2. Centralized supply chain with blockchain

When blockchain is available, real-time visibility of the suppliers' operations allows the central planner to coordinate the productions of the three suppliers and increase efficiency. In particular, the central planner can hold the decision of q_3 until the realizations of $\hat{q}_1$ and $\hat{q}_2$ are known, i.e., the optimal production quantity q_3 should always be equal to the manufacturer's needs $d_1 + d_2$ to eliminate excess production. To obtain the optimal outputs

[9]For the sake of space, we omit the explicit forms of these functions, which are available upon request from the authors.

of the manufacturer d_1^* and d_2^*, we can solve the following problem,

$$\max_{d_1,d_2} \quad C_{SC} = (a - d_1 - \gamma d_2)d_1 + (a - d_2 - \gamma d_1)d_2 - c(q_1 + q_2 + d_1 + d_2) \tag{8}$$
$$s.t. \quad 0 \le d_1 \le \hat{q}_1,\ 0 \le d_2 \le \hat{q}_2.$$

Similarly, we can show the existence of the optimal production quantities.

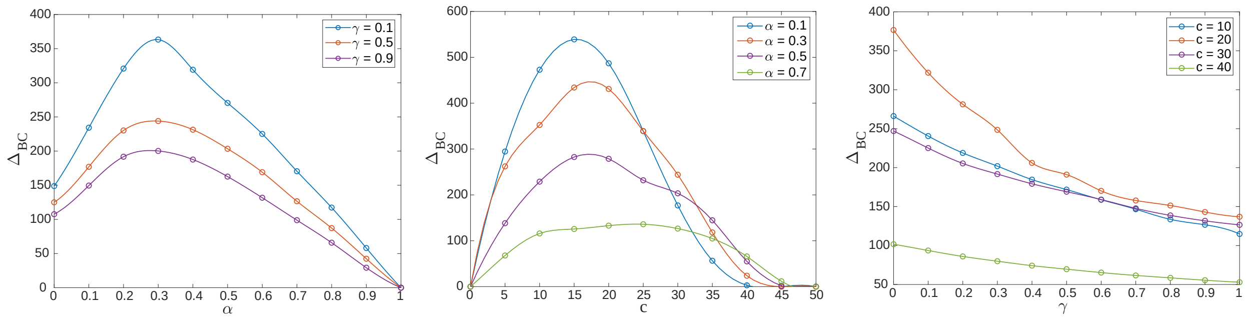
Proposition 9. *There exists a set of optimal production decisions of suppliers 1 and 2, (q_1^*, q_2^*), that maximize the expected profit of the supply chain with blockchain adoption. The manufacturer's optimal production decisions (d_1^*, d_2^*) are determined as in (8). The optimal production strategy of supplier 3 satisfies $q_3^* = d_1^* + d_2^*$.*

We note that the optimal centralized solutions in Proposition 9 can be realized by smart contracts with varying price schedules and revenue sharing similarly as in Section 5.2. We omit the details for brevity.

6.3. Comparison of supply chains without and with blockchain

In this section, we analyze how the benefits of utilizing blockchains and the optimal supplier strategies (with and without blockchain) depend on product substitutability, yield/defect uncertainty, and production cost/profit margin. Given the complexity and intractability of analytical solutions, we provide insights through numerical analysis. We choose the parameter values $a = 100$, $c = 30$, $\alpha = 0.6$, and $\gamma = 0.5$ as the benchmark case. The supply chain profit difference (Δ_{BC}) with and without blockchain is shown in Figure 6.

Figure 6(a) shows how the benefit of blockchain Δ_{BC} depends on the random yield α and the product substitutability γ. The figure shows that the blockchain's benefit is again first increasing and then decreasing in the random yield α, consistent with the "sustenance effect" and "uncertainty effect" for extreme values of α discussed before. Interestingly, the benefit of blockchain is larger when the two intermediate goods 1 and 2 have low substitutability. The intuition is a "diversification effect." When the two goods are less substitutable, the



(a) α and γ (b) c and α (c) γ and c

Figure 6: The benefits of blockchain Δ_{BC}

idiosyncratic shocks in their random yields do not diversify away and have to be individually absorbed by the manufacturer, generating more inefficiency in the supply chain and more room for blockchain to improve. For perfectly substitutable goods, shocks to their production outputs hedge each other and the manufacturer is only subject to the aggregate uncertainty generated by their random yields, thus blockhain does not give rise to as much benefit.

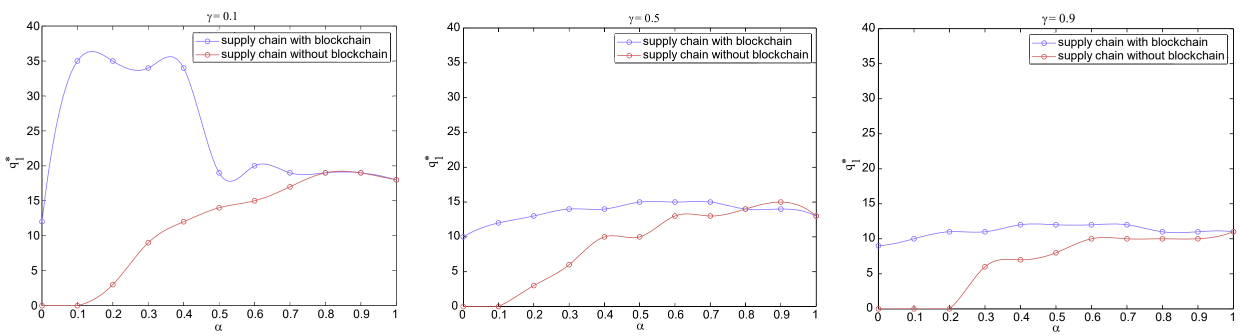
Figure 6(b) presents how the benefit of blockchain Δ_{BC} depends on the production cost c and the random yield α. The figure shows that the benefit of blockchain is non-monotonic in the production cost. When the production cost is very low, the suppliers have strong incentives to produce the maximum possible quantities ($q_{i,max} = d_i/\alpha$). This will always lead to an excess supply of intermediate goods and there is little blockchain can do to increase the efficiency. When the production cost is too high, the overall supply chain surplus is low and there is also limited benefit from blockchain adoption. The maximum benefit is thus achieved for medium values of production costs.

Figure 6(c) shows how the benefit from blockchain Δ_{BC} depends on γ and c. We observe that the benefit from blockchain adoption is monotonically decreasing in the product substitutability γ and non-monotonic in c, consistent with our findings above.

Figures 7 shows how the optimal production quantity q_1^* varies over the random yield α for different values of product substitutability γ.[10] We first observe that the optimal produc-

[10]Due to the symmetry of suppliers 1 and 2 in the model, their optimal production quantities q_1^* and q_2^* are equal and thus we only need to show one of them.

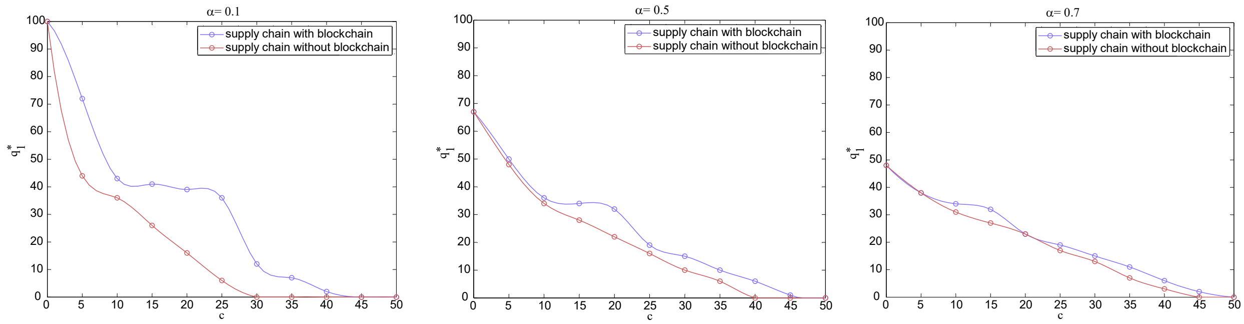
tion quantity q_1^* with blockchain is generally greater than without blockchain. Blockchain reduces ex-post waste and thus allows each supplier to commit to a larger quantity ex-ante. This effect is especially strong when product substitutability is low, since in this case the production risks of the intermediate products do not diversify each other and the blockchain thus has a stronger influence. Second, when the random yield increases, the optimal production quantity for the case with blockchain is non-monotone, consistent with the earlier observed "sustenance" and "uncertainty" effects. In contrast, the optimal production quantity for the case without blockchain generally increases, consistent with the great profits realized due to fewer defective products. Finally, as γ increases, the optimal production quantity q_1^* decreases (for both the case with and without blockchain). As product substitutability increases, competition reduces profit from each product type and thus the optimal quantity.



(a) $\gamma = 0.1$ (b) $\gamma = 0.5$ (c) $\gamma = 0.9$

Figure 7: Supplier 1's optimal input quantity q_1^*: α and γ

Figure 8 shows how the optimal production quantity q_1^* varies over production cost c (for different values of products' random yield α). We continue to observe that the optimal production quantities under blockchain are higher than those without blockchain. Further, consistent with intuition, the production quantity decreases when it is more expensive to produce, i.e., under higher cost c.



(a) $\alpha = 0.1$ (b) $\alpha = 0.5$ (c) $\alpha = 0.7$

Figure 8: Supplier 1's optimal input quantity q_1^*: c and α

7. Blockchain Implementation

To the extent that blockchain can offer substantial benefits to a decentralized supply chain, and given it is a new and evolving technology, we follow with discussion of some valuable considerations regarding implementation of blockchain in the supply chain. To demonstrate the dynamics of both cooperative/complementary suppliers and competing ones, we consider the three-suppliers-one-manufacturer supply chain considered in Section 6 (see also Figure 5). Figure 9 shows the important elements and components for blockchain implementation.

7.1. Components of Blockchain in the Supply Chain

We discuss below the proposed integrated blockchain and supply chain system and how each party functions and interacts with the system.

1. **The Blockchain:** The proposed blockchain system consists of the following key elements.

    - **Blockchain platform:** Blockchain platform is the decentralized or distributed network where blockchain data and programs reside. There are many platform options, including public blockchains such as Ethereum and Solana, and permissioned blockchains such as IBM's Hyperledger and R3's Corda. The choice of platform depends on specific applications and considerations such as data privacy, costs, and security. We will discuss various choices and considerations for the blockchain platform and the associated infrastructure later in this section.

- **Smart contracts**: Smart contracts are an important part of the implementation of the optimal decentralized solution. Smart contracts in our model are programs that rely on real-time data on the blockchain. Given that such programs are pre-written on the blockchain platform and immutable, they are self-enforceable.
- **User interface**: Different parties in the blockchain system share real-time production data and interact with the blockchain via a user interface. The user interface can be directly integrated with a production management and control system, or connected to smart internet-of-things (IoT) sensors that can record and upload data. The designer of the blockchain also needs to consider how to ensure the accuracy of data put on the blockchain. Production outputs can be easily verified later with inventory and shipping records; production inputs can be cross-checked, for example, with purchase and inventory records. Data analytic tools such as artificial intelligence can also be used to analyze data for accuracy.
- **Product digitalization**: The information exchange between the blockchain and the physical world requires the digitization of production information. This can be achieved by utilizing various IoT technologies, e.g., UPC, QR code, RFID (radio-frequency identification), and NFC (near-field communication). Applying these technologies to the input materials, intermediate components, and final products as they are shipped, used, or produced will ensure real-time production information is shared with the blockchain.

2. **The Suppliers:** The suppliers are key providers of information on the blockchain. By integrating the blockchain user interface with their production and management systems, they can share supply-relevant information with the supply chain, such as inventory updates, shipping records, production progress, and machine/environment

conditions. Based on the model, it is particularly important for the suppliers to provide the supply chain with information about the yield of non-defective products, as smart contracts can be contingent upon such information. Data shared among suppliers via the blockchain can also serve as verifiable records upon which the suppliers can potentially rely in transactions with their other business partners, e.g., their upstream suppliers or banks.

3. **The Manufacturer:** The manufacturer is a central player on the blockchain and in the supply chain. Given its hub position, the manufacturer is expected to initiate the smart supply contracts with the suppliers. Such contracts utilize real-time data on the blockchain and can increase supply chain efficiency by considerably reducing surpluses and deficits of the intermediate products. Furthermore, the manufacturer has a direct relationship with both its suppliers and the retailer. The feedback from such relations is valuable in both directions. The manufacturer can share useful information on sales, shipping, and defective components with the blockchain. Such information can provide important input variables for the smart contracts. Further information about defective components can also help suppliers improve product quality in the future.

4. **The Retailer:** The retailer can record sales information and product feedback on the blockchain, such as product defects and product reviews. Such feedback can be beneficial for the manufacturer and particularly for the suppliers, given there is no direct relationship between the retailer and suppliers. This is not directly related to our model with supply uncertainty, but can still enhance the overall efficiency of the supply chain.

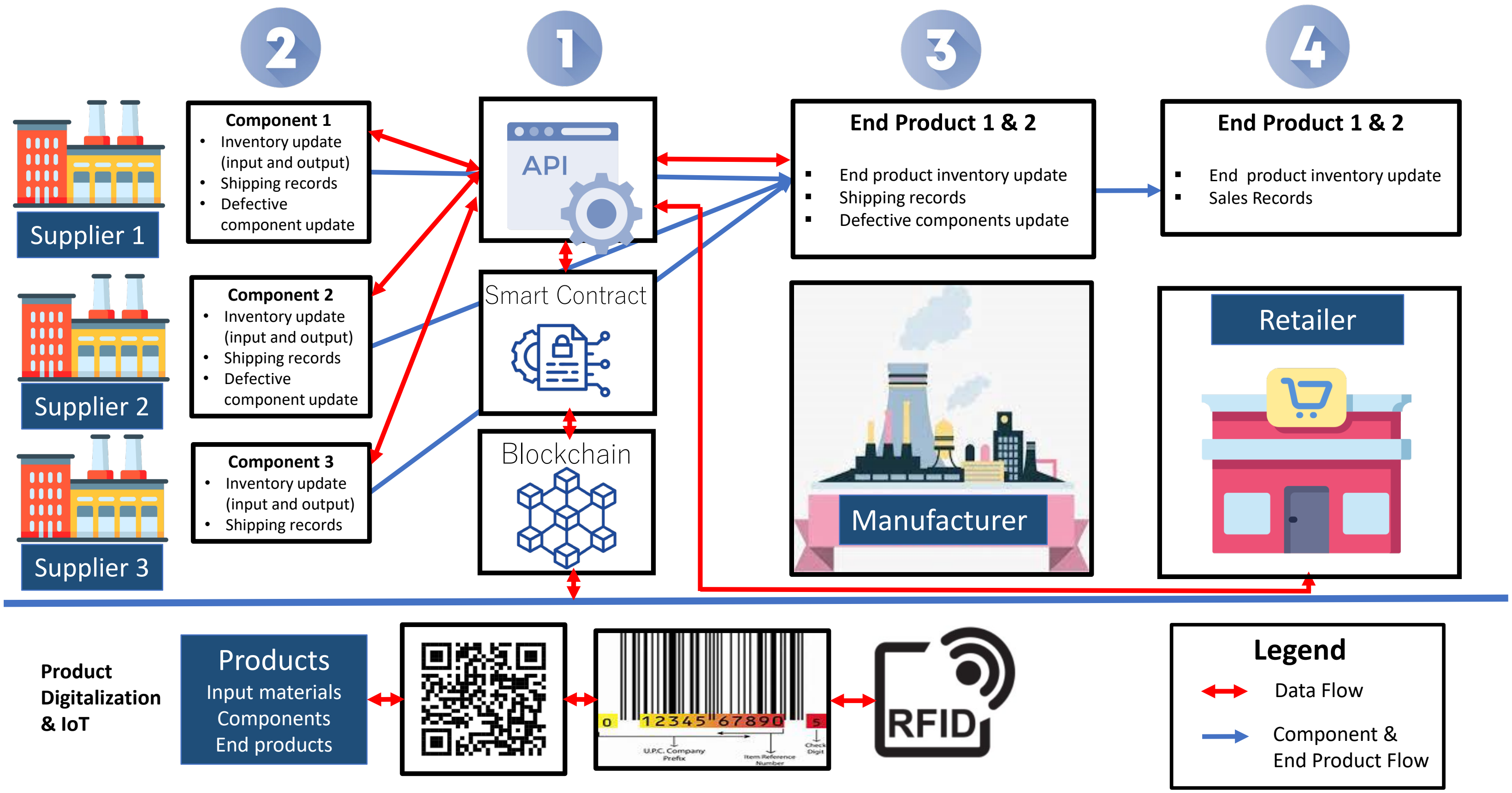


Figure 9: The implementation of a blockchain system

7.2. Practical Considerations in Blockchain Implementation

There are several elements to consider regarding the decision to adopt blockchains. Here we discuss some implementation considerations in detail with regard to blockchain platforms, costs, privacy, and security.

7.2.1. Permissionless vs. permissioned blockchains

Supply chain companies need to decide whether to use a permissionless or permissioned blockchain platform. Permissionless or public blockchain platforms, such as Ethereum, Solana, and Polygon, have the benefits of being transparent, reliable, immutable, and open-sourced. Maintenance costs can also be small (e.g., transaction costs on the Solana network are only around $0.00025 per transaction and the network maintenance is shared by a public network of validators). However, public blockchains offer limited protection of data privacy, lower scalability,[11] and limited choices of consensus and governance mechanisms for the blockchain. Permissioned blockchains are typically more customizable, provide more privacy of data, and allow larger capacity for data and throughput. However, they may also carry higher development/maintenance costs due to having a dedicated system. Several big-tech companies now offer integrated blockchain services, e.g, Amazon AWS, IBM Hyperledger, Oracle, and Microsoft Azure. Overall, in the current application, given that real-time production data on the blockchain are mainly used for improving supply-chain efficiency and that firms may not be willing to share the data publicly, permissioned blockchains would be a better choice.

[11]Ethereum currently only handles fewer than 100 transactions per second. The newer public platforms such as Solana and Polygon can, in theory, support more than 50,000 transactions per second, although the network can at times be unstable and suffer outages. See for example "Once billed as a rising star in crypto, Solana's sixth outage this month–and founder's 'lol' tweet–frustrates traders," Emily Nicolle, January 25, 2022, *Bloomberg.*

7.2.2. Costs

Blockchain adoption will incur various costs. The initial adoption typically involves substantial investment costs, including consultation, design, development, purchase, and installation costs. As blockchain systems become more standardardized, such costs will reduce. After a blockchain is in place, the supply chain participants need to pay for maintenance and monitoring on a regular basis. Considering the manufacturer reaps the most direct benefits from adopting blockchain, the most feasible solution might be for the downstream company to bear the majority of the design and development costs and share the maintenance costs with the upstream suppliers. The Food Chain project by Walmart and IBM operates in this fashion.[12]

7.2.3. Data storage, security, and privacy

Given that blockchains enable data and information sharing among multiple business entities, data security and privacy are important issues to consider. In the current model, data on the blockchain are shared among all players, as sharing the data is ultimately beneficial to all parties. However, when multiple horizontal players are competing, situations may arise whereby information sharing benefits a firm's competitors. In such a case, one possible solution is to construct more localized blockchains, e.g. private channels of blockchains that only include certain parties (Hyperledger), or to consider encrypted data to which only authorized parties have access. Blockchain participants can also choose to store publicly shareable information on the blockchain and other sensitive or voluminous data off-chain (with characteristic data such as hashes stored on the chain for linkage or verification purposes).[13] Given major cloud computing platforms (e.g., AWS and Azure) have offered blockchains as a service, storing data on the cloud with the appropriate access rights to the relevant parties

[12] "Walmart-Led Blockchain Effort Seeks Farm-to-Grocery-Aisle View of Food Supply Chain," Kim S. Nash, June 25, 2018, *Wall Street Journal*.

[13] See, for example, Cao et al. (2019).

could also be a feasible solution.

8. Conclusion

In this paper, we study whether or not, and to what extent, real-time information visibility on the blockchain increases supply chain efficiency. In the main model, we consider two suppliers of intermediate components and one manufacturer of final product, with one supplier having an imperfect technology that may generate defective products. We show that a blockchain that shares verifiable real-time production information among suppliers and the manufacturer can improve supply chain efficiency. The benefit of blockchain adoption is non-monotonic in the random yield of components and the profit margin of the final product. In the decentralized setting, the optimal contracts that implement the optimal supply chain allocation are "smart contracts" contingent upon information stored on the blockchain. We extend the main model to consider competing imperfect suppliers, where the downstream manufacturer produces two partially substitutable products in the market. We demonstrate that blockchain technology continues to improve supply chain efficiency. Furthermore, the benefit of blockchain decreases with product substitutability. We also discuss in detail the implementation of blockchain in a supply chain with cooperating/competing suppliers and manufacturer.

There are several directions for future research. First, while we have considered deterministic demand from the market for tractability, one could extend the analysis to stochastic demand. Second, considering a supply chain with multiple periods could potentially provide additional insights. Finally, one could consider multiple competing manufacturers in the downstream supply chain. These extensions would help shed more light on the functions of blockchain technology in supply chains.

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Appendix A: Blockchains and Smart Contracts

Blockchains, or more generally, distributed ledger technologies, are based on several advancements in computer sciences, including hashing, digital signature, distributed systems, and consensus mechanisms. Although these individual elements were introduced in earlier work, Nakamoto (2008) first brings them all together and proposes a peer-to-peer distributed transaction and ledger system, i.e., Bitcoin. Bitcoin aims to solve a number of problems facing decentralized digital currencies, such as double-spending, consensus, economic incentives of peer nodes, and security. Since then, many more applications of blockchains have been developed, including fundraising through initial coin offerings on social platforms, trades and settlements of financial securities, supply chain management, healthcare data management, and many others. The key features of a blockchain typically include transparency, immutability, security, and resilience, which make blockchain an attractive option in financial or business applications. We refer the reader to Harvey (2016) and Yermack (2017) for some excellent introductions to the basics and business applications of blockchains.

Although early public blockchains and cryptocurrencies (Bitcoin, Litecoin, Zcash) are designed for the currency and payment functions, Ethereum is the first public blockchain that provides a general-purpose platform. In particular, Ethereum enables computing and data storage on the blockchain that are verifiable on the entire network. This makes "smart contracts," or programs on the blockchain that process data and automate business logics, possible.

Smart contracts have enabled a wide range of applications, including the recent fast-growing applications in decentralized financing (DeFi). DeFi is a catch-all term that refers to decentralized financial solutions that are disruptive to the traditional financial services industry. For example, decentralized exchanges (Uniswap, 0x, Augur) utilize smart contracts to enable the exchange of digital assets and implementation of complicated securities such as derivatives in a trustless, decentralized setting. Other important applications of DeFi include decentralized lending (Maker, Aave, Compound), tokenized assets (WBTC, RenBTC), and stablecoins (Tether, USDC, Dai). The ease of use and low entrance hurdle offered by DeFi fueled its popularity. Nasdaq first introduced a DeFi index, DeFix, in 2019.[14] In 2020, the trading volume on Uniswap exceeded that on Coinbase Pro, the biggest centralized cryptocurrency exchange in the US (Godbole 2020). See Harvey et al. (2021) for a survey of the recent developments in DeFi.

While public or permissionless blockchains such as Bitcoin or Ethereum typically allow anyone to join as peer nodes in the network, a permissioned blockchain only includes identified nodes that can be trusted to some extent. The nodes on the network can still be motivated by individual economic incentives, for example, permissioned blockchains can be operated by members of industry consortiums. One main benefit of the permissioned blockchain is it can adopt a more efficient consensus algorithm (e.g., majority voting) and thus prevent the energy waste associated with mining and proof-of-work (the consensus algorithm currently employed by Bitcoin and many other cryptocurrencies; see, for example, Chiu and Koeppl (2019) and Cong et al. (2021a). Permissioned blockchains are also more secure from attacks and can handle higher throughput. Open-source software for permissioned blockchains include Corda (by R3), Hyperledger Fabric (by IBM), and Quorum (by J.P. Morgan). Various companies also developed their proprietary permissioned blockchain systems. For example, Digital Asset Holdings helped the Australian Stock Exchange in transitioning their trading and settlements to a new system based on permissioned blockchains.[15]

[14] See details at `https://defix.fund/`.

[15] See "Australia Banks on Bitcoin Tech to Keep Tabs on Stocks," Robb Stewart, December 6, 2017, *Wall Street Journal*.

Appendix B: Proofs of Propositions

Proof of Proposition 1

Proof. The coefficient of q_2, $\frac{p}{2} - c$, is always positive. The following discussion is based on the value of the coefficient of q_1.

When $\frac{p\alpha}{2} - c > 0$, i.e. $\frac{2c}{p} < \alpha \leq 1$, C_{SC} is monotonically increasing with respect to q_1 and q_2, so the optimal input quantities of two suppliers are $q_1^* = \frac{d}{\alpha}$, $q_2^* = d$, and the maximum expected profit of supply chain is $C_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$.

When $\frac{p\alpha}{2} - c \leq 0$ and $\frac{p}{2} - c > c - \frac{p\alpha}{2}$, i.e. $\max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \leq \frac{2c}{p}$, C_{SC} is monotonically decreasing with respect to q_1 and monotonically increasing with respect to q_2, but the increase with respect to q_2 is faster than the decrease with respect to q_1. Therefore, the optimal input quantities of two suppliers are $q_1^* = d, q_2^* = d$, and the maximum expected profit of supply chain is $\Pi_{SC}^{C*} = \left[\frac{(1+\alpha)p}{2} - 2c\right] d$.

When $\frac{p\alpha}{2} - c \leq 0$ and $\frac{p}{2} - c \leq c - \frac{p\alpha}{2}$, i.e. $0 < \alpha \leq \max\left\{\frac{4c-p}{p}, 0\right\}$, C_{SC} is monotonically decreasing with respect to q_1 and monotonically increasing with respect to q_2, but the decrease with respect to q_1 is faster than the increase with respect to q_2. Therefore, the optimal input quantities of two suppliers are $q_1^* = 0, q_2^* = 0$, and the maximum expected profit of supply chain is $\Pi_{SC}^{C*} = 0$.

In sum, when $0 < \alpha \leq \max\left\{\frac{4c-p}{p}, 0\right\}$, then $q_1^* = 0, q_2^* = 0, C_{SC}^* = 0$; when $\max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \leq \frac{2c}{p}$, then $q_1^* = d, q_2^* = d, C_{SC}^* = \left[\frac{(1+\alpha)p}{2} - 2c\right] d$; when $\frac{2c}{p} < \alpha \leq 1$, then $q_1^* = \frac{d}{\alpha}, q_2^* = d, C_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$. □

Proof of Proposition 2

Proof. We divide the value interval $L = \left[0, \frac{d}{\alpha}\right]$ of q_1 into two subintervals for discussion respectively: $L_1 = [0, d)$ and $L_2 = \left[d, \frac{d}{\alpha}\right]$.

For $q_1 \in L_1 = [0, d)$, $B_{SC} = \left[\frac{(p-c)(1+\alpha)}{2} - c\right] q_1$. When $\frac{(p-c)(1+\alpha)}{2} - c > 0$, i.e. $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq 1$, B_{SC} is monotonically increasing with respect to q_1, so the optimal input quantity is $q_1^{L_1} = d$ and the expected profit is $B_{SC}^{L_1} = \frac{p-3c+(p-c)\alpha}{2} d$. When $\frac{(p-c)(1+\alpha)}{2} - c \leq 0$, i.e. $0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$, B_{SC} is monotonically decreasing with respect to q_1, so the optimal input quantity is $q_1^{L_1} = 0$ and the expected profit is $B_{SC}^{L_1} = 0$.

For $q_1 \in L_2 = \left[d, \frac{d}{\alpha}\right]$, $B_{SC} = \frac{(p-c)d}{2} + \left[\frac{(p-c)\alpha}{2} - c\right] q_1$. When $\frac{(p-c)\alpha}{2} - c > 0$, i.e. $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$, B_{SC} is monotonically increasing with respect to q_1, so the optimal input quantity is $q_1^{L_2} = \frac{d}{\alpha}$ and the expected profit is $B_{SC}^{L_2} = \left(p - c - \frac{c}{\alpha}\right) d$. When $\frac{(p-c)\alpha}{2} - c \leq 0$, i.e. $0 < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$, B_{SC} is monotonically decreasing with respect to q_1, so the optimal input quantity is $q_1^{L_2} = d$ and the expected profit is $B_{SC}^{L_2} = \frac{p-3c+(p-c)\alpha}{2} d$.

Since $\frac{3c-p}{p-c} < 1$, $\frac{2c}{p-c} > 0$ and $\frac{3c-p}{p-c} < \frac{2c}{p-c}$, we have $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \min\left\{\frac{2c}{p-c}, 1\right\}$. Therefore, we discuss the following three cases:

Case 1: $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$.

$B_{SC}^{L_2} - B_{SC}^{L_1} = \left(p - c - \frac{c}{\alpha}\right) d - \frac{p-3c+(p-c)\alpha}{2} d = \frac{-(p-c)\alpha^2+(p+c)\alpha-2c}{2\alpha} d$. Since $-(p-c)\alpha^2 + (p+c)\alpha - 2c$ is greater than or equal to 0 when $\alpha \in (\min\{\frac{2c}{p-c}, 1\}, 1]$, $B_{SC}^{L_2} \geq B_{SC}^{L_1}$ always holds. Therefore, $q_1^* = \frac{d}{\alpha}$ and $B_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$.

Case 2: $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$.

$B_{SC}^{L_1} = B_{SC}^{L_2} = \frac{p-3c+(p-c)\alpha}{2} d$. Therefore, $q_1^* = d$ and $B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2} d$.

Case 3: $0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$.

$B_{SC}^{L_2} - B_{SC}^{L_1} = \frac{p-3c+(p-c)\alpha}{2} d \leq \max\{0, p - 3c\}$. Notice that the prerequisite of this case is $\frac{3c-p}{p-c} > 0$, which is bound to derive $p - 3c < 0$, so $\max\{0, p - 3c\}$=0. Therefore, $q_1^* = 0$ and $B_{SC}^* = 0$.

In sum, when $0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$, then $q_1^* = 0$ and $B_{SC}^* = 0$; when $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$, then $q_1^* = d$ and $B_{SC}^* = \frac{p-3c+(p-c)\alpha}{2} d$; when $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$, then $q_1^* = \frac{d}{\alpha}$ and $B_{SC}^* = \left(p - c - \frac{c}{\alpha}\right) d$. □

Proof of Proposition 3

Proof. When $0 < \alpha \leq \max\left\{\frac{3c-p}{p-c}, 0\right\}$ or $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$, $\Delta_{BC} = 0$.

When $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \max\left\{\frac{4c-p}{p}, 0\right\}$, $\Delta_{BC} = \frac{p-3c+(p-c)\alpha}{2} d > \frac{d}{2} \max\{0, p - 3c\} \geq 0$.

When $\max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \leq \frac{2c}{p}$, $\Delta_{BC} = \frac{(1-\alpha)cd}{2} > 0$.

When $\frac{2c}{p} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$, $\Delta_{BC} = \frac{(p-c)\alpha^2-(p+c)\alpha+2c}{2\alpha} d$. $(p - c)\alpha^2 - (p + c)\alpha + 2c$ is a quadratic convex function of α with the symmetry axis $\frac{p+c}{2(p-c)}$. Since $\frac{p+c}{2(p-c)} - \min\left\{1, \frac{2c}{p-c}\right\} = \max\left\{\frac{3c-p}{2(p-c)}, \frac{p-3c}{2(p-c)}\right\} \geq 0$, $\Delta_{BC} \geq \left\{(p - c)\left[\min\{1, \frac{2c}{p-c}\}\right]^2 - (p + c)\min\left\{1, \frac{2c}{p-c}\right\} + 2c\right\} \frac{d}{2\alpha} = \left[\min\left\{p, \frac{3c^2+pc}{p-c}\right\} - \min\left\{p, \frac{c^2+pc}{p-c}\right\}\right] \frac{d}{2\alpha} \geq 0$.

In sum, $\Delta \geq 0$ always holds. □

Proof of Proposition 4

Proof. The proof of Proposition 3 gives several cases for the value of Δ_{BC}.

(1) When $\max\left\{\frac{3c-p}{p-c}, 0\right\} < \alpha \leq \max\left\{\frac{4c-p}{p}, 0\right\}$, $\Delta_{BC} = \frac{p-3c+(p-c)\alpha}{2} d$ is increasing in both α and p/c.

(2) When $\max\left\{\frac{4c-p}{p}, 0\right\} < \alpha \leq \frac{2c}{p}$, $\Delta_{BC} = \frac{(1-\alpha)cd}{2}$ is decreasing in α and constant in p/c.

(3) Finally, when $\frac{2c}{p} < \alpha \leq \min\left\{\frac{2c}{p-c}, 1\right\}$, $\Delta_{BC} = \frac{(p-c)\alpha^2-(p+c)\alpha+2c}{2\alpha} d$ is decreasing in both α and p/c.

Note that when $p > 4c$, only cases (2) and (3) can happen, and when $p \leq 4c$, all three cases can happen. Taken together, the proposition follows easily.

□

Proof of Proposition 5

Proof. Supplier 1's expected profit depends on the values of q_1 and o_1. For $0 \le q_1 < o_1$, $D_{S_1} = \left[\frac{1}{2}w(1+\alpha) - c\right] q_1$. When $\frac{1}{2}w(1+\alpha) - c \le 0$, i.e. $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0\right\}$, we have $q_1^* = 0$ and $D_{S_1}^* = 0$; when $\frac{1}{2}w(1+\alpha) - c > 0$, i.e. $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le 1$, we have $q_1^* = o_1$ and $D_{S_1}^* = \left[\frac{1}{2}w(1+\alpha) - c\right] o_1$. For $o_1 \le q_1 \le \frac{o_1}{\alpha}$, $D_{S_1} = \left(\frac{1}{2}w\alpha - c\right) q_1 + \frac{1}{2}wo_1$. When $\frac{1}{2}w\alpha - c \le 0$, i.e. $0 < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, we have $q_1^* = o_1$ and $D_{S_1}^* = \left[\frac{1}{2}w(1+\alpha) - c\right] o_1$; when $\frac{1}{2}w\alpha - c > 0$, i.e. $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, we have $q_1^* = \frac{o_1}{\alpha}$ and $D_{S_1}^* = \left(w - \frac{c}{\alpha}\right) o_1$.

Since $\max\left\{\frac{2c}{w} - 1, 0\right\} < \min\left\{\frac{2c}{w}, 1\right\}$, we discuss three cases:

(1) when $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0\right\}$, $\left[\frac{1}{2}w(1+\alpha) - c\right] o_1 \le \left[\frac{1}{2}w\left(1 + \max\left\{\frac{2c}{w} - 1, 0\right\}\right) - c\right] o_1 \le \max\left\{\frac{w}{2} - c, 0\right\} o_1$. Note that the premise of this case is $\max\left\{\frac{2c}{w} - 1, 0\right\} > 0$, i.e., $\frac{2c}{w} - 1 > 0$, which leads to $\frac{w}{2} - c < 0$. Therefore, $\left[\frac{1}{2}w(1+\alpha) - c\right] o_1 \le 0$. Then, $q_1^* = 0$ and $D_{S_1}^* = 0$;

(2) when $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, $q_1^* = o_1$ and $D_{S_1}^* = \left[\frac{1}{2}w(1+\alpha) - c\right] o_1$;

(3) when $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, $\left(w - \frac{c}{\alpha}\right) o_1 - \left[\frac{1}{2}w(1+\alpha) - c\right] o_1 = \frac{-w\alpha^2 + (2c+w)\alpha - 2c}{2\alpha} o_1$. Since $-w\alpha^2 + (2c+w)\alpha - 2c \ge 0$ always holds when $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, $\left(w - \frac{c}{\alpha}\right) o_1 \ge \left[\frac{1}{2}w(1+\alpha) - c\right] o_1$. Then, $q_1^* = \frac{o_1}{\alpha}$ and $D_{S_1}^* = \left(w - \frac{c}{\alpha}\right) o_1$. □

Proof of Proposition 6

Proof. According to Proposition 5, when $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0\right\}$, $D_M = -wo_2$. Then, $o_1^* = o_2^* = 0$ and $D_M^* = 0$.

When $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, $D_M = -wo_2 + \frac{1}{2}(po_2 - wo_1) + \frac{1}{2}[p\min\{\alpha o_1, o_2\} - w\alpha o_1]$. It needs to discuss two cases: (1) when $o_2 < \alpha o_1$, $D_M = (p-w)o_2 - \frac{w(1+\alpha)}{2} o_1$. If $p - w > \frac{w(1+\alpha)}{2\alpha}$, $o_1^* = \frac{d}{\alpha}$ and $o_2^* = d$; if $p - w \le \frac{w(1+\alpha)}{2\alpha}$, $o_1^* = o_2^* = 0$. We can see that both of the two pairs of optimal order quantities satisfy $\alpha o_1 = o_2$. Therefore, $\alpha o_1^* > o_2^*$ is impossible; (2) when $\alpha o_1 \le o_2 \le \min\{o_1, d\}$, $D_M = \frac{p\alpha - (1+\alpha)w}{2} o_1 + (\frac{1}{2}p - w)o_2$. If $p\alpha - (1+\alpha)w > 0$, i.e. $\alpha > \frac{w}{p-w}$, $o_1^* = \frac{d}{\alpha}, o_2^* = d$ and $D_M^* = \left[p - \frac{(1+3\alpha)w}{2\alpha}\right] d$; if $w - \frac{1}{2}p < \frac{p\alpha - (1+\alpha)w}{2} \le 0$, i.e. $\frac{3w-p}{p-w} < \alpha \le \frac{w}{p-w}$, $o_1^* = o_2^* = d$ and $D_M^* = \left[\frac{1}{2}p + \frac{1}{2}p\alpha - \frac{1}{2}(3+\alpha)w\right] d$; if $\frac{p\alpha - (1+\alpha)w}{2} \le w - \frac{1}{2}p$, i.e. $\alpha \le \frac{3w-p}{p-w}$, $o_1^* = o_2^* = 0$ and $D_M^* = 0$.

When $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, $D_M = -wo_1 + (p-w)o_2$. Since $p > 2w$, $o_1^* = o_2^* = d$ and $D_M^* = (p-2w)d$.

In sum, when $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0\right\}$ or $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$ & $\alpha \le \frac{3w-p}{p-w}$, i.e. $0 < \alpha \le \max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\}$, $o_1^* = o_2^* = 0$ and $D_M^* = 0$; when $\max\{\frac{2c}{w} - 1, 0\} < \alpha \le \min\{\frac{2c}{w}, 1\}$ & $\frac{3w-p}{p-w} < \alpha \le \frac{w}{p-w}$, i.e. $\max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\}$, $o_1^* = o_2^* = d$ and $D_M^* = \left[\frac{1}{2}p + \frac{1}{2}p\alpha - \frac{1}{2}(3+\alpha)w\right] d$; when $\max\left\{\frac{2c}{w} - 1, 0\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$ & $\alpha > \frac{w}{p-w}$, i.e. $\min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\} < \alpha \le \min\left\{\frac{2c}{w}, 1\right\}$, $o_1^* = \frac{d}{\alpha}, o_2^* = d$ and $D_M^* = \left[p - \frac{(1+3\alpha)w}{2\alpha}\right] d$; when $\min\left\{\frac{2c}{w}, 1\right\} < \alpha \le 1$, $o_1^* = o_2^* = d$ and $D_M^* = (p-2w)d$. □

Proof of Proposition 7

Proof. As analyzed in Section 5.2, there are three non-trivial cases where the optimal policies for the decentralized supply chain with wholesale contracts (Table 2) are different from those for the centralized supply chain with blockchain (Table 1). These cases are also summarized in Table 3. We examine each case in detail below.
Case 1: $\max\left\{\frac{3c-p}{p-c},0\right\}<\alpha\le\min\left\{\frac{2c}{p-c},1\right\}$ and
$\max\left\{\frac{2c}{w}-1,0,\min\left\{\frac{3w-p}{p-w},\frac{2c}{w}\right\}\right\}<\alpha\le\min\left\{\frac{2c}{w},\max\left\{\frac{w}{p-w},\frac{2c}{w}-1\right\}\right\}$

With blockchain, the maximum expected profit of the supply chain is increased by $B^*_{SC}-D^*_{SC}=\frac{(1+\alpha)p-(3+\alpha)c}{2}d-\left(\frac{p+p\alpha}{2}-2c\right)d=\frac{(1-\alpha)cd}{2}$. For supplier 1, the production quantity in the case of centralized system with blockchain is the same with that in the case of decentralized system, so adopting blockchain or not does not change its profit, i.e., $B^*_{S_1}=D^*_{S_1}$. For supplier 2, $B^*_{S_2}-D^*_{S_2}=\frac{1}{2}(w-c)(1+\alpha)d-(w-c)d=\frac{(\alpha-1)(w-c)d}{2}<0$, thus its profit is decreased by $\frac{(1-\alpha)(w-c)d}{2}$. For the manufacturer, $B^*_M-D^*_M=\frac{1}{2}(p-2w)(1+\alpha)d-\left[\frac{1}{2}p+\frac{1}{2}p\alpha-\frac{1}{2}(3+\alpha)w\right]d=\frac{(1-\alpha)wd}{2}>0$. Therefore, the profit of the manufacturer is increased by $\frac{(1-\alpha)wd}{2}$.

In sum, adopting blockchain decreases the profit of supplier 2 by $\frac{(1-\alpha)(w-c)d}{2}$, and increases the profit of the manufacturer by $\frac{(1-\alpha)wd}{2}$. This is because with a blockchain, the manufacturer can make a more precise order decision to supplier 2 that is coordinated with the output quantity of supplier 1. In order to achieve global optimality, the manufacturer should make a transfer of $\frac{(1-\alpha)(w-c)d}{2}$ to supplier 2 to compensate for the decline, and then the remaining profit $\frac{(1-\alpha)wd}{2}-\frac{(1-\alpha)(w-c)d}{2}=\frac{(1-\alpha)cd}{2}$ can be shared arbitrarily among the three parties.
Case 2: $\max\left\{\frac{3c-p}{p-c},0\right\}<\alpha\le\min\{\frac{2c}{p-c},1\}$ and $\min\left\{\frac{2c}{w},\max\left\{\frac{w}{p-w},\frac{2c}{w}-1\right\}\right\}<\alpha\le\min\left\{\frac{2c}{w},1\right\}$

By adopting blockchain, the maximum expected profit of the supply chain is increased by $B^*_{SC}-D^*_{SC}=\frac{(1+\alpha)p-(3+\alpha)c}{2}d-\left(p-c-\frac{c}{\alpha}\right)d=\frac{(p-c)\alpha^2-(p+c)\alpha+2c}{2}d$. For supplier 1, since $B^*_{S_1}-D^*_{S_1}=\frac{1}{2}w(d+\alpha d)-cd-\left[\frac{1}{2}w(1+\alpha)-c\right]\frac{d}{\alpha}=\left(1-\frac{1}{\alpha}\right)\left[\frac{1}{2}w(1+\alpha)-c\right]d<0$, its profit decreases by $\left(\frac{1}{\alpha}-1\right)\left[\frac{1}{2}w(1+\alpha)-c\right]d$. For supplier 2, $B^*_{S_2}-D^*_{S_2}=\frac{1}{2}(w-c)(d+\alpha d)-(w-c)d=\frac{(\alpha-1)(w-c)d}{2}<0$. Hence supplier 2's profit decreases by $\frac{(1-\alpha)(w-c)d}{2}$. For the manufacturer, $B^*_M-D^*_M=\frac{1}{2}(p-2w)(1+\alpha)d-\left[p-\frac{(1+3\alpha)w}{2\alpha}\right]d=\frac{[(p-2w)\alpha-w](\alpha-1)d}{2\alpha}$.

Therefore, the manufacturer needs to share at least $(\frac{1}{\alpha}-1)[\frac{1}{2}w(1+\alpha)-c]d$ with supplier 1 and $\frac{(1-\alpha)(w-c)d}{2}$ with supplier 2 in order for all parties to be willing to adopt blockchain. With the low-level blockchain, the manufacturer can only observe the output quantity of supplier 1. In order to ensure that supplier 1 selects input quantity d, the manufacturer can design an output-based wholesale contract, in which its payment P depends on supplier 1's output quantity $\hat{q}_1$. There may be many such contracts. An example is provided as follows:

$$P=\begin{cases}(\frac{w}{\alpha}-\varepsilon)\hat{q}_1, & \text{if } 0\le\hat{q}_1<\alpha d,\\ (\frac{w}{\alpha}-\varepsilon)\alpha d+\frac{\alpha\varepsilon}{1-\alpha}(\hat{q}_1-\alpha d), & \text{if } \alpha d<\hat{q}_1\le d,\\ wd, & \text{if } d<\hat{q}_1\le\frac{d}{\alpha},\end{cases}$$

in which $\varepsilon > 0$ is sufficiently small.
Case 3: $\min\left\{\frac{2c}{p-c}, 1\right\} < \alpha \leq 1$ and
$\max\left\{\frac{2c}{w} - 1, 0, \min\left\{\frac{3w-p}{p-w}, \frac{2c}{w}\right\}\right\} < \alpha \leq \min\left\{\frac{2c}{w}, \max\left\{\frac{w}{p-w}, \frac{2c}{w} - 1\right\}\right\}$

Blockchain adoption increases the total profit for the entire supply chain by $[p-c-\frac{c}{\alpha}]d - [\frac{(1+\alpha)p}{2} - 2c]d = \frac{[-p\alpha^2+(p-2c)\alpha-2c]d}{2\alpha}$. For supplier 1, $B^*_{S_1} - D^*_{S_1} = wd - \frac{cd}{\alpha} - \left[\frac{1}{2}w(1+\alpha) - c\right]d = \frac{(1-\alpha)(w\alpha-2c)d}{2\alpha}$. Since $w\alpha - 2c \leq 0$, the profit of supplier 1 is decreased by $\frac{(1-\alpha)(2c-w\alpha)d}{2\alpha}$. For supplier 2, $B^*_{S_2} = D^*_{S_2}$. That is, the profit of supplier 2 does not change. For the manufacturer, $B^*_M - D^*_M = (p-2w)d - \left[\frac{1}{2}p + \frac{1}{2}p\alpha - \frac{1}{2}(3+\alpha)w\right]d$.

The manufacturer must pay at least $\frac{(1-\alpha)(2c-w\alpha)d}{2\alpha}$ to supplier 1. With a low-level blockchain, the manufacturer can only observe the output quantity of supplier 1. In order to ensure supplier 1 selects input quantity $\frac{d}{\alpha}$, the manufacturer can design an output-based varying-price contract, in which its payment P depends on supplier 1's output quantity $\hat{q}_1$. There may be many such contracts. An example is provided as follows

$$P = \begin{cases} w\hat{q}_1, & \text{if } 0 \leq \hat{q}_1 < d, \\ wd + \frac{c}{2}(\hat{q}_1 - d), & \text{if } d < \hat{q}_1 \leq \frac{d}{\alpha}. \end{cases}$$

□