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Innovative applications of O.R.

Blockchain enabled traceability — An analysis of pricing and traceability effort decisions in supply chains

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ABSTRACT

Despite numerous use cases, enterprise-wide implementations of blockchains have seen limited success. This raises the question of when do firms adopt blockchains and do blockchains benefit supply chains. To answer this, we examine a dyadic supply chain consisting of a buyer and a supplier and analyze their traceability effort and pricing decisions. Our results show that the demand-side, supply-side and reputational factors influencing blockchain adoption are primarily complementary and in the absence of one of them, firms can still adopt blockchain. Furthermore, even in the absence of individual benefits for a supply chain partner, there exist conditions under which blockchain adoption benefits the supply chain that can incentivize players to join blockchain. Overall, we contribute by offering a framework that supply chain players can use to assess the likelihood of blockchain implementation success or failure and address the challenges pertaining to incentives and cost imbalances in blockchain implementation.

1. Introduction

Consider the following – *"Unfortunately, while we successfully developed a viable platform, the need for full global industry collaboration has not been achieved. As a result, TradeLens has not reached the level of commercial viability necessary to continue work and meet the financial expectations as an independent business".*[1] – *Maersk.*

In November 2022, Maersk, one of the world's largest container shipping lines and vessel operators, acknowledged that despite setting up a viable blockchain platform with IBM, the lack of partners onboarding the platform was a key reason for the failure of the enterprise-wide initiative that resulted in the shipping company halting its blockchain initiative (Bousquette, 2022). Several other organizations that undertook blockchain implementation at scale have faced slow progress. Walmart, for example, which began tracking *leafy greens* in 2018 via its blockchain initiative, has added only *green bell peppers* to its blockchain portfolio (Bousquette, 2022). Despite the retailer's announcement to bring together consumer food companies such as Nestle, Tyson and Dole on its platform, blockchain implementation has not met expectations.[2] In the business-to-business scenario, HSBC closed its trade-based platform *Serai* in 2022 after the platform failed to generate enough collaborators and demonstrate viability. *Serai* was launched in 2019 in Hong Kong to connect small and medium-sized apparel makers with component suppliers worldwide.[3] Even before these failures came to light, Capgemini in 2018 reported that only 3% of blockchain use cases have reached at scale (Pai et al., 2018).

This lack of success is attributed to several factors – technological complexity of blockchain, difficulties in enlisting participants to grow the network, and blockchain development and scale-up time have been identified as critical (Bousquette, 2022). Even before Maersk's announcement, there were concerns about the ability of Maersk to enlist sufficient participants (such as ports, shippers and suppliers) to join its blockchain network (Allison, 2018). Part of these concerns emerged from the governance of blockchain networks and concerns related to getting supply chain partners to trust each other to share their data. In addition, the costs of developing the blockchain were a major concern (Tinianow, 2018). Though Maersk successfully added a few container terminal services and ports of Halifax, Rotterdam, Bilbao, and others to join its network, it was not enough to cover its costs. As a result, Maersk scaled back its investment in the platform (Bartlett, 2022).

Empirical studies in this context provide further evidence. Sodhi et al. (2022) in a survey of more than 400 supply chain managers, identify technical set-up cost, training cost, ongoing support cost and

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[1] https://www.maersk.com/news/articles/2022/11/29/maersk-and-ibm-to-discontinue-tradelens Accessed on 22nd December 2023.

[2] https://www.imd.org/ibyimd/supply-chain/where-does-blockchain-go-from-here/ Accessed on 20th January 2024.

[3] https://www.cnbc.com/2022/06/09/hsbc-shutters-hong-kong-based-trade-start-up-serai.html Accessed on 5th February 2024.

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security concerns as the top constraints in implementing blockchain. Wang et al. (2019) highlight that confidence issues of supply chain partners in data sharing and blockchain governance, technological and network interoperability issues, and cost, privacy and legal issues are challenges to blockchain usage in supply chains. Bateman and Bonanni (2019) similarly highlight that supply chain firms often fear divulging too much information and return on investments from blockchain initiatives are not always realized in the near term. Consequently, enterprise-wide initiatives of blockchain have not sustained and there remain challenges in blockchain implementation. Among the aforementioned factors, the supply chain's lack of cooperation and investment costs of blockchain development form the central tenet of our study (Kouhizadeh et al., 2021; Wang et al., 2019). Analytical work examining them is still nascent and we seek to contribute to this emerging literature.

Background –Traceability technologies and blockchain. Our study, though based on traceability driven by blockchain and its associated challenges, also applies to other technologies. Traceability is defined as the tracking and tracing of a product along the supply chain keeping records at each stage (Bateman, 2015). Any traceable system requires three key attributes: (i) capture and record traceability data - this involves transforming physical data into digital data (such as factory, farm location, temperature, humidity, chemical composition, batch number, expiry and shipping dates etc.); (ii) a mechanism to access the records - this involves moving the data to cloud systems or databases; and (iii) transmit and share traceability data - this requires access and collaboration between multiple parties (Dong et al., 2023). Various technologies enable the traceability of components and products in supply chains. For example — RFID tags, bar codes and Geographic Information Systems (GIS) (Bateman, 2015; Razak et al., 2023). Bar codes are economical and frequently used, though they require manual screening. RFID tags, on the other hand, make real-time information available, although in some applications, seamless data collection and transmission are prohibitively costly. GIS helps in real-time planning as it processes satellite-based signals.

Blockchains, however, stand out from these applications because of the key features of (i) a distributed database, (ii) security and (iii) immutability. A blockchain-based traceability system can share transaction records with distributed nodes or parties in the system. These transactions are encrypted and the nodes or parties in the system have to perform cryptographic calculations to verify that the transactions are legitimate. Once verified, these transactions get added to the ledger. 'Blocks' store all transactions in the blockchain and it is computationally impractical to tamper or alter the information once recorded. These properties provide firms with an indelible record of transactions (Dong et al., 2023; Jansson & Petersen, 2017). The availability of such records facilitates product tracking, source identification in case of a supply chain hazard, and the return and reuse of products as well. Therefore, end users and supply chain firms are offered a substantial service with the product's origin information owing to the availability of data. An illustration of origin information and traceability in pork supply chains has been provided by Cui et al. (2023).

The challenge, however, is the implementation of traceability via blockchain as it requires buy-in and coordination between supply chain entities (Iansiti & Lakhani, 2017). Additionally, product provenance information from traceability can lead to positive or negative consumer reactions. This can result in the product's demand expansion or reduction. For example, information on the components sourced from conflict zones in Asia or Africa, or factories deploying child labor can cause significant adverse consumer reactions. Furthermore, consumers' willingness to pay for traceability is an important concern for firms (Amed et al., 2019).[4]

In summary, we pose the following research questions – *under what conditions do a firm and its supply chain partner adopt blockchain (and exert traceability effort)? Can product collection and reuse enable blockchain adoption?* Given that traceability can positively or negatively influence demand, *how do a firm and its supply chain partner price a traceable product to augment or compensate for the traceability effect? And lastly, does blockchain adoption create a surplus for the supply chain?*

Our paper aims to answer these through a stylized analytical model that considers (i) market heterogeneity, (ii) consumer sensitivity towards traceability, (iii) blockchain costs and (iv) unit cost saving from product collection and reuse as key factors that influence blockchain adoption. We first begin by examining the conditions when a firm invests in blockchain and extend the analysis to a supply chain consisting of a buyer and supplier. We conduct an in-depth analysis of the traceability, pricing decisions and profits of the entities. We note that our analysis of traceability effort in a blockchain is akin to traceability effort in other digital systems. Therefore, our modeling and analysis, though closely motivated by blockchain developments are also applicable to other digital technologies that enable supply chain traceability.

Summary of findings. A key insight from our analysis is that (i) demand-side (consumer sensitivity), supply-side (unit cost saving) and reputational factors are strategic complements that drive a firm's blockchain adoption decision. (ii) When the downstream entity (the buyer) has a relatively greater impact on traceability, the supply chain incurs higher profits than a single firm. Furthermore, the consumer welfare is also higher in the supply chain. (iii) We find that blockchain adoption creates a surplus in a supply chain that can incentivize players to offset the higher costs of technology implementation. (iv) Additionally, traceability has implications for supply chain design. When product collection and reuse is at the buyer's end, it yields greater supply chain profits when demand and supply-side factors are favorable. Otherwise, the supplier's involvement in product collection and reuse leads to higher profits.

While several studies have focused on the benefits of blockchain technology, few have examined lesser-known aspects of blockchain adoption such as supply and demand characteristics and reputational factors that affect supply chain coordination. Yet, these are critical as evident from Maersk's and other blockchain failures. Our paper attempts to address this gap. The rest of the paper is organized as follows: In Section 2, we discuss the relevant background literature pertaining to our study. Section 3 presents the model and analysis for the single firm. Section 4 presents the supply chain model and comparative results. Section 5 extends our analysis while managerial insights and concluding remarks are discussed in Section 6.

2. Literature review

We aim to contribute to two significant streams of literature — one is the emerging stream of traceability in supply chains, which focuses on the importance of tracking and documenting the movement of goods through the supply chain (Section 2.1). The second is blockchain applications for traceability, which explores how blockchain technology can be applied across different industries and sectors (Section 2.2). In our review of the literature, we examine these two streams. We further delve into general blockchain applications (Section 2.2.1) and sector-specific applications of blockchain (Section 2.2.2). We highlight research gaps and position our work in this developing body of literature (Section 2.3).

2.1. Traceability in supply chains

Traceability (or the ability to track and trace products) is posited to improve the management of supply chains. To examine the value of traceability, Aiello et al. (2015) use numerical approaches to identify

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[4] In its 2022 survey of consumer behavior and attitude, Deloitte reported that only *one in five consumers* rate carbon labeling important during their purchase. See https://www2.deloitte.com/uk/en/pages/consumer-business/articles/sustainable-consumer.html Accessed on 20th February 2024.

the optimal level of granularity in a traceable system that maximizes the profits of a bilateral supply chain. Piramuthu et al. (2013) consider a perishable supply network and analyze the effect of traceability level while considering the liability cost of contamination for each member of the network. Both Aiello et al. (2015) and Piramuthu et al. (2013) discuss traceability enabled through RFID systems though there are no pricing or contractible effort decisions in the studies. Saak (2016) considers a general traceability system and its effect on reputation in supply chains. Similar to our postulation, the study assumes that provenance information has both positive and negative reputational effects, however, consumer heterogeneity, investment cost and unit cost savings from traceability are not the primary considerations in their study. Yao and Zhu (2020) analyze the role of traceability in combating product label misconduct and derive optimal inspection policies. Product labels are considered to drive traceability in the study.

While the aforementioned studies have looked at general traceability systems, separate research has looked at traceability driven by blockchains, which we discuss next.

2.2. Blockchain applications for traceability

Blockchain's distinct features have increasingly intertwined product and component traceability. Cui et al. (2023) examine the value and design of traceability-driven blockchains in serial and parallel supply chains and infer that firms operating in different kinds of supply chains may face different implications of traceability. Iyengar et al. (2023a) and Iyengar et al. (2023b) study the issue of blockchain adoption as we have attempted in this paper. In the former, the authors examine a manufacturer-led serial supply chain that purchases from suppliers and sells to consumers. The study shows that the manufacturer will adopt blockchain if the implementation cost is low and improves his welfare. The latter study examines the economics of permissioned blockchain and its impact on social welfare. The study shows that by reducing information asymmetry, consumer welfare is improved though the improvement in welfare is not sufficient to drive blockchain adoption if the cost of implementation is high. Our paper is related to the two studies, however, our analysis goes beyond investment costs to include consumer heterogeneity, reputational effects and unit cost-saving effects of traceability which lend further richness to the findings in this emerging field.

2.2.1. General blockchain applications

Studies have highlighted various applications of blockchain in the supply chain context. These include combating counterfeiting, product collection and reuse and coordination.

Counterfeiting and product quality. As blockchain technology drives transparency and traceability, it is considered a solution for combating counterfeiting in supply chains and signaling product quality (Naoum-Sawaya et al., 2023; Pun et al., 2021; Shen et al., 2021a, 2022, 2021b, 2020). Pun et al. (2021) study the effectiveness of blockchain in combating counterfeits vis-a-vis differential pricing in the presence and absence of government subsidy. Shen et al. (2021a, 2022) use the quality disclosure effect of blockchain technology as an effective tool to indicate product authenticity.

Product collection and reuse. Research on blockchains as an enabler of circular supply chain practices has received limited attention despite their enormous usability. Babich and Hilary (2020) suggest that blockchain technology offers the possibility of tracking both forward and reverse goods flows. Studies also propose that product lifecycle management via blockchain can enable better monitoring of resources, thereby reducing costs and saving time in collection (see Upadhyay et al., 2021, Shojaei et al., 2021, Kouhizadeh et al., 2020). Nandi et al. (2021) argue that blockchain-enabled product collection, reuse and recycling practices can help firms in localization, and become more agile. Since blockchain implementation to drive circular supply chains is still in its early stages, it is timely to examine how it will encourage supply chain entities to utilize blockchain. This motivates our modeling and analysis in this paper.

Coordination. Coordination issues in blockchains have also received scant attention. Fan et al. (2022) discuss coordination between a three-stage supply chain that adopts blockchain where the retailer and manufacturer share their revenues with upstream partners. De Giovanni (2020) discusses 'smart' wholesale and revenue-sharing contracts (residing in the blockchain) between a supplier and retailer and shows that such contracts can improve supply chain performance. An interesting subject of distrust among supply chain partners is discussed by Biswas et al. (2023) who show that blockchains can alleviate distrust only partially. Coordination literature in blockchain is still developing. In this paper, we draw attention to coordination challenges in blockchain implementation and show how the supply chain surplus from blockchain can incentivize players to adopt.

2.2.2. Sector-specific blockchain applications

The discussion on traceability technologies and blockchain in Section 1 raises the subject of different sector-specific applications which we review below. A key area of blockchain implementation has been in the food and agri-business sector. Menon and Jain (2021) analyze twenty-five use cases at different stages of development in agri-supply chains. These include IBM Food Trust involving IBM, Walmart, Nestle, Tyson and others to track fruits and vegetables; Honeysuckle White by Cargill to track turkey; Ripe.io (a supply chain platform for food traceability using blockchain) and Zego (a blockchain platform to track allergens, heavy metals and chemicals in food products).

Kshetri (2022) notes several traceability initiatives in the diamond industry, such as those by the De Beers group, who developed the blockchain platform *Tracr* to trace the origins of diamonds. Studies on blockchains have also examined applications in food processing, shipping, mining and pharmaceutical sectors (Cao et al., 2022; Dong et al., 2023; Liu et al., 2022). Other application areas include luxury supply chains (Choi, 2019), medicine supply chains (Niu et al., 2021) and air logistics (Choi et al., 2019). We observe from the aforementioned cases that firms across different sectors have undertaken blockchain development due to benefits such as tracking and tracing, reduction of information asymmetry and transaction costs, and improvement of efficiencies in supply chains. Noticeable, and in line with our postulation, most of the study examples are still in their early stages of development and have not yet been implemented at scale.

2.3. Blockchain challenges and research gaps

Despite its numerous benefits, blockchain technology also comes with various challenges. Few studies have highlighted that blockchain adoption can result in social and environmental damage. The computation-intensive nature of blockchain requires significant energy usage and can be detrimental to the environment (Esmaeilian et al., 2020). The cost of investment and privacy concerns of users are two other impediments to blockchain technology that scholars have looked at Bavassano et al. (2020), Cao et al. (2022).

Although research into the use of blockchain technology in supply chains is expanding, there remains significant scope to improve our understanding of blockchain-enabled traceability in supply chains. Aspects such as consumer sensitivity, market heterogeneity, cost savings through product collection and reuse, and reputational consequences influence a firm's decision on traceability and require further analysis. The strategic interaction between firms in blockchain-enabled supply chains also requires much attention (Niu et al., 2021; Zhu et al., 2022). The paper seeks to address this gap. We summarize relevant literature and position our work in Table 1.

3. The model

In this section, we present the model preliminaries. First, we analyze blockchain adoption that drives the traceability effort of a firm.

Table 1
Summary of literature.

Articles	Problem's objective	Decision	Surplus and welfare analysis
Traceability in supply chains			
Aiello et al. (2015)	Total expected profits	Optimal granularity level	×
Piramuthu et al. (2013)	Expected liability cost	Traceability level	×
Saak (2016)	Expected profits	Product quality and effort	×
Yao and Zhu (2020)	Expected profits	Optimal inspection policy	×
Blockchain applications for traceability			
Cui et al. (2023)	Expected profits	Quality and prices	×
Iyengar et al. (2023a)	Expected profits	Quality and effort	✓
Iyengar et al. (2023b)	Expected profits	Fulfillment levels and prices	✓
General blockchain applications			
Pun et al. (2021)	Expected profits	Blockchain adoption and prices	✓
Shen et al. (2021a)	Expected profits, Social health risk	Prices and quality inspection effort	×
Shen et al. (2022)	Expected profits	Prices and quality	✓
Upadhyay et al. (2021)	Blockchain narrative and integrative literature review	×	×
Kouhizadeh et al. (2020), Nandi et al. (2021), Shojaei et al. (2021)	Blockchain case studies	×	×
Fan et al. (2022)	Expected profits	Blockchain adoption and prices	×
De Giovanni (2020)	Expected profits	Order quantity, prices and effort	×
Biswas et al. (2023)	Total profits	Quality and prices	×
Sector specific blockchain applications			
Kshetri (2022), Menon and Jain (2021)	Blockchain case studies and thematic analysis	×	×
Cao et al. (2022), Dong et al. (2023), Liu et al. (2022)	Total profits	Prices, production quantity, effort	✓
Choi (2019)	Expected profits	Prices	✓
(Niu et al., 2021), Choi et al. (2019)	Expected profits	Order quantity	×
Blockchain challenges			
Bavassano et al. (2020), Esmaeilian et al. (2020)	Literature review, survey	×	×
Zhu et al. (2022)	Literature review	×	×
Our paper	Total profits	Traceability effort and prices, Blockchain adoption	✓

Our single firm (or centralized supply chain) analysis is motivated by Walmart's initiative to develop a blockchain after a successful proof-of-concept with IBM and Tsinghua University in 2016 (Goldsby & Hanisch, 2022). Since blockchain implementation requires an investment in technological systems, we consider a fixed cost K, incurred by the firm (De Giovanni, 2020). From the cases of Maersk and Walmart, we note that traceability is a continuous effort of the firm to track and trace the flow of products and components. We let $\tau \geq 0$ represent this effort. Traceability in a supply chain is a complex activity — the greater the number of supply chain echelons and entities, the more effort is required to achieve end-to-end traceability (Manupati et al., 2020). This requires coordination among multiple entities, setting up technology teams, information sharing standards, and agreements. Traceability effort also includes designing membership profiles for blockchain participants, data sharing, access control and other activities performed on the blockchain (Gaur & Gaiha, 2020). Therefore, we consider traceability as a continuous effort (τ) of the firm.

Traceability entails costs that influence the effort decisions of a firm — in 2012, for example, Tesco dropped its plan of carbon labeling its products as it acknowledged that even for a minimal set of products, the effort required was significant to fulfill its pledge.[5] To represent this, we consider the cost of traceability effort non-linearly as $C_\tau = \gamma\tau^2$, where $\gamma > 0$, denotes the investment parameter. γ can be interpreted as a parameter measuring the inefficiency of the traceability effort. The higher the inefficiency, the higher the traceability cost. We next outline

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[5] https://www.theguardian.com/environment/2012/jan/30/tesco-drops-carbon-labelling Accessed on 15th January 2024.

Table 2
Model notations.

Notations	Description	Notations	Description
Decisions			
p	Normalized price of the product (p_m is optimal p)	W	Normalized price charged by the supplier
τ	Traceability effort of single firm (τ_m is optimal τ)	τ_b	Traceability effort of buyer
P	Normalized price charged by the buyer	τ_s	Traceability effort of supplier
Outcomes			
Π	Profit of the single firm	Π^*_{b0}	Optimal profit of buyer in the absence of blockchain
Π_b	Profit of the buyer	Π^*_{s0}	Optimal profit of supplier in the absence of blockchain
Π_s	Profit of the supplier	Π_{sc}	Total Profit of the supply chain
Q	Market Demand	S_b, S_s	Surplus of the buyer and supplier respectively
τ_{sc}	Supply chain traceability effort	Q_{sc}	Market Demand in supply chain case
Π_{sc1}	Profit of the supply chain with buyer recycling	τ_{sc1}	Supply chain traceability effort when buyer is recycling
Π_{sc2}	Profit of the supply chain with supplier recycling	τ_{sc2}	Supply chain traceability effort when supplier is recycling
Parameters			
A	Total Population	U_B	Utility functions of the base consumer
α	Proportion of population that values traceability	U_S	Utility functions of the traceability sensitive consumer
$\hat{v}$	Consumer's Actual Valuation of the product	γ	Investment coefficient of traceability effort
v	Consumer's Normalized Valuation of the product	γ_b	Investment coefficient of buyer's traceability effort
$\hat{p}$	Actual price of the product charged by the firm	γ_s	Investment coefficient of supplier's traceability effort
θ	Consumer's sensitivity to traceability effort	K_b	Fixed cost of traceability of buyer
K	Fixed cost of traceability	K_s	Fixed cost of traceability of supplier
δ	Impact of buyer's effort on demand	ϵ	Unit manufacturing cost reduction coefficient
C_0	Unit cost of manufacturing	β	Impact of Supplier's effort on her profit
C_r	Reduced unit cost of manufacturing	C_{rb}	Reduced unit cost of buyer
Δ	Unit cost saving from product collection and reuse	C_{τ_s}	Cost of supplier's traceability effort
C_τ	Cost of traceability effort	C_{τ_b}	Cost of buyer's traceability effort
CS	Consumer surplus in single firm case	CS_{sc}	Consumer surplus in supply chain case
P_0	Price when demand is zero	OP^*	Optimal price for surplus computation
C_{rs}	Reduced cost of supplier	R	Supplier's marginal cost of raw material procurement

the market demand and profit function of the firm. Table 2 provides the model notations.

3.1. Consumer heterogeneity and market demand

We consider a market with 'A' potential consumers who are heterogeneous in their preferences for traceability. The market consists of two types of consumers — traceability sensitive and others. Let α $(0 \leq \alpha \leq 1)$ denote the fraction of consumers who are traceability sensitive, hence they scrutinize the traceability effort of the firm and $(1-\alpha)$ denote the fraction of consumers who do not.

Each consumer also has a distinct valuation of the product $(\hat{v})$ uniformly distributed between 0 to A, i.e. $\hat{v} \in [0, A]$. We assume that a consumer can buy a maximum of one unit of the product. The manufacturer realizes positive demand only when the price $\hat{p} \leq A$. Accordingly, $\hat{p} \in [0, A]$. Without loss of generality, we normalize the consumer's valuation and the price to lie between 0 and 1. i.e. normalized valuation $v \in [0, 1]$ and normalized price $p \in [0, 1]$. For the rest of the paper, we use price to mean normalized price and valuation to mean normalized valuation.

From the above, the utility function for both types of consumers can be specified as $U_B = (v - p)$ and $U_S = (v + \theta\tau - p)$, where, subscript B denotes the base consumers and subscript S denotes the traceability sensitive consumers. Base consumers do not scrutinize traceability and therefore, traceability effort by the firm does not change their valuation of the product. However, traceability sensitive consumers may get a higher or lower value from the product depending on the value of θ. θ represents the consumer's sensitivity to the traceability effort (τ) of the firm that can be positive or negative. *Negative* value indicates that the traceability effort reveals provenance information that is perceived negatively. This leads to reduced market demand (Sodhi & Tang, 2019). In contrast, a positive θ indicates that information from traceability is valued favorably by the consumers and leads to an increase in demand. We term the first case $(\theta < 0)$ as the *demand reduction effect* and the second $(\theta > 0)$ as the *demand expansion effect of traceability*. Our model thus, reflects the consumer pressures that firms face (consumers are sensitive to price and heterogeneous towards their valuation of the product, and not all consumers are sensitive to the traceability effort of the firm) (Villena & Dhanorkar, 2020).

The market demand for the product is derived from the sum of demand from both types of consumers. All consumers with a positive utility from unit purchase of the good $(U_i \geq 0)$, $i \in (B, S)$ will buy the good. Therefore, the demand equation can be written as

$$Q = \alpha A \int_p^{1+\theta\tau} dv + (1-\alpha)A \int_p^1 dv \tag{1}$$

The first term in Eq. (1) represents the demand from the set of consumers who scrutinize traceability and receive a value $\theta\tau$ in addition to the value v from the product. Therefore, all traceability sensitive consumers with the perceived value $v + \theta\tau \geq p$ will buy the product. The second term represents the demand from base consumers who do not value traceability and will buy the product when $v \geq p$. Eq. (1), on simplification, gives the market demand of the firm as

$$Q = [\alpha A(1 + \theta\tau - p) + (1-\alpha)A(1-p)] = A(1 - p + \alpha\theta\tau) \tag{2}$$

In Eq. (2), θ can be positive or negative such that $\frac{-(1-p)}{\alpha\tau} \leq \theta \leq \frac{(1-p)}{\alpha\tau}$, allowing us to consider the practicable traceability effects on consumers. The bounds are algebraically derived from the non-negativity conditions of market demand in Eq. (2). The bounds ensure that for the fraction of consumers who are traceability sensitive $(\alpha > 0)$, the traceability sensitivity coefficient is not too high or low to make consumer demand infinite or unrealistic.

3.2. Traceability and unit cost savings

Blockchains have the potential to allow tracking and tracing of product components and reuse (Centobelli et al., 2022; Saberi et al., 2019). The Ellen Macarthur Foundation notes that *"blockchains can enable monitoring and identifying materials through the supply chains so that they can be reused, remanufactured or recycled"*.[6] Circularize, the

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[6] www.ellenmacarthurfoundation.org/tech-enablers-series/part-2 Accessed on 20th April 2024.

Table 3
Optimal decisions of the firm.

Decision variables	Optimal values
p_m	$\dfrac{\gamma(2+2C_0-A\epsilon^2)-A(C_0+1)\alpha\sqrt{\gamma}\epsilon\theta-AC_0\alpha^2\theta^2}{4\gamma-A(\alpha\theta+\epsilon\sqrt{\gamma})^2}$
τ_m	$\dfrac{A(1-C_0)(\alpha\theta+\epsilon\sqrt{\gamma})}{4\gamma-A(\alpha\theta+\epsilon\sqrt{\gamma})^2}$

blockchain software developer has partnered with Porsche that can allow the manufacturer to trace components used in its vehicles and recycle parts.[7] Circularize has also partnered with firms to trace e-waste in the electronics sector with the objective to trace parts and enable used product collection and recycling.[8] Traceability enables firms to monitor and regulate the collection and reuse of products by tracking the location, time, quality, and condition of products and components.

We model product collection and reuse in our problem. Let C_0 denote the unit cost of manufacturing for the firm, Δ denote the unit cost saving realized from product collection and reuse and C_r denote the reduced unit cost. Then, $C_r = C_0 - \Delta$. We assume Δ to be a function of the firm's investments in traceability ($C_\tau = \gamma\tau^2$, as specified in Section 3) (Savaskan et al., 2004). Therefore, $\Delta = \epsilon\sqrt{C_\tau} = \epsilon\sqrt{\gamma\tau^2} = \epsilon\tau\sqrt{\gamma}$ where, $\epsilon\sqrt{\gamma}$ is a scaling parameter. Substituting this in C_r equation, we get $C_r = C_0 - \epsilon\tau\sqrt{\gamma}$.

Here, $C_r \geq 0$. Coefficient $\epsilon \geq 0$ denotes the impact of traceability on unit cost saving. When $\epsilon > 0$, traceability enables used product tracking, collection and reuse leading to cost saving for the firm. We term this the *cost saving effect*. In contrast, $\epsilon = 0$ denotes that traceability does not impact collection and reuse and, therefore, has no effect on unit cost. We, thus, evaluate generalized cases where investments in traceability may not always improve product collection and reuse. Similar cost structures have been considered in the literature on remanufacturing, and closed-loop supply chains as a function of the return rate of used products (Savaskan et al., 2004). In the operations literature as well, similar cost structures have been considered to investigate process improvements and lot sizing decisions in set-up cost reduction (Fine & Porteus, 1989). The profit of the firm is thus given as:

$$\Pi = (p-C_r)Q - C_\tau - K = \left[p-(C_0-\epsilon\tau\sqrt{\gamma})\right]\left[A(1-p+\alpha\theta\tau)\right]-\gamma\tau^2-K \quad (3)$$

Note that the profit equation represents certain *trade-offs* – while the firm benefits from investments in traceability effort enabled by blockchain, negative effects from traceability lead to reduced demand. Furthermore, investment in blockchain is costly for the firm and though traceability drives unit cost savings for the firm, here as well, cost savings depend on the value of ϵ. The firm incurs the blockchain-related setup cost K first if it decides to implement blockchain. However, the firm engages in decision-making ex-ante. This decision depends on whether the firm benefits from blockchain implementation (Refer to Remark 1). Upon determining that a specific investment is profitable, the firm proceeds with the investment ex-post. The firm's objective is to set price (p) and traceability effort (τ) that maximize its profit. The firm's objective function is represented as:

$$(p_m, \tau_m) = arg \max_{p,\tau} \quad \Pi(p,\tau), \quad (4)$$

We solve the above problem to get optimal decisions (p_m and τ_m, presented in Table 3). Proofs are provided in Appendix A. Index m denotes the single firm. We analyze the results next.

3.3. The single firm case – Results and analysis

We begin by presenting a formal result on the role of investment cost (K) in blockchain adoption. We highlight the threshold beyond which a firm will not adopt blockchain. We then analyze the traceability effort and pricing decisions of the firm to answer *if the firm exerts traceability effort under negative consumer reaction*.

Remark 1 (*Fixed Cost of Traceability: Single Firm*)**.** When $K > \omega$, where, $\omega = \frac{A^2(C_0-1)^2(\alpha\theta+\epsilon\sqrt{\gamma})^2}{4(-A(\alpha\theta+\epsilon\sqrt{\gamma})^2+4\gamma)}$ the firm will incur losses by adopting technology to ensure traceability.

Proof. See Appendix A.1. The threshold on K indicates the conditions when the single firm will not invest in blockchain due to high blockchain implementation costs. Moreover, the same threshold can be used by a regulator to decide the level of subsidy to compensate for the blockchain implementation losses and make blockchains a viable option. The cost threshold is decreasing in the investment cost coefficient (γ), indicating that investments for blockchain technology (and alike) are economic deterrents for firms. Iyengar et al. (2023b) recognize that blockchain adoption costs are important for manufacturers; and need to be coordinated across multiple entities for cost savings to materialize. We discuss cost savings from blockchain adoption later in Section 4.3.

Proposition 1. (a) ***(Traceability effort when*** $\theta > 0$***):*** *The firm exerts positive traceability effort when either θ or ϵ is positive. If both θ and ϵ are zero, then the optimal traceability effort is zero.*

(b) ***(Traceability effort when*** $\theta < 0$***):*** *When $\theta < 0$, the firm exerts positive traceability effort, only if $\epsilon > \dfrac{\alpha \mid \theta \mid}{\sqrt{\gamma}}$. If $\epsilon = 0$, then the optimal traceability effort is zero.*

Proof. See Appendix A.2. Result (a) shows that in the presence of demand expansion or unit cost saving effects, the firm exerts traceability effort. Note that the presence of either of these effects leads the firm to invest in traceability, thus, displaying complementariness between the benefits from demand expansion and unit manufacturing cost savings (τ_m is convex increasing in θ and ϵ). **[*Case Instance 1:*]** In this regard, Porsche's partnership with Circularize to develop a blockchain to help trace its materials from the suppliers up to the *recycling stage* highlights the impact of a higher ϵ (unit cost saving realization). Cost saving from product tracking and recycling therefore drives the firm's traceability decision.[9]

Result (b) shows despite the firm experiencing a demand reduction effect, it still exerts a traceability effort if the unit cost savings compensate for the loss due to demand reduction. The result importantly shows that firms' common concerns about the negative effects of traceability can be alleviated if traceability enables product collection and reuse. Considering unit cost saving as a *supply-side* effect, we infer that despite a negative demand-side impact, the supply-side benefits can incentivize firms to adopt blockchains and invest in traceability.

Proposition 2. *(a)* ***(Price change when*** $\theta > 0$***):*** *When $\theta > 0$, $\epsilon > \sqrt{\dfrac{2}{A}}$ is a sufficient condition for optimal price to be decreasing in θ $\left(i.e.\ \dfrac{\partial p_m}{\partial \theta} < 0\right)$*

(b) ***(Price change when*** $\theta < 0$***):*** *When $\theta < 0$, the optimal price is always decreasing in θ (i.e. $\dfrac{\partial p_m}{\partial \theta} < 0$).*

Proof. See Appendix A.3. Result (a) shows when the unit cost saving effect is above a threshold, the optimal price of the firm decreases under

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[7] https://www.circularise.com/resource/achieving-visibility-into-the-porsche-supply-chain Accessed on 11th Aug 2024.

[8] https://www.circularise.com/resource/activating-circular-services-in-the-electric-and-electronic-sector-c-servees Accessed on 11th Aug 2024.

[9] Retrieved from: https://www.circularise.com/case-study/porsche. Accessed on 22nd January 2024.

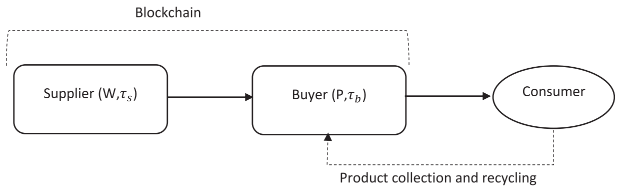


Fig. 1. Supply chain schematic where a buyer and supplier form a blockchain.

the demand expansion effect. Contrary to intuition where one would expect the firm to charge a price premium with demand expansion, our result shows that the firm reduces its price. The reason is as follows: as θ increases, the firm experiences demand expansion. An increase in θ increases traceability effort which in turn lowers the unit manufacturing cost, thereby, helping the firm to realize the supply-side benefit. As the firm realizes manufacturing cost saving, it shares this benefit with the consumers by reducing the price. Result (b) shows that under demand reduction, the firm reduces its price.

A comparison of the results provides an interesting insight – though the optimal price of the firm decreases in both cases, the reasons are different – in result 2 (a), the presence of unit cost saving above a threshold (ϵ) and demand expansion allows the firm to reduce its price and benefit the consumer. We term this the *shared-savings* approach of the firm. In contrast, in result 2 (b) the firm reduces its price to preclude the loss from demand reduction.

4. The supply chain model

The single-firm model delineates the traceability and pricing decisions of the firm highlighting the conditions of blockchain adoption. Since blockchain's success depends on the coordination between firms, we next analyze a supply chain. The supply-chain model differs from single firm model in two key parameters: (a) Supplier's reputational risk (β)- In addition to consumer's reaction to traceability information, suppliers also face reputation risk of information disclosure. We incorporate these traceability effects between the buyer and supplier in the profit function of the supplier. (b) Traceability effort of supply chain (τ_{sc})- we consider the traceability effort of the supply chain to be a weighted sum of individual efforts. We explain the model below:

We consider a two-tier supply chain consisting of a buyer and a supplier who form a blockchain that enables traceability and product collection and reuse (refer to Fig. 1). The supply chain's traceability effort is a sum of the firm's (*within-organization*, for example, Maersk's own blockchain platform developmental effort) and its partner's (*inter-organizational*) efforts. When both the buyer and supplier invest in traceability efforts (given by τ_b and τ_s respectively), the supply chain traceability effort is a weighted sum of the individual efforts, given as $\tau_{sc} = \delta\tau_b + (1-\delta)\tau_s$, where, δ, $(0 \le \delta \le 1)$ represents the impact of the buyer's effort. The weighted function helps us evaluate cases when the effect of the traceability effort of one entity is greater than the other. The demand function is given as:

$$Q_{sc} = A\left[1 - P + \alpha\theta\left(\delta\tau_b + (1-\delta)\tau_s\right)\right] \tag{5}$$

Index sc denotes the supply chain. Similar to the single firm model, the traceability cost for the buyer and supplier are respectively given as $C_{\tau_b} = \gamma_b\tau_b^2$ and $C_{\tau_s} = \gamma_s\tau_s^2$. We consider that traceability enables product collection and reuse at the buyer's end, which leads to unit cost savings. For parsimony, we consider the downstream buyer to collect and reuse the product. This allows us to examine any cross-effects on the supplier's decisions. We later extend the analysis to the case where the supplier conducts collection and reuse (see Section 5). The reduced unit cost of the buyer due to traceability is given as $C_{r_b} = W - \epsilon\sqrt{C_{\tau_b}}$, where, W represents the unit cost of procurement of the buyer. We also consider fixed costs of blockchain implementation for the buyer and supplier, denoted by K_b and K_s, respectively. The profit of the buyer is given as:

$$\begin{aligned}\Pi_b &= Q_{sc}(P - C_{r_b}) - C_{\tau_b} - K_b \\ &= A[1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)][P - (W - \epsilon\sqrt{C_{\tau_b}})] - \gamma_b\tau_b^2 - K_b\end{aligned} \tag{6}$$

and the profit of the supplier is given as:

$$\Pi_s = Q_{sc}W + \beta\tau_s - C_{\tau_s} - K_s = A[1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)]W + \beta\tau_s - \gamma_s\tau_s^2 - K_s \tag{7}$$

Table 4
Equilibrium decisions of the buyer and supplier in the supply chain.

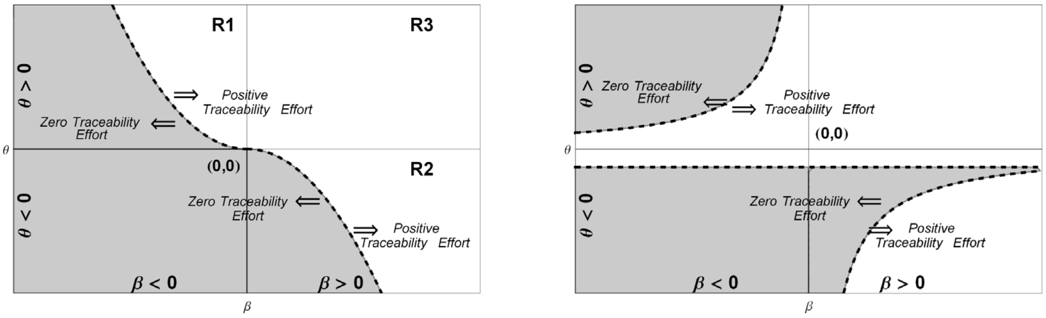
Decision variables	Equilibrium values
τ_b^*	$\dfrac{0.5A(2\gamma_s + \alpha\beta\theta(1-\delta))\left(\alpha\delta\theta + \epsilon\sqrt{\gamma_b}\right)}{\gamma_b\left(8\gamma_s - A\alpha^2\theta^2(1-\delta)^2\right) - 2A\gamma_s\left(\sqrt{\gamma_b}\epsilon + \alpha\delta\theta\right)^2}$
τ_s^*	$\dfrac{A\alpha\gamma_b\theta(1-\delta) + \beta\left(4\gamma_b - A(\sqrt{\gamma_b}\epsilon + \alpha\delta\theta)^2\right)}{\gamma_b\left(8\gamma_s - A\alpha^2\theta^2(1-\delta)^2\right) - 2A\gamma_s\left(\sqrt{\gamma_b}\epsilon + \alpha\delta\theta\right)^2}$
P^*	$\dfrac{0.5\left(2\gamma_s + \alpha\beta\theta(1-\delta)\right)\left(6\gamma_b - A\left((\alpha\delta\theta + \epsilon\sqrt{\gamma_b})^2 + \gamma_b\epsilon^2 + \alpha\delta\theta\epsilon\sqrt{\gamma_b}\right)\right)}{\gamma_b(8\gamma_s - A\alpha^2\theta^2(1-\delta)^2) - 2A\gamma_s(\alpha\delta\theta + \sqrt{\gamma_b}\epsilon)^2}$
W^*	$\dfrac{0.5\left(2\gamma_s + \alpha\beta\theta(1-\delta)\right)\left(4\gamma_b - A(\alpha\delta\theta + \epsilon\sqrt{\gamma_b})^2\right)}{\gamma_b(8\gamma_s - A\alpha^2\theta^2(1-\delta)^2) - 2A\gamma_s(\alpha\delta\theta + \sqrt{\gamma_b}\epsilon)^2}$

For model simplicity, we assume the marginal cost for the supplier is zero. Note the term $\beta\tau_s$ in Eq. (7) measures the effect of information from the supplier's traceability effort. Recall from our previous discussion that suppliers face reputational risk from traceability. The coefficient (β) reflects this impact on the profitability of the supplier. β can be positive or negative, depending on the component information disclosed to the buyer. Accordingly, we term this the *positive or negative traceability effect* on the supplier.

We derive the decision outcomes in a Stackelberg game when the supplier moves first and decides her wholesale price (W) and traceability effort (τ_s) followed by the buyer who decides the price (P) and traceability effort (τ_b). The demand is realized following the decisions of the supply chain entities. Note that before deciding the levels of traceability efforts and prices, the firms decide on incurring the fixed costs (K_b, K_s). Like the single firm case, the choice of incurring K_b and K_s depends on whether implementing blockchain technology can produce a surplus for each player. The blockchain surplus for the buyer and supplier is presented in Proposition 6. We solve for the equilibrium decisions in the sequential game as given in Table 4. Proofs are provided in Appendix B.

4.1. The supply chain case – Results and analysis

We characterize the supply chain decisions in this section. Both the buyer and supplier have thresholds on the fixed cost of investment – when $K_b > \frac{A\gamma_b(\alpha\beta(1-\delta)\theta+2\gamma_s)^2\left(4\gamma_b - A\left(\sqrt{\gamma_b}\epsilon+\alpha\delta\theta\right)^2\right)}{4\left(A\alpha^2\gamma_b\theta^2(1-\delta)^2+2A\gamma_s\left(\sqrt{\gamma_b}\epsilon+\alpha\delta\theta\right)^2-8\gamma_b\gamma_s\right)^2}$ and $K_s > \frac{\beta^2\left(4\gamma_b - A\left(\sqrt{\gamma_b}\epsilon+\alpha\delta\theta\right)^2\right)+2A\gamma_b(\alpha\beta(1-\delta)\theta+\gamma_s)}{8\gamma_b\gamma_s - A\alpha^2\gamma_b\theta^2(1-\delta)^2 - 2A\gamma_s\left(\sqrt{\gamma_b}\epsilon+\alpha\delta\theta\right)^2}$, the buyer and supplier will incur losses by adopting blockchain technology (see Appendix B.1). Therefore, the participation of supply chain entities is contingent on the fixed costs of technology adoption. If, however, blockchain adoption generates a surplus, then to lower the developmental costs suitable mechanisms can be designed to incentivize players. We examine this issue in Section 4.3.



(a) Impact of θ and β on the supplier's effort

(b) Impact of θ and β on the buyer's effort

Fig. 2. Supplier's and Buyer's Effort.

We next analyze the supplier's and buyer's decisions and compare the relative effort of each player in the supply chain. Our objective is *to examine the conditions when the buyer and supplier will exert traceability effort despite the demand reduction effect*, and *whether the unit cost saving effect or the traceability effect influences the traceability efforts.*

Proposition 3 (*Supplier's Traceability Effort*). *(a) Even if $\theta = 0$ and $\epsilon = 0$, the supplier exerts positive effort if $\beta > 0$; else, the supplier does not exert any effort.*

(b) When $\theta < 0$, the supplier exerts positive effort if $\beta > \left\{ \dfrac{A\alpha\gamma_b(1-\delta)\theta}{4\gamma_b - A(\sqrt{\gamma_b}\epsilon + \alpha\delta\theta)^2} \right\}$*, otherwise the supplier does not exert any effort.*

Proof. See Appendix B.2.1. Result (a) shows that as long as the supplier observes a positive traceability effect ($\beta > 0$), she will exert traceability effort even if there is no demand expansion or cost saving effect in the supply chain. **[*Case Instance 2:*]** While examining automotive supply chains, Dahlbäck and Söderlund (2020) state that not all companies can force their suppliers to join blockchain networks. Instead, external factors that result in a higher β can encourage participation in blockchain networks, specifically under non-binding contractual conditions as shown in our result. Result (b) shows that even under the demand reduction effect, the supplier will invest in traceability, if the traceability effect is above a threshold. Such a scenario may arise when the information from the downstream buyer's effort results in a negative consumer reaction ($\theta < 0$), whereas the supplier's own component traceability has a positive impact on the firm ($\beta >$ threshold).

We further analyze the threshold on β to characterize the supplier's effort and highlight the conditions when the supplier will exert traceability effort. In Fig. 2(a), *R1–R3* show the regions where the supplier will exert traceability effort. Note that in region $R2$, the supplier (and the supply chain) faces a demand reduction effect ($\theta < 0$). Despite this, the supplier invests in traceability when the traceability effect is above a threshold.

The coefficient β represents the effect of component traceability (financial or reputational) on the supplier. As this effect increases, the seller exerts a positive traceability effort. **[*Case Instance 3:*]** In this context, Walmart Canada's initiative with its third-party transport partners is noteworthy. First piloted between Walmart and Bison Transport (one of Walmart's largest transporters), the blockchain implementation demonstrated significant efficiency gains between the parties through faster payments, reduced invoicing discrepancies and quick resolution to any payment issue. Such efficiency gains allowed the transport partners to actively participate in the initiative and help scale the blockchain solution. Walmart Canada as a result was able to deploy an automated system to seventy of its third-party freight carriers (Vitasek et al., 2022).

We next examine the buyer's decision.

Proposition 4 (*Buyer's Traceability Effort*). *(a) Even if $\theta = 0$, the buyer exerts positive effort, if $\epsilon > 0$ and vice-versa.*

(b) When $\theta < 0$, if $\mid \theta \mid < \dfrac{2\gamma_s}{\alpha\beta(1-\delta)}$ *and* $\epsilon > \dfrac{\alpha\delta \mid \theta \mid}{\sqrt{\gamma_b}}$*, then* $\tau_b^* > 0$.

Proof. See Appendix B.3.1. We find that complementarity between the traceability drivers (θ and ϵ) exists in the supply chain as well. Fig. 2(b) shows the regions of buyer's traceability effort. Under the demand reduction effect ($\theta < 0$), the buyer invests in traceability when the traceability effect (β) is above a threshold and increasing (unshaded regions in the plot). Analogously, with a higher negative traceability effect ($\beta < 0$), demand-side effects are limited in their influence and the buyer does not invest in traceability (shaded regions in the plots). Importantly, note that even with a risk of demand reduction ($\theta < 0$) and reputational damage ($\beta < 0$), the buyer still exerts a traceability effort when the cost saving effect (ϵ) is above a threshold as outlined in our result. Therefore, supply chain firms can determine the areas of collaboration by carefully examining the demand-side, supply-side and reputational effects of traceability.

Comparison of the buyer's and supplier's efforts. A primary concern in the blockchain is *which player in the supply chain will initiate blockchain and exert effort to ensure traceability* (Ghode et al., 2020). To answer this, we examine the conditions when both the buyer and supplier exert traceability effort, when neither partner does and when only one of the supply chain partners exerts traceability effort (Refer Fig. 3, regions are derived from Propositions 3 and 4). A key observation is that the unshaded areas demonstrating traceability effort exerted by both the supply chain partners occur even under negative effects (*i.e.* either $\theta < 0$ or $\beta < 0$). These areas can be termed as *successful blockchain formation zones*. **[*Case Instance 4:*]** The light-shaded areas show regions of only one of the players exerting effort and can be termed *risky zones of blockchain formation* akin to Maersk's case where only the shipping company developed the platform. The dark-shaded areas are the *no blockchain formation zones* as none of the players exert any traceability effort. A key lesson for firms undertaking blockchain implementation is that a negative impact by itself is *not* a deterrent to traceability efforts if complementary drivers of traceability exist. Furthermore, our analysis enables firms to identify the zones of joint effort. Crucially, firms lying in risky zones (such as Maersk) or no zones of blockchain formation, will need to create suitable incentives for their supply chain partners to join the blockchain network or not invest at all.

The results thus far have examined the traceability efforts of supply chain partners. We next examine the supply chain pricing decisions.

Proposition 5 (*Price Analysis*). *Price analysis for the buyer and supplier is presented in Table 5*[10]

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[10] Refer to Table B.7 in the Appendix B.5 for expressions for θ_1, θ_2, ϵ_1, and β_1.

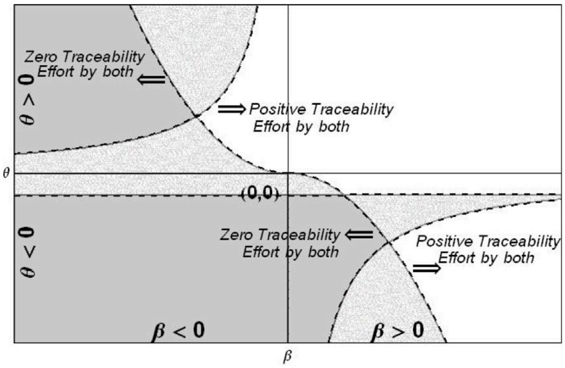


Fig. 3. Regions of buyer's and supplier's traceability efforts; dark-shaded areas show regions of no effort, light-shaded areas show regions of only one player exerting effort, unshaded areas show both players exerting positive traceability effort.

Table 5
Buyer's and Supplier's price analysis.

(a) Impact of β on buyer's and supplier's equilibrium prices.		
	Impact on P^*	Impact on W^*
	For $\theta > 0$	
β	$\frac{\partial P^*}{\partial \beta} > 0$	$\frac{\partial W^*}{\partial \beta} > 0$
	For $\theta < 0$	
β	$\frac{\partial P^*}{\partial \beta} < 0$	$\frac{\partial W^*}{\partial \beta} < 0$

(b) Impact of ϵ on buyer's and supplier's equilibrium prices		
	Impact on P^*	Impact on W^*
	For $\theta > 0$	
ϵ	$\frac{\partial P^*}{\partial \epsilon} > 0$ if $\theta > \theta_1$	$\frac{\partial W^*}{\partial \epsilon} > 0$
	For $\theta < 0$	
ϵ	$\frac{\partial P^*}{\partial \epsilon} > 0$ if $\beta < \beta_1$ and $\epsilon < \epsilon_1$	$\frac{\partial W^*}{\partial \epsilon} > 0$ if $\mid \theta \mid < \theta_2$

Proof. See Appendix B.4. Table 5 presents the impact of traceability effect coefficient (β) on P^* and W^* for demand expansion as well as demand reduction effects. We observe that the equilibrium prices of the buyer (P^*) and supplier (W^*) are increasing in β when there is a demand expansion effect of traceability ($\theta > 0$) and are decreasing in β when there is a demand reduction effect ($\theta < 0$). The buyer and supplier charge a price premium as β increases, though the converse happens under demand reduction. Interestingly though, the cost-saving effect from traceability (increase in ϵ) induces a price increase under certain thresholds for both the demand expansion and demand reduction effects (Table 5). This indicates a *margin* realization for the players. We infer that product collection and reuse enabled by traceability can allow the firms to charge a premium. The finding is especially relevant for managers considering blockchain adoption since a *price-premium* strategy is feasible for the buyer and the supplier, driven by unit cost savings. **[*Case Instance 5:*]** Our result finds support in practice as firms often charge a premium for product categories such as blockchain-based extra virgin oil labels (Violino et al., 2019) and traceable beef (Lin et al., 2022). Traceable pork, milk and cooking oil also fetch a price premium (Zhang et al., 2012).

4.2. Profit and consumer surplus analysis

A question of interest is *how does the relative impact of each player's effort drive total supply chain profit?* To answer this, we conduct a numerical analysis where we compare the optimal profits of the single firm (Π^*) and supply chain (Π^*_{sc}). Our objective is to understand *if supply chain traceability effort drives higher profit in a supply chain than what a single firm can yield;* also, *if consumer welfare is higher in the supply chain as compared to the single firm.* The comparisons show that for*the demand expansion effect*, when the relative impact of the buyer's effort on supply chain traceability (δ) is above a threshold, the supply chain generates a higher profit than a single firm. We also find that consumer welfare is higher in the supply chain.

The profits for the single firm and supply chain are derived from the equilibrium values in Tables 3 and 4. We select the following parameter values that satisfy the concavity and feasibility conditions: $\gamma = \gamma_b = \gamma_s = 100$, $C_0 = 0.25$, $\alpha = 0.1$, $K = K_b = K_s = 10$, $A = 70$ and $\beta = 10$. We plot Π^* and Π^*_{sc} for the entire range of δ (i.e. $0 \leq \delta \leq 1$). We vary θ ($\theta = -1, 1$) and ϵ ($\epsilon = 0.19, 0.21$) to create a grid of plots presented in Fig. 4.

The following are the key observations: *Under the demand expansion effect* (Figs. 4(a) and 4(b)), the supply chain profit (Π^*_{sc}) increases with δ and is higher than the profit of the single firm (for a higher δ threshold). We infer that as δ increases it leads to a greater traceability impact of the buyer that drives the increase in supply chain profit. This is further amplified by ϵ, the cost saving effect. The results find support in observations from practice. ***[Case Instance 6:]*** (Gaur & Gaiha, 2020) note that in enhancing traceability in supply chains, firms closer to consumers such as Walmart, and a large pharmaceutical company in their study collaborated with their supply chain partners to use blockchain. Faced with the risks of food safety, counterfeits and spurious products, such firms have initiated blockchain in their supply chains. We find that this also drives higher profits for the supply chains.

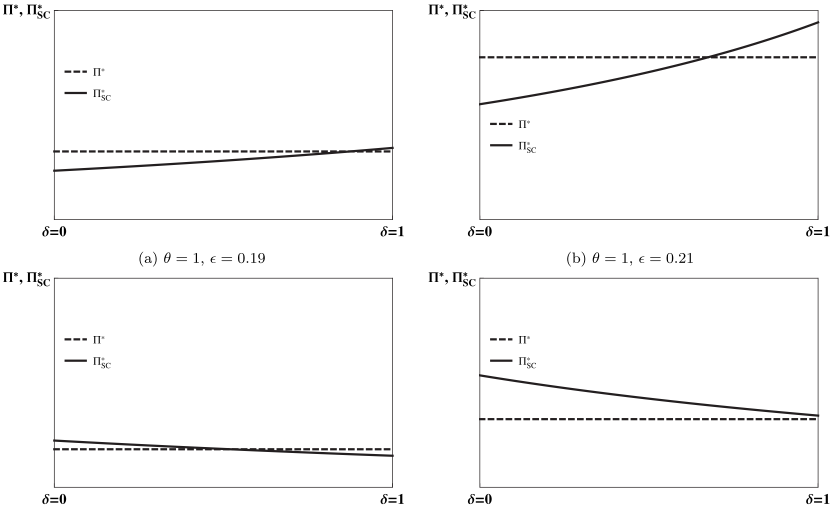
Under the demand reduction effect (Figs. 4(c) and 4(d)), the converse occurs. The supply chain profit (Π^*_{sc}) decreases as δ increases. Here as well, to preclude the loss from demand reduction, the buyer lowers his effort which reduces the supply chain traceability effort to lower the total supply chain profit.

Consumer surplus. To understand how consumers may benefit from blockchain implementation, we compare the consumer surplus for a single firm with that of the supply chain. We calculate consumer surplus (CS) as: $CS = \int_{OP^*}^{P_0} Q(P)dP = \frac{1}{2}Q^*(P_0 - P^*)$, P_0 is the price when demand Q is zero, OP^* is the optimal price (p_m and P^* for single firm and supply chain, respectively) and Q^* is the demand at equilibrium. We calculate consumer surplus for the single firm (CS) and supply chain (CS_{sc}) and conduct a numerical analysis to compare the two. We specify the same parameters as above for the analysis. From Fig. 5 we observe that the consumer surplus for the supply chain is higher than that of the single firm.

The profit and consumer welfare comparisons show that blockchain adoption not only increases supply chain profits (above certain thresholds), but also benefits the consumer. Blockchain adoption enhances consumer utility through traceability effort which increases consumer welfare. Furthermore, the consumer surplus difference between the single firm and the supply chain suggests that firms can extract additional surplus in a supply chain through pricing. Our pricing analysis demonstrated that firms can charge a price premium under blockchain adoption. This result further highlights that the opportunity to extract consumer surplus exists in blockchain-based supply chains.

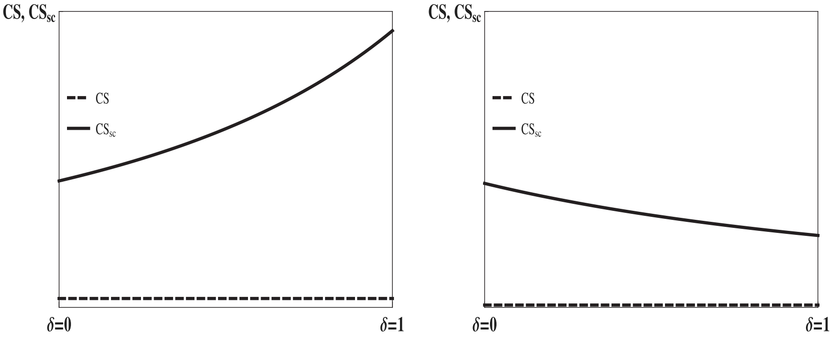
4.3. Blockchain surplus

The comparative analysis above leads us to ask *if blockchain adoption creates a surplus for the supply chain and how does it compare to the case of no adoption?* The buyer's and the supplier's surpluses are defined as the *additional* profits generated through the blockchain implementation. Specifically, the buyer's surplus (S_b) can be obtained as $S_b = \Pi^*_b - \Pi^*_{b0}$. Similarly, the supplier's surplus (S_s) is $S_s = \Pi^*_s - \Pi^*_{s0}$. Π^*_b and Π^*_s are the buyer's and supplier's profits obtained using equilibrium decisions presented in Table 4. Π^*_{b0} and Π^*_{s0} are the buyer's and the supplier's



(a) $\theta = 1$, $\epsilon = 0.19$
(b) $\theta = 1$, $\epsilon = 0.21$
(c) $\theta = -1$, $\epsilon = 0.19$
(d) $\theta = -1$, $\epsilon = 0.21$

Fig. 4. Profit comparison: Single firm (Π^*) and Supply Chain ($\Pi^*_{sc} = \Pi^*_b + \Pi^*_s$).



(a) $\theta = 1$, $\epsilon = 0.21$
(b) $\theta = -1$, $\epsilon = 0.21$

Fig. 5. Consumer surplus comparison.

profits when there is no blockchain implementation (reservation profits of each where $K_b = K_s = \tau_b = \tau_s = 0$). The buyer and the supplier will participate in the blockchain if and only if their surpluses through blockchain are positive. We state this formally as:

Proposition 6. *The blockchain implementation will result in a surplus if $K_b < \omega_b$ for the buyer and $K_s < \omega_s$ for the supplier, where, $\omega_b = A(P - W + \epsilon\tau_b\sqrt{\gamma_b})(1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)) - \gamma_b\tau_b^2 - \frac{A}{16}$, and $\omega_s = \tau_s(\beta - \gamma_s\tau_s) + \frac{A}{8}(8W(1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)) - 1)$*

Proof. See Appendix C.1.

ω_b and ω_s are the buyer's and the supplier's surpluses through blockchain implementation, respectively. We observe that ω_b is decreasing in W (price charged by the supplier). Therefore, higher levels of W will disincentivize the buyer to participate in the blockchain. Specifically, if $W > \overline{W} = P + \epsilon\tau_b\sqrt{\gamma_b} - \frac{A+16\gamma_b\tau_b^2}{16A(1-P+\alpha\theta(\delta\tau_b+(1-\delta)\tau_s))}$, the buyer will have a negative surplus ($S_b < 0$) and therefore, he will not participate in the blockchain.

From the expression for ω_s we observe if $\gamma_s > \overline{G_s} = \frac{8\beta\tau_s - A(1-8\ W(1-P+\alpha\theta(\delta\tau_b+(1-\delta)\tau_s)))}{8\tau_s^2}$, then the supplier does not have an incentive to join the blockchain. The investment cost threshold determines the buyer's decision to join the blockchain. The buyer's and supplier's individual incentives to join the blockchain are, therefore, dependent on W, γ_b (for the buyer) and γ_s (for the supplier). Furthermore, both ω_b and ω_s are increasing in ϵ indicating that the cost saving effect increases the surplus from blockchain implementation for each player.

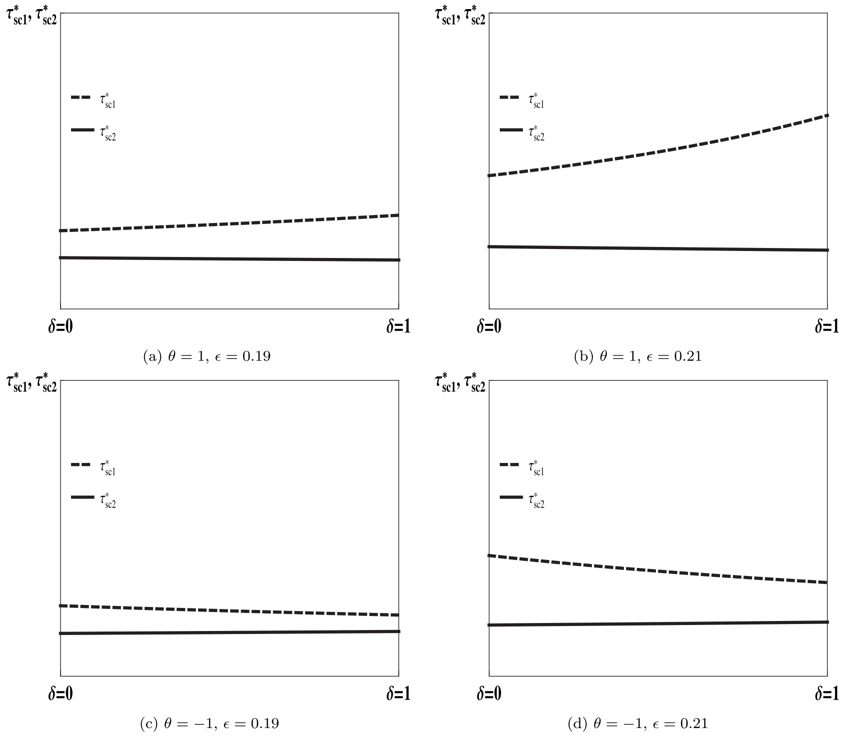
Next, we ask *if blockchain implementation generates a surplus for the overall supply chain.* We find that indeed the supply chain benefits. The supply chain surplus can be represented as:

$$\begin{aligned} S &= \Pi_b^* + \Pi_s^* - \Pi_{b0}^* - \Pi_{s0}^* \\ &= \tau_s(\beta - \gamma_s\tau_s) + A(P + \epsilon\tau_b\sqrt{\gamma_b})(1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)) \\ &\quad - K_b - K_s - \gamma_b\tau_b^2 - \frac{3A}{16} \end{aligned} \tag{8}$$

Corollary 7. *The blockchain implementation will result in a supply chain surplus if $K_b + K_s < \omega_t$ where, $\omega_t = \tau_s(\beta - \gamma_s\tau_s) + A(P + \epsilon\tau_b\sqrt{\gamma_b})(1 - P + \alpha\theta(\delta\tau_b + (1-\delta)\tau_s)) - \gamma_b\tau_b^2 - \frac{3A}{16}$*

Proof. See Appendix C.2. The result shows that the total fixed costs of technology implementation must be lower than the supply chain surplus for blockchain implementation. Iyengar et al. (2023b) discuss welfare implications for manufacturers who adopt blockchain and infer that blockchain adoption always lowers welfare as the manufacturers have to bear the cost of technology implementation. This occurs when $(K_b + K_s)$ exceeds the surplus ω_t. Furthermore, higher levels of γ_b and γ_s also result in $\omega_t < 0$ and disincentivize blockchain implementation.

Conversely though, blockchain adoption creates economic value for the supply chain members and increases their welfare, that is, if either K_b or K_s or both are lower, then the necessary condition is satisfied. For instance, Proposition 6 shows when $K_s > \omega_s$, the supplier will not participate in the blockchain. However, if K_b is low



(a) $\theta = 1$, $\epsilon = 0.19$

(b) $\theta = 1$, $\epsilon = 0.21$

(c) $\theta = -1$, $\epsilon = 0.19$

(d) $\theta = -1$, $\epsilon = 0.21$

Fig. 6. Total supply chain traceability effort comparison: When the buyer recycles (τ^*_{sc1}) and the supplier recycles (τ^*_{sc2}).

Table 6
Equilibrium decisions in the supply chain with supplier getting traceability benefits.

	Equilibrium values
τ^*_b	$\frac{\alpha A\delta\theta\left(\alpha\beta(\delta-1)\theta-\beta\sqrt{\gamma_s}\epsilon+2(R-1)\gamma_s\right)}{2\alpha^2A\theta^2\left(\gamma_b(\delta-1)^2+2\gamma_s\delta^2\right)-4\alpha A\gamma_b\sqrt{\gamma_s}(\delta-1)\theta\epsilon+2\gamma_b\gamma_s\left(A\epsilon^2-8\right)}$
τ^*_s	$\frac{\beta\left(\alpha^2A\delta^2\theta^2-4\gamma_b\right)+A(R-1)\gamma_b\left(\sqrt{\gamma_s}\epsilon-\alpha(\delta-1)\theta\right)}{\alpha^2A\theta^2\left(\gamma_b(\delta-1)^2+2\gamma_s\delta^2\right)-2\alpha A\gamma_b\sqrt{\gamma_s}(\delta-1)\theta\epsilon+\gamma_b\gamma_s\left(A\epsilon^2-8\right)}$
P^*	$\frac{\alpha^2A\delta^2\theta^2\left(-\alpha\beta(\delta-1)\theta-\beta\sqrt{\gamma_s}\epsilon+2(R+1)\gamma_s\right)+2\gamma_b\left(\sqrt{\gamma_s}\epsilon(\beta-\alpha A(R+1)(\delta-1)\theta)+\alpha(\delta-1)\theta(\alpha AR(\delta-1)\theta+3\beta)+\gamma_s\left(A\epsilon^2-2R-6\right)\right)}{2\alpha^2A\theta^2\left(\gamma_b(\delta-1)^2+2\gamma_s\delta^2\right)-4\alpha A\gamma_b\sqrt{\gamma_s}(\delta-1)\theta\epsilon+2\gamma_b\gamma_s\left(A\epsilon^2-8\right)}$
W^*	$\frac{\alpha^2A\delta^2\theta^2\left(-\alpha\beta(\delta-1)\theta-\beta\sqrt{\gamma_s}\epsilon+2(R+1)\gamma_s\right)+2\gamma_b\left(\sqrt{\gamma_s}\epsilon(2\beta-\alpha AR+1)(\delta-1)\theta+\alpha(\delta-1)\theta(\alpha AR(\delta-1)\theta+2\beta)+\gamma_s\left(A\epsilon^2-4R-4\right)\right)}{2\alpha^2A\theta^2\left(\gamma_b(\delta-1)^2+2\gamma_s\delta^2\right)-4\alpha A\gamma_b\sqrt{\gamma_s}(\delta-1)\theta\epsilon+2\gamma_b\gamma_s\left(A\epsilon^2-8\right)}$

to ensure $K_b + K_s < \omega_t$, then the buyer may share the supplier's cost of blockchain implementation to incentivize the supplier's participation in the blockchain. Therefore, managers can choose to share the one-time fixed costs of technology adoption with their supply chain partners to lower the cost. Since blockchain's success crucially depends on supply chain partners' adoption and traceability effort, surplus sharing or cost sharing mechanisms can incentivize partners. **[*Case Instance 7:*]** Importantly, Maersk's inability to cover the costs of blockchain development and the resulting closure of its project highlights the need to coordinate and share costs across multiple entities for such initiatives to be sustained.

5. Model extension: Supplier cost saving through traceability

As an extension of our study, we now consider that instead of the buyer, the supplier collects and reuses the product. i.e. traceability enables cost saving for the supplier. Our objective here is to understand – *is product collection and reuse more beneficial to the supply chain at the buyer's or the supplier's end?*. Furthermore, *in which case is the total traceability effort higher*? We represent the unit cost of supplier due to traceability as $C_{rs} = R - \epsilon\sqrt{C_{\tau_s}}$ where R represents the supplier's marginal cost of procuring raw material. Other terms remaining the same as the supply chain model, the profit functions of the buyer and supplier are given as $\Pi_b = A(P-W)(1-P)+\alpha\theta(\delta\tau_b+(1-\delta)\tau_s)-\gamma_b\tau_b^2-k_b$ and $\Pi_s = A\left(W - R + \sqrt{\gamma_s}\tau_s\epsilon\right)(1-P+\alpha\theta(\delta\tau_b+(1-\delta)\tau_s))+\beta\tau_s-\gamma_s\tau_s^2-k_s$.

Proposition 8. *Solving the above gives equilibrium decisions outlined in Table 6.*[11]

We substitute $R = 0$ in the equilibrium values in Table 6 to allow us to compare the values with those in Table 4. We represent the output of the earlier supply chain case where the buyer invests in recollection and reuse using a subscript $sc1$ and where the supplier invests in recollection and reuse with $sc2$. The comparisons pose some degree of analytical complexity, and hence, we conduct a numerical analysis (Figs. 6 and 7). We observe from Fig. 6 that the total supply chain traceability effort is higher in the case when the buyer does product collection and reuse. We infer that the buyer's benefit from manufacturing cost saving drives higher traceability effort than in the case of the supplier.

However, the supply chain benefits differently, as the profit comparisons demonstrated in Fig. 7. For a lower cost-saving coefficient (ϵ), the supply chain profit is higher when product collection and reuse is at the supplier's end (Fig. 7(a)). However, as ϵ increases, the supply chain has a higher profit when product collection and reuse is at the buyer's end (Fig. 7(b)). This can be reasoned from the observation of the traceability effort. In magnitude, the supply chain traceability effort significantly rises (for a higher ϵ) which drives the supply chain profit.

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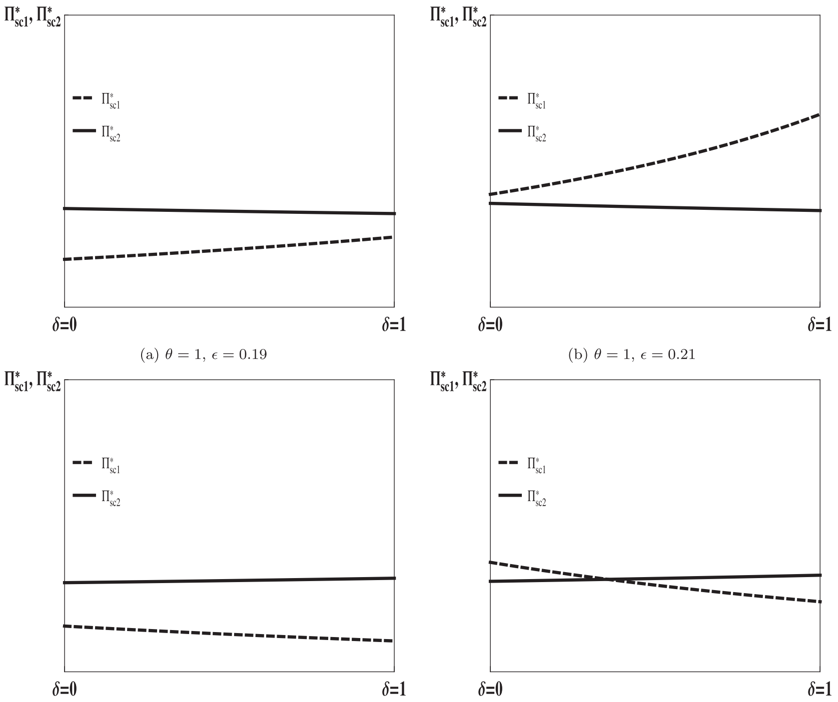
[11] See Appendix D for proof.



(a) $\theta = 1$, $\epsilon = 0.19$ (b) $\theta = 1$, $\epsilon = 0.21$

(c) $\theta = -1$, $\epsilon = 0.19$ (d) $\theta = -1$, $\epsilon = 0.21$

Fig. 7. Total Supply chain Profit Comparison: When the buyer recycles (Π^*_{sc1}) and the supplier recycles (Π^*_{sc2}).

Under the demand reduction effect, however, the supply chain profit is higher when the supplier conducts product collection and reuse (for a given ϵ, and higher threshold δ values). When faced with demand reduction, the buyer reduces his traceability effort which lowers the overall supply chain traceability and profit. In such a case, product collection and reuse at the supplier's end yield higher profit for the supply chain.

The results importantly highlight the necessity of the right supply chain design under blockchain, particularly when traceability enables circularity. Our results show that for a dyadic supply chain, though the total traceability effort is higher when manufacturing cost saving is realized at the buyer's end, the overall supply chain profit realization is more nuanced. Under a higher cost saving effect, product collection and reuse by the buyer generates higher profit but under a lower cost saving effect or demand reduction, the supply chain is better off when collection and reuse occur at the supplier's end. Managers will note therefore that the downstream player's involvement in circularity benefits the supply chain more when both demand-side and supply-side benefits are higher, however, under negative consequences of demand or lower supply-side benefits, the supply chain is better off with the upstream partner's involvement in circular supply chain operations.

6. Discussion and conclusion

Motivated by the instances of blockchain implementation failures, in this paper, we examine the conditions of blockchain-enabled traceability efforts in a supply chain. We analyze the influence of different factors on blockchain adoption decisions and draw several insights from our models.

6.1. Study insights

While drawing lessons from a blockchain pilot, Sternberg et al. (2021) note that blockchain adoption is an inter-organizational systemic decision and managers must comprehend the underlying trade-offs between the potential advantages and challenges of blockchain implementation. By integrating demand-side, supply-side and reputational factors, we analytically demonstrate the conditions that facilitate blockchain adoption and importantly highlight that a negative demand-side or reputational effect by itself is not a deterrent. If supply side effects are present, traceability can still be initiated in supply chains.

Our findings also provide an analytical basis for explaining Maersk's issue. Acknowledging the challenges for Maersk during the developmental stages, Marvin Erdly, head of TradeLens at IBM Blockchain said –*"We do need to get the other carriers on the platform. Without that network, we do not have a product"*.[12] Our analysis of the efforts made by the supplier and the buyer in a supply chain illustrates the conditions of shared effort, where one entity puts forth effort or none at all. As presented in Table 7, identifying such zones of blockchain formation would be advantageous for managers considering blockchain implementation.

The comparative analysis of the supply chain and single firm shows that with a greater relative impact of the downstream entity on supply chain traceability, the supply chain incurs higher profits than a single firm (in the presence of positive demand-side ($\theta > 0$), supply-side ($\epsilon > 0$) and reputational ($\beta > 0$) factors). We infer, therefore, that traceability enhances the economic value of the supply chain under certain conditions. And, the downstream entity's relative impact drives supply chain profits. This is well observed in the food sector in practice. Faced with consumer pressures and the necessity to convince consumers of food safety, several blockchain initiatives have been initiated by large retailers such as Walmart, Carrefour, Tesco, Co-op and Kroger in the US, France and the UK.[13]

Importantly, we find that blockchain adoption creates a supply chain surplus that can allow surplus- or cost-sharing mechanisms to

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[12] www.coindesk.com/markets/2018/10/26/ibm-and-maersk-struggle-to-sign-partners-to-shipping-blockchain/ Accessed on 22nd January 2024.

[13] www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/companies-use-blockchain-to-track-food-products-from-farm-to-fork-49267094 Accessed on 22nd January 2024, www.greenbiz.com/article/implications-walmarts-blockchain-mandate-food-suppliers Accessed on 22nd January 2024.

Table 7
Framework for blockchain implementation.

Key dimensions	Reference results	Recommended measures for supply chain partners
Buyer's and Supplier's traceability efforts	Propositions 3 and 4	(a) Examine the complementarity of demand-side, supply-side and reputational factors.
	Figs 2 and 3	(b) Identify zones of operations and potential collaborations to avoid unfavorable zones that hinder blockchain adoption.
Supply chain profit	Fig. 4	(a) Identify whether the buyer's or supplier's effort has more impact on the traceability outcome (b) Assess potential benefits of joining under prevalent demand expansion or reduction effect
Blockchain surplus	Proposition 6, Corollary 7	(a) Assess individual partner's costs of blockchain implementation and participate if both have lower costs (b) Even if one of the supply chain partner's blockchain costs outweigh the benefits, explore the possibility of compensating the same through higher supply chain surplus derived through blockchain implementation
Point of recollection- Reverse supply chain design	Proposition 8; Figs. 6 and 7	(a) For low cost saving effect, the supply chain is better off with product recollection at supplier's end. (b) For high cost saving effect, under demand expansion supply chain is better off with recollection at buyer's end

incentivize members to join blockchain. While examining potential blockchain applications, Cole et al. (2019) note that managers must consider how to incentivize organizations to adopt blockchain, and how to share or redistribute the costs of implementation. Accordingly, we first show that blockchains generate economic value and second, we provide directions to obtain buy-in from other actors in the supply chain.

We also find that traceability has implications for supply chain design. When demand-side, supply-side and reputational factors are favorable, product collection and reuse by the downstream buyer generates a higher profit, otherwise, the supply chain is better off with the upstream supplier conducting product collection and reuse. Emphasizing the potential of blockchain in circular supply chain operations, the Ellen Macarthur Foundation notes that by allowing a greater degree of product traceability and monitoring, blockchains can enable greater levels of material circulation.[14] Some early-stage applications in this context are the waste management company Suez's blockchain usage to record sludge transfer from wastewater to agricultural soils,[15] Coca-Cola's blockchain usage in waste collection in Africa[16] and Elelctrolux's initiatives to recycle products from refrigerators.[17] Our results show that cost savings from product collection and reuse can be a strong enabler of blockchain adoption.

We summarize the key dimensions and recommended measures for supply chain partners in Table 7. This framework can be used by supply chain partners as a tool to assess potential benefits and challenges in blockchain implementation and measures to mitigate the challenges.

6.2. Concluding remarks

The models presented in the paper have certain applications – Our results challenge the common belief that blockchain adoption fails if consumers do not respond, we show that several other factors can act as strategic complements that drive the traceability effort of supply chain partners. While we identify conditions when the buyer's and supplier's efforts vary depending on market characteristics, a central issue in driving blockchain adoption is the distribution of surplus or benefits in the supply chain (Niu et al., 2021). We show that there is economic value in blockchain adoption which can be used to incentivize supply chain partners. Thereby, we find that under the investment cost thresholds, blockchain adoption leads to welfare for supply chain entities and consumers.

Our study has certain limitations — while we analyze a static model of decision-making in our paper, a dynamic model may generate several additional insights. We have assumed common knowledge between the supply chain partners. This may be relaxed to consider information asymmetry cases which may provide additional insights. The formation of industry consortia to enable competing firms to join blockchain networks is another initiative that has been undertaken in the banking, finance, shipping and maritime sectors.[18] However, this presents an interesting *coopetition paradox* where competitors cooperate in blockchain networks to share data and trade information. Additional research is needed to ascertain the potential success of such blockchain consortia.

It is crucial for scholars and managers to delve into the issues highlighted in this paper to gain a deeper comprehension of the conditions of blockchain adoption. The lack of successful cases in enterprise blockchain and the hesitance of supply chain entities to participate in blockchain networks call for more extensive and in-depth attention than what has been covered in extant scholarly literature and business press. There is a greater need for managers to understand the conditions that enable traceable system implementation, especially in large enterprises. Our paper presents an analytical model that aims to address this issue.

In addition to the demand–supply perspective presented in our paper, there are several other challenges that hinder blockchain implementation. For instance, firms face technological issues due to the highly energy-intensive computing requirements, along with significant financial and human resource needs. Additionally, large enterprises need to overcome organizational and governance challenges. Though these factors are not the subject of our present study, they significantly impact the willingness of enterprises to invest in blockchain development and require further consideration (Kinni, 2023).

CRediT authorship contribution statement

Prakash Awasthy: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Tanushree Haldar:** Writing – review & editing, Writing

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[15] www.suez.com/en/about-us/innovation-approach/circularchain-the-circular-economy-blockchain Accessed on 25th February 2024.

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[17] circular-foam.eu/ Accessed on 25th February 2024.

[18] https://www.ft.com/content/0064e0a2-2210-45de-b366-b0439cb575a2. Accessed on 5th May 2024.

– original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Debabrata Ghosh:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejor.2024.10.019.

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