Transportation Research Part E 195 (2025) 103962

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

The new supply chain information sharing Renaissance through crypto valuation mechanism of digital assets

Arjun Rachana Harish [a,d], Xinlai Liu [e], Ming Li [a,b,c,f,*], Ray Y. Zhong [d], George Q. Huang [a,b]

[a] Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China
[b] Research Institute for Advanced Manufacturing, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China
[c] Research Centre for Digital Transformation of Tourism, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China
[d] Department of Data and Systems Engineering, The University of Hong Kong, Hong Kong, China
[e] Department of Systems Engineering, Cornell University, Ithaca, NY, United States
[f] Collaborative Generative AI (Co-GenAI) Research Centre, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China

A R T I C L E I N F O

Keywords:
Supply Chain Information sharing
Digital Assets
Blockchain Technology
Internet of Things (IoT)
Valuation Mechanism

A B S T R A C T

It is well known that supply chains should leverage information sharing from stakeholders as a measure to drive business growth. However, the practice of information sharing for supply chain management has been fairly limited due to the high cost of meeting differential user needs, information-island from centralized storage, and inefficient information value capture. To address these concerns, we investigate a crypto-valuation mechanism of digital assets (DAs) inspired by a standard monopolistic screening model. Our model consists of a DAs provider with a unique cost structure of sharing DAs and users who experience participation costs. The DAs are digital replicas of physical assets (e.g., workforce, trucks, and cargo) in the supply chain. The provider produces DAs with maximum features (e.g., carbon emission, customer satisfaction, etc.) to give users differential feature access for set valuations (crypto-token payment). When the consumers experience participation costs, we find that the marginal sharing and participation costs determine the optimality of DAs versioning. By endogenizing the highest quality (or level of digitization), we find that an increase in the cost of delivering DAs results in every user getting access to fewer features. Interestingly, cost factors do not directly influence user coverage, i.e., costs do not determine who gets access to DAs. However, the provider's decision to absorb a portion of user participation cost can contract the user coverage. Overall, this study contributes a novel valuation mechanism to the literature on blockchain adoption for information sharing in the supply chain. It also offers insights and recommendations based on critical parameters to guide supply chains that leverage the mechanism for business growth.

1. Introduction

Modern supply chains are constantly challenged to leverage information for effective business growth, from abiding by sustainability norms to ensuring the resiliency of operations. A well-known approach to dealing with such a challenge is delegating

* Corresponding author at: Ming Li at Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China.

E-mail address: ming.li@polyu.edu.hk (M. Li).

https://doi.org/10.1016/j.tre.2025.103962
Received 26 July 2024; Received in revised form 30 November 2024; Accepted 3 January 2025
Available online 17 January 2025
1366-5545/

information acquisition responsibilities to a stakeholder who is most knowledgeable about its intimate surroundings (Hayek, 1945). The supply chains have been attempting to promote inter-stakeholder information sharing through direct sharing programs or third-party service providers (such as SymphonyIRI) (Shang et al., 2016). For instance, P&G, Johnson & Johnson, and Pepsi leverage routine sales information updates from their retailers to monitor the sell-through rate of their consumer packaged goods (Munves, 2013). However, information sharing in supply chains is not a new proposition; rather, it has been a well-entrenched practice whose potential benefits have been propounded extensively by researchers and practitioners alike.

Notably, its popularity over the past two decades is predicated on three fundamental changes to the supply chain management landscape. First, (Lee et al., 1997) opened up discussions on the strategic significance of information sharing when they addressed the bullwhip effect in supply chains through point-of-sales (POS) data sharing. The flurry of studies that ensued focused on leveraging information to create opportunities in operations, administration, marketing, among others (Ha et al., 2011; Lee & Whang, 2000; Los et al., 2020; Zhao et al., 2024). Second, the rise of information and communication technologies (ICT) has been paramount in answering *how to share information* (Chatterjee & Ravichandran, 2013; Ha & Tong, 2008). The use of distributed databases, online servers, and Inter-organizational Information systems has led to the so-called 'Internet-enabled Supply Chain' (Anderson & Hau, 2000), catapulting the supply chain partners to be connected as never before. Finally, when it came to *how to collect information*, the Internet of Things (IoT) technology has been a game-changer (Camdereli & Swaminathan, 2010; Lee & Özer, 2007). Thanks to their improved sensing and communicating capabilities, state-of-the-art Mobile sensing and specialized IoT technologies have become the building blocks for the earlier *Walmart Mandate* (Kaplan, 2018), as well as the modern Crowdsensing (Harish, Wu, et al., 2023) and Cyberphysical Systems (CPS) (Harish et al., 2021).

However, most of the success stories of technology adoption have been limited to individual firms, while the supply chain joint ventures for effective inter-stakeholder information sharing mostly remain elusive. For instance, a study on sustainability practices revealed that almost 81 % of the surveyed 1,700 companies displayed partial to complete lack of visibility into their suppliers (TSC, 2016). More recently, the COVID-19 pandemic has fast-tracked the preexisting risks in the supply chains and brought the lack of technology adoption and visibility from information sharing to the fore (Harapko, 2023). The resistance from the supply chain stakeholders towards technological adoption for information sharing comes from three unaddressed aspects.

- *Cost of Sharing:* The supply chain participants vary in terms of their need for information, meaning customer reviews and location tracking may suffice one participant, whereas another participant with sustainability commitments may request access to carbon emission information of the carriers as well (Dai & Tang, 2022). However, given the cost (e.g., deploying IoT technology) to collect and share/serve individual information or features (Harish, Wu, et al., 2023; Liu et al., 2022), whether the service providers can fulfill all the user needs deserves more attention.
- *Reliable Storage:* The resilient/sustainable supply chains demand reliable storage/support systems to deliver instantaneous information availability and real-time recalibration. The traditional private storage solutions produce information silos and asymmetry, whereas the centralized solutions that promote/enable shared storage or third-party storage are vulnerable to a single point of attack. As an example of the disadvantages of centralized storage, Amazon has been accused of leveraging suppliers' data to cannibalize demand through search results manipulation and knockoff goods production (Kalra & Stecklow, 2021). Not surprisingly, almost 75 % of the Inter-organizational Information systems are met with underutilization or non-participation (Chatterjee & Ravichandran, 2013).
- *Value of Information:* The traditional incentive mechanisms use one-off monetary transactions (e.g., cash based side payments) to motivate information sharing (Jiang & Hao, 2016; Shang et al., 2016), similar to the pricing of physical goods. However, it is difficult to set a fixed price for information as its value to a user cannot be measured reliably. The value/benefit of information to its user may not be realized immediately when shared. Rather, a user may consume it over extended periods, thereby making it essential to gauge/track the usage to establish a reliable valuation mechanism.

Blockchain technology is suitable to address these concerns. Its decentralized storage mechanism supports reliable information storage (Davies et al., 2024; Fang et al., 2024; Tiwari et al., 2023). It allows the information provider to set up custom smart contracts that serve a suitable amount (or versions) of information to individual users (Li et al., 2023; Liu et al., 2020). The blockchain network allows the information provider to gauge the user's value for information through their consumption behavior, which determines the level of technology adoption (or cost) to serve information to individual users. In addition, users can pay the information provider in crypto-tokens in return for the information they consume. These tokens enhance value capture as they hold fixed value for extended periods to serve as a screening criterion or value indicator for the information provider to attract symbolic benefits from its supply chain stakeholders (e.g., access to finance). For instance, (Harish et al., 2021) discuss using non-fungible crypto tokens to capture the value of information and support the financing needs of small and medium-sized transportation companies. However, such a mechanism requires answers to the following questions to prove its relevance in information sharing.

Why should a provider offer users access to the information? If offered, how should the provider determine the valuation structure (i.e., tokens to charge from users) and sharing structure (i.e., how much information to share with users)? When is the sharing strategy optimal? What is the impact/influence of various factors (e.g., provider's sharing cost, user's participation cost, etc.) on the optimal sharing strategy?

To address these questions, we aim to investigate a crypto-valuation mechanism of digital assets (DAs) using a general model that takes inspiration from a standard monopolistic screening model (Laffont & Martimort, 2001). The model in this study consists of a principal—DAs producer with a unique cost structure of creating/sharing DAs and agents—users who experience participation constraints in consuming DAs. The DAs are the digital replica of physical assets (e.g., workforce, trucks, and cargo) that entangle information and material flows to bring visibility into the supply chain operations and logistics (Harish et al., 2021, 2023a,b). The visibility over its stakeholders helps a supply chain participant to extract value through cost reduction, performance optimization, or even reliability/resilience improvement. For instance, a supplier uses the logistics carriers' real-time tracking information (e.g., order status, estimated pickup time, etc.) to optimize the inventory level. That is, the DAs can be composed of features or functionalities that depict the supply chain operations (e.g., customer rating, carbon emission, etc.), where more functions/features signify the higher quality of DAs. Once the producer creates the highest quality DAs, it can create versions of lower quality (fewer features) to serve different users and set their valuations (token payment for a version) accordingly. We first investigate the model under complete information, where the principal knows the individual user types (marginal value for quality) to deliver the versions, followed by a mechanism design under incomplete information to give a more general understanding of DAs creation and versioning in the supply chain.

We summarize the major findings of this study as follows. Under complete information, irrespective of the principal's cost of creating/sharing DAs, there is an upper limit on the highest quality available. In the absence of costs, all the users get access to the quality or version of their choice (first-best solution or type customized access to DAs). On the other hand, finite costs split the users into two segments, one offering type-customized access and the other where the users uniformly get access to the highest quality DAs. The latter segment represents the users who are willing to pay for more quality or features than what is on offer from the producer. Notably, all users get access to DAs under complete information. The scenario with imperfect information does not induce full user coverage as it divides the users into three segments where the smallest types do not get access to DAs, the middle types get type-customized access to their individual needs, and the highest types are bunched together, and get the same/uniform DAs quality.

Interestingly, cost factors, both the principal's sharing cost and the user's consumption/participation cost, do not affect user coverage under complete and imperfect information scenarios. We find that the access to DAs is purely a function of the user type distribution. However, the costs influence the quality of DAs produced and the size of the user segment that gets customized access to DAs. The size of the middle segment expands with the user's participation costs, whereas it reduces with the producer's sharing costs. In addition, all users access a lower-quality version of DAs as the marginal costs increase.

In addition to these findings, we offer extensions to explore two additional aspects − a) the cost of versioning or differential access to DAs and b) hybrid storage solutions to reduce user participation cost, for their impact on the qualitative implications of this study.

To summarize, this study makes the following contributions:

- This is one of the early studies to address challenges to information sharing in supply chains, such as the cost of differential provision, shortcomings of centralized storage, and inefficiencies in capturing the value of information.
- This study advances the literature on blockchain adoption for information sharing and supply chain applications. We introduce a novel crypto-valuation mechanism of digital assets inspired by the standard monopolistic screening model to facilitate information sharing for supply chain applications.
- The results capture the impact of various critical parameters, such as value for information and user participation cost, among others, on the optimal DAs provisioning strategy under complete and incomplete information. We derive analytical expressions that show the role of parameters in determining the difference in DAs quality and access given to different user types.

The content in the rest of the paper is summarized as follows. In Section 2, we discuss the literature relevant to this study. The mechanism for DAs sharing appears in Section 3. Section 4 examines the mathematical model for the complete and incomplete information cases; these results aid in evaluating model extensions through comparison in Section 5. We conclude with future research directions in Section 6.

2. Literature Review

The following subsections summarize the supporting literature used to construct the valuation mechanism in this study −(1) Incentive Mechanisms for Information Sharing, (2) Blockchain for Supply Chains, and (3) Quality Segmentation of goods.

2.1. Incentive mechanisms for information sharing

This paper is naturally related to the supply chain literature on designing incentive mechanisms for vertical information sharing. One of the most prominent (initial) application of information sharing came with a study from (Lee et al., 1997), who discuss the "Bullwhip effect" or information distortion that create inefficiencies across the supply chain, such as missed schedules, poor inventory management, and inefficient logistics, among others. The flurry of research that ensued has explored/investigated the strategic role of demand information sharing from various contexts, such as capacity planning (Chu et al., 2017; Kapuściński & Parker, 2022; Lin et al., 2024; Ren et al., 2010), sales forecasting (Cachon & Lariviere, 2001; Shamir & Shin, 2016), horizontal competition (Ha & Tong, 2008; Shang et al., 2016; Wang et al., 2022), and cost reduction (Ha et al., 2017; Leng & Parlar, 2009). Most of these studies assume that the information provider possesses the necessary information to share, thereby not considering the role of initial investment (in technology or resources) required to acquire/share the data.

Unlike these studies, (Ha & Tong, 2008) consider two competing supply chains that incur differential initial investment to share information. They discuss the conditions to translate an information investment to a competitive advantage for one supply chain over the other. However, similar to many other studies in literature, the focus of this study is limited to one-to-one demand information sharing between an upstream and downstream participant. Modern supply chains require the sharing of a wide array of information, such as demand, fuel consumption, and customer perception, among multiple supply chain participants, i.e., there is a need for a broader scope in terms of the information shared as well as the participants involved.

Closer to our study, more recent literature on mobile crowdsensing develops on this setting to produce platform-leading incentive mechanisms (Duan et al., 2014; Harish, Wu, et al., 2023; Luo et al., 2016; Tao et al., 2020). These mechanisms promote general information sharing from smartphone users by delivering necessary incentives as compensation for their efforts. They broaden the scope of information sharing but rarely discuss the choice of information sharing or the differential sharing of information, catering to specific user requirements/needs. In most crowdsensing literature, the participants engage in one-off information sharing transactions with an upfront monetary incentive (e.g., cash, side payment, etc.). However, unlike physical goods/services, it is difficult to price information as its value to users in supply chain may realize with use/usage over time. In addition, supply chain stakeholders span national/international borders, making the monetary incentives vulnerable to inflation, local policies, and global exchange rates.

Our model considers using non-monetary (symbolic) incentives delivered via blockchain/crypto tokens to enable information sharing. This feature has no counterpart in the literature on supply chain information sharing.

2.2. Blockchain for information sharing

Like any other ICT service provider, blockchain networks essentially act as a center for converting and disseminating data as valuable information (Govindan et al., 2024; Mishra et al., 2024). (Franke et al., 2023) explores the advantage of blockchain adoption against traditional centralized storage solutions for data sharing/provision. They show that the credible value signal associated with blockchain adoption helps it outperform conventional institutions in delivering firm value. More recently, the cryptotokens and smart contracts have been the driving force behind several initiatives which have now led to Initial Coin Offerings attracting investments (Chod et al., 2022; Gan et al., 2021), as well as the latest Metaverses thriving on Non-Fungible Tokens. Subsequently, studies have explored the application of utility tokens for fundraising (Chod et al., 2022; Holden & Malani, 2022; Malinova & Park, 2023) and goods exchange (Shakhnov et al., 2023; Sockin & Xiong, 2023), replacing the traditional funding mechanisms (e.g., equity, debt, etc.).

Closer to our research, few studies demonstrate blockchain application alongside IoT technologies in supply chains. (Meyer et al., 2019) used digital signatures from the stakeholders signed in the smart contract to confirm the genuineness of supply chain transactions. On the other hand, (Harish et al., 2021) proposed the use of non-fungible utility tokens to design incentive mechanisms for motivating the sharing of logistics information collected using mobile sensing and IoT technology. The tokens enabled information valuation, i.e., users paid the information provider in tokens in return for the information they consumed. However, these studies remain qualitative in using tokens for information sharing applications in supply chains.

Unlike these studies, (Harish et al., 2023b) introduce a Stackleberg game in a supply chain setting to capture the interaction between an information provider and users. They use a Stackelberg game to show that tokenization effectively promotes ESG disclosure from supply chain participants. However, their study fell short in addressing the need for differential provision and valuation of information according to the individual user needs.

To summarize, the existing studies have explored the application of blockchain to facilitate supply chain tracking and tracing through digitization. Their exploration in an industrial setting has revealed its feasibility and practitioners' perceptions of the practicality of blockchain adoption. However, most of these studies are limited to qualitative discussions without the economic or strategic considerations required to cater to information sharing in the supply chain.

2.3. Valuation of goods

Extant research has discussed vertical differentiation or quality segmentation of physical and digital goods, focusing on feature/functionality differentiation and pricing (Mussa & Rosen, 1978; Varian, 1997; Wei & Nault, 2014). (Varian, 1997) and (Wei & Nault, 2014) refer to such strategies on digital goods as versioning, where one creates the highest quality digital product (flagship product) and then disable/remove feature/functions to generate lower quality versions to serve various customer needs. The studies on versioning span across a variety of contexts to tackle aspects such as market segmentation (Bhargava & Choudhary, 2008), reservation utilities (Chen & Seshadri, 2007), consumer group taste (Wei & Nault, 2014), privacy and personalization (Chellappa & Shivendu, 2010; Lahiri & Dey, 2012), among others.

Though these studies produce a rich set of results to understand versioning strategy, a hitherto unaddressed factor is of use in our study. The supply chain information sharing is contingent on the presence of necessary technology/resources with the participants. Generally, the versioning literature either exogenously specifies the highest quality of the good and assumes its development cost is sunk or ignores the development costs (Bhargava & Choudhary, 2008). However, there are exceptions in information goods literature. For instance, (Jones & Mendelson, 2011) factor in the cost of developing the information goods, even though they did not discuss its direct impact on the versioning strategy. (Wei & Nault, 2013) introduce a cost function in the model setup to address the production cost of the highest quality goods. Even though they displayed the correlation between the convexity of the cost function and the quality, their study did not investigate the optimality of quality menu or the highest quality produced.

A similar study from (Hahn, 2000) in physical goods literature investigates the development cost of the flagship product while considering the additional costs of serving users. Our study takes inspiration from this study to bring together the impact of sharing/creation cost (incurred by the information provider) and the consumption/participation cost (suffered by the user) for supply chain information sharing.

To summarise, studies discuss quality segmentation of physical and digital goods. They generally focus on two aspects: feature/functionality differentiation and pricing across various contexts, such as market segmentation, consumer group taste, and privacy, among others. However, the traditional pricing mechanisms do not factor in the specific needs of information sharing, such as the need for technology investment, which has significant practical implications for businesses and consumers alike.

2.4. Summary

We summarize the gap/observations from the literature in Table 1:

- Most supply chain incentive mechanisms deal with demand information sharing and its strategic advantages to stakeholders. Even though other studies (e.g., crowdsensing literature) discuss information sharing from a broader point of view, they still mostly rely on transactions with fixed monetary incentives.
- Blockchain technology is prevalent in supply chain contexts/applications to tackle centralization. Its tokens incentivize information sharing, even though most studies remain qualitative in their discussion.
- Even though studies on quality segmentation provide valuable insights into the differential sharing of goods with users, they need to be improved to address problems specific to information sharing in the supply chain.

Therefore, we extend these previous studies to construct a novel token-enabled DAs valuation mechanism to promote information sharing. This paper is one of the first attempts at DAs valuation, albeit using a crypto-valuation mechanism, for information sharing in supply chains. The mechanism aims to drive information sharing by eliminating the concerns related to centralization, differential provision of information, and value capture. By demonstrating an optimal solution, we draw attention to the potential benefits of the mechanism for information providers and users. This study offers several insights and recommendations to guide supply chains that leverage DAs sharing for business growth.

3. Digital asset valuation for information sharing

The purpose of this section is two-fold. First, we introduce a scenario highlighting the significance of information sharing in supply chains. Second, we present a crypto-valuation mechanism to promote information sharing in the supply chain.

3.1. Recognizing and sharing Information: Rubik's cube Vs supply chain

The role of information sharing in the supply chain is comparable to solving a Rubik's cube. Even though both tasks seem complex at first, with the right resources and approach, one can unravel the value of the information, just as they would perfectly align the distorted squares/colors of the cube. We dedicate this section to discussing three interesting/striking similarities between the role of information sharing in the supply chain and the iconic puzzle of Rubik's cube (refer to (Agostinelli et al., 2019) for the properties of a Rubik's cube). To discuss the three similarities, we consider a scenario with the logistics of prefabricated construction modules, which

Table 1
Benchmarking the current study with other related streams of literature.

Authors/Year	Research Scope	Key Findings	Research Gap
(Lee et al., 1997), (Chu et al., 2017; Kapuściński & Parker, 2022; Lin et al., 2024; Ren et al., 2010), (Cachon & Lariviere, 2001; Shamir & Shin, 2016), (Ha & Tong, 2008; Shang et al., 2016; Wang et al., 2022), (Ha et al., 2017; Leng & Parlar, 2009), and (Duan et al., 2014; Harish, Wu, et al., 2023; Luo et al., 2016; Tao et al., 2020).	Incentive Mechanisms for Information Sharing	• Sharing of sales information and the strategic benefits in the supply chain. The advent of platform-leading incentive mechanisms for crowdsensing. Studies on practical application with a focus on scalability, privacy, and security aspects.	Lack of mechanisms that address supply chain-specific needs, such as the differential provision of information to users and the associated costs.
(Govindan et al., 2024; Mishra et al., 2024), (Franke et al., 2023), (Chod et al., 2022; Gan et al., 2021), (Chod et al., 2022; Holden & Malani, 2022; Malinova & Park, 2023), (Shakhnov et al., 2023; Sockin & Xiong, 2023), (Meyer et al., 2019), (Harish et al., 2021), and (Harish, Wu, et al., 2023).	Blockchain for Information Sharing	• Role of decentralization for tracking and tracing. Core blockchain technologies and their industrial application alongside IoT technologies. Application of tokenization in operations and finance.	Studies are limited to qualitative discussions on decentralization without the economic or strategic considerations required to cater to information sharing in the supply chain.
(Mussa & Rosen, 1978; Varian, 1997; Wei & Nault, 2014), (Varian, 1997), (Wei & Nault, 2014), (Bhargava & Choudhary, 2008), (Chen & Seshadri, 2007), (Wei & Nault, 2014), (Chellappa & Shivendu, 2010; Lahiri & Dey, 2012), (Bhargava & Choudhary, 2008), (Jones & Mendelson, 2011), (Hahn, 2000), and (Wei & Nault, 2013).	Valuation of Goods	• Studies have focussed on quality segmentation of physical and digital goods. Focus on two aspects: feature/functionality differentiation and pricing. Appear in various contexts, such as market segmentation, consumer group taste, and privacy.	Traditional pricing mechanisms used for physical goods are not ideal for value capture in information pricing.

consists of a module provider (manufacturer/supplier), module logistics, and construction site (or its contractor).

1) Visibility for value extraction: A player starts by examining the initial arrangement of colored squares on each cube face to make sense of the Rubik's cube. Having access to one additional face, or even a square within, allows the player to plan/optimize the next move, taking him one step closer to the final solved state/configuration with a coherent pattern of colors. In a supply chain setting, this phase involves a participant trying to get visibility over its stakeholders to extract value through cost reduction, performance optimization, or even reliability/resilience improvement. For instance, the module provider uses the logistics carriers' real-time tracking information (e.g., order status, estimated pickup time, etc.) to optimize the inventory level. This minimizes the storage cost, while avoiding potential losses from supply disruptions or stock-outs.

2) Cost commitment: Having access to one or more cube faces does not guarantee an immediate transition to the solved state. Rather, the players use a combination of their ability to recognize patterns, knowledge of cube properties, and standard algorithms to formulate a strategy and achieve the goal state/configuration. Therefore, there is an associated commitment in time and effort to performing a series of cube twists that lead to the solution. Similarly, integrating newly available information in the supply chain comes with an associated cost. For instance, for the module provider, the costs accrue from data/system integration, which requires resource commitment (e.g., trial testing, training of the workforce, etc.) to uncover/extract valuable insights from the shared information (Guan & Chen, 2017).

3) Unique goals: Players differ in their goals (e.g., solve one side, two sides, or the entire cube). Not everyone wants to solve the (entire) puzzle. In a supply chain, the information users distinguish themselves in terms of the subset of information they choose/use to serve a unique application. For example, when the module provider decides to use the carrier's tracking information to optimize its operations, the construction contractor may demand historic information, such as emission and reputation (among customers), to choose a carrier that helps meet its sustainability goals/commitments. Therefore, serving versions of states (traceability) and status (visibility) of carriers, as shown at the right hand side of Fig. 1, to participants specific to their needs or requirements is the key to maximizing the resiliency and sustainability of the supply chain. The figure visualizes information as a three-dimensional dataset encompassing multiple carriers' information across time and attributes (e.g., reliability, sustainability, service quality, etc.). A participant may choose a subset of the dataset to serve a unique application, delivering a unique value. The subset on the right-hand side of the figure holds information about one carrier across all attributes and time. However, the lower half of the figure shows further subdivision across both attribute and time to deliver suitable/relevant information units to the interested users/participants.

Note that the Rubik's cube has become quite solvable over the years, thanks to the best practices and a plethora of algorithms. On the other hand, the supply chains have become increasingly complex and dynamic, raising questions about the performance and resilience from poor information sharing practices. This could be attributed to factors such as a) the cost of differential provision of information (or features) catering to user needs, (b) shortcomings of centralized storage, and (c) inefficiencies in capturing the value of information. Without a suitable mechanism to promote/sustain information sharing, supply chains will remain plagued with performance inefficiencies and risks, such as sustainability concerns, failed or delayed deliveries, and increased costs or lead times.

3.2. Crypto-Valuation mechanism of digital assets for information sharing

We introduce a crypto-valuation mechanism of digital assets (DAs) to promote information sharing in supply chains, as shown in Fig. 1. The DAs capture the operations information of the tangible (e.g., trucks, cargo, workforce) and intangible (e.g., customer

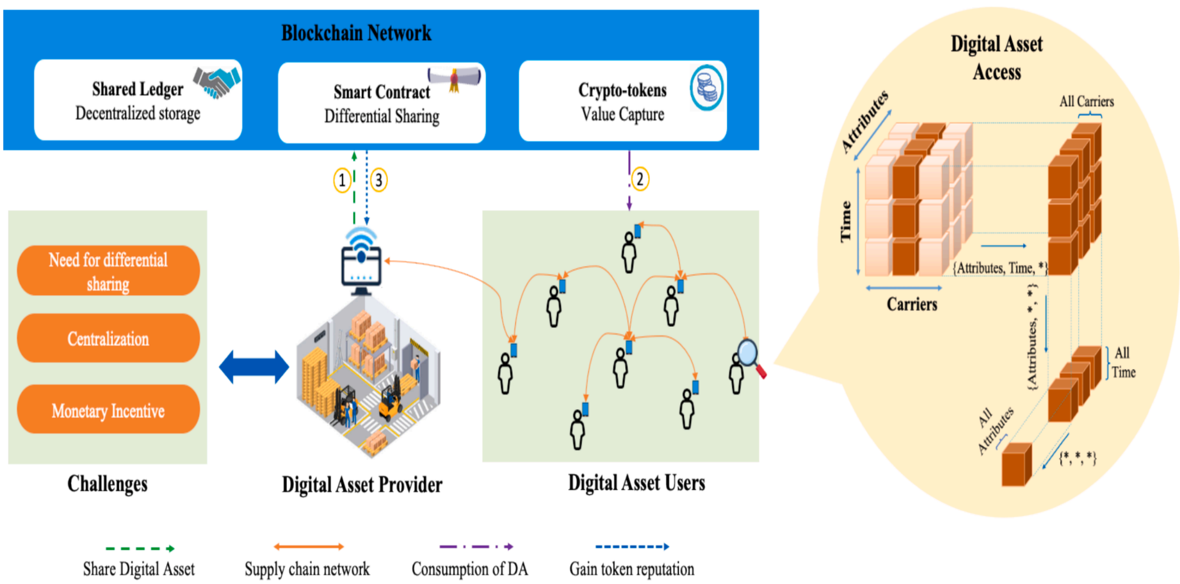

Fig. 1. Crypto Valuation Mechanism of Digital Assets.

ratings) physical assets in the supply chain and logistics (Harish et al., 2021, 2023a,b). The DAs provider equips its physical assets with smart technology (e.g., RFID tags, smartphones) to bring visibility into the 5Ms of supply chain operations. Thus, visibility enables supply chain stakeholders to extract value through cost reduction, performance optimization, or reliability/resilience improvement. For instance, a logistics company equips its truck drivers (workforce) with a simple smartphone to collect and share information such as order status and location updates, thereby mapping/capturing the changes in the driver's physical space (physical asset) to the digital space (digital asset). A supplier could use the tracking information to optimize its inventory level. This minimizes the storage cost while avoiding potential losses from supply disruptions or stock-outs.

When an information provider shares its DAs, the smart contract corresponding to it appears as a transaction in the blockchain network. Once stored, the blockchain network facilitates the creation of versions of a smart contract specific to the user/participant needs (refer to (Liu et al., 2020) for further details on smart contract versioning). By version, we mean a smart contract with fewer features than the initial/main smart contract. For instance, if the main contract contains features such as carbon emission and a carrier's reputation, the user interested only in the reputation can access a custom smart contract that removes or disables unnecessary features/functions. A participant may choose a custom contract to serve a unique application, delivering a unique value.

Whenever the participant uses/consumes the DAs (or a version), he gains utility from having access to information. On the other hand, the DAs provider/contributor sets the valuation, i.e., charges a fixed amount of tokens, to grant access to each version of the DAs. The information contributor gains a reputation with the tokens it collects, which makes it eligible for non-monetary (symbolic) benefits (e.g., awards, technical support, etc.). The reputation of a logistics company within its supply chain often signals its quality and leads to customer acquisition opportunities (e.g., potential investments) (Harish et al., 2021, 2023a; Niu et al., 2024). Fig. 2 shows the stages leading DAs sharing through the underlying blockchain network, starting from setting up valuation rules to achieving DAs sharing.

To summarize, the blockchain-based mechanism allows the differential provision of DAs tailored to the specific needs or applications of the supply chain participants to establish a sustainable and resilient supply chain. Note that the term "Digital Asset" appears in various contexts, such as intellectual property, blockchain technology, and supply chain digitization, based on the application or industry. For instance, blockchain literature commonly refers to cryptocurrency (e.g., Bitcoin, Ethereum, or Litecoin) or tokens as digital assets. However, the digital assets in this study are inspired by their application in the supply chain digitization context (refer to (Harish et al., 2021, 2023a,b) which use digital assets for supply chain visibility).

4. Mechanism formulation

Fig. 3 illustrates the integration of the proposed mechanism into the global supply chain decision matrix, which spans sourcing, production, distribution, and after-sales, as illustrated by (Ivanov, 2018). The elements of the figure marked in green represent the proposed mechanism and its influence on the supply chain decision matrix. The mechanism contributes to the strategic and planning

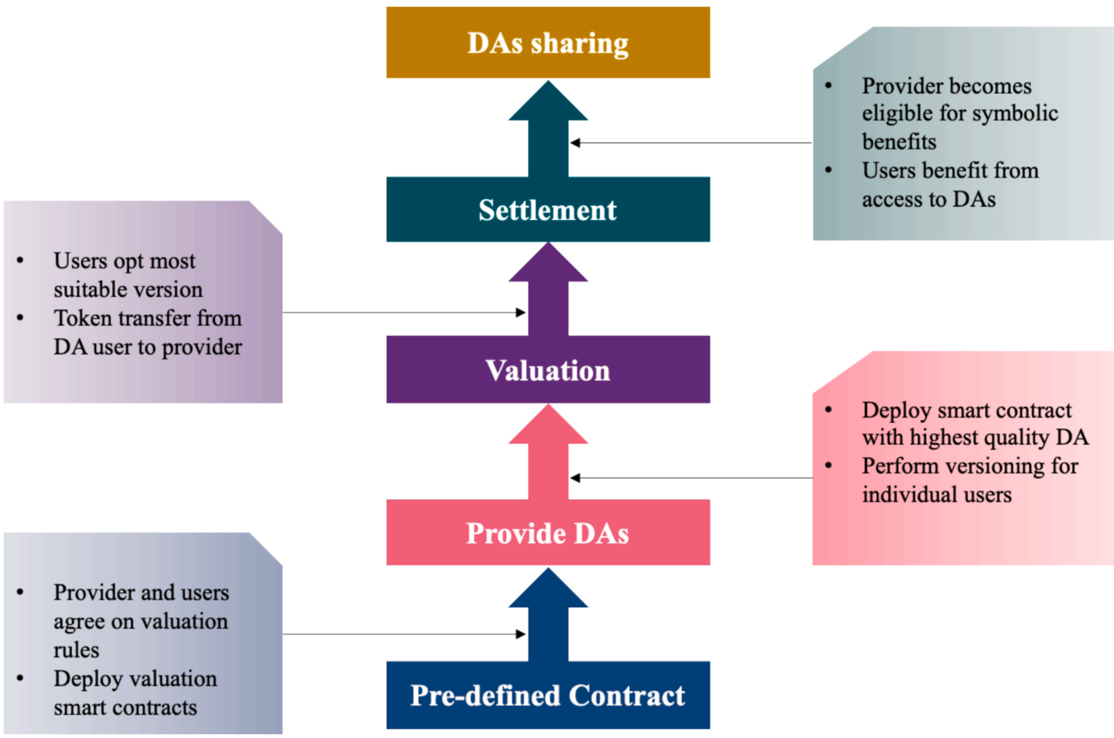

Fig. 2. Steps in sharing digital assets through the blockchain network.

aspects of supply chains. For instance, it allows an information provider to make strategic decisions to maximize its surplus from differential sharing and valuation of DAs with its supply chain stakeholders (or users). The shared information, in turn, helps the users make tactical decisions to improve their operations (e.g., aggregate planning by supplier and transportation planning by logistics provider). By facilitating these two levels of decision-making, our mechanism encourages DAs sharing and use for comprehensive supply chain management.

A defining attribute of the proposed mechanism is its differential provision of DAs to individual users and the decision-making it enables, both in terms of the DAs contributor's quality (or total number of features) of DAs and the level of user access to quality (or number of features each user gets). The monopolist screening model based on vertical quality differential is suitable in such a scenario where individual user preferences, characteristics, or capabilities influence the decision/behavior of the DAs provider, as it has been used successfully in contexts involving goods pricing (Bhargava & Choudhary, 2008; Varian, 1997; Wei & Nault, 2013). Therefore, the formulation of the base model in this study is based on the standard vertical differentiation model of quality. We consider digital assets as an economic bundle of infinitesimally small data units or features that serve different applications in the supply chain, such that the DAs' quality increases with the addition of more data units.

The model includes a principal—a DAs contributor with a unique cost structure of producing/sharing DAs and agents—the users who experience participation constraints in consuming/using the DAs. Let $q : q \in \mathbb{R}^+$ be the quality of DAs such that higher q stands for a higher quality DAs. Recall that quality stands for/represents the number of unique data units in the dataset to serve various applications in the supply chain. The higher the quality of DAs, the more the number of features it delivers to the users. The principal may costlessly transform the DAs of quality $\overline{q}$ to versions of inferior quality $q \in [0, \overline{q}]$ by recombining or removing data units. We assume that the users have their marginal value for quality $\theta \in [\underline{\theta}, \overline{\theta}]$ which is distributed with density function $f(\theta)$ and cumulative density $F(\theta)$ that is continuously differentiable. This assumption that index/categorize users based on their marginal value for quality is common in vertical differentiation literature (Bhargava & Choudhary, 2008; Mussa & Rosen, 1978; Varian, 1997; Wei & Nault, 2013). Furthermore, we assume that $f(\theta)$ is unimodal and its hazard function fulfills the monotone hazard rate property, i.e., $h(\theta) = f(\theta)/F(\theta)$. This is a common assumption (sufficient condition) for distributions in vertical discrimination/differentiation literature (Sundararajan, 2004), and majority of the parametric single-peak densities meet the distribution requirement (Bagnoli & Bergstrom, 2005).

The users incur disutility while using DAs due to the intrinsic participatory nature of service delivery. The participation demands commitment in time and effort from the users. We consider the users to be homogeneous in their disutility, given by the parameter $\tau (\tau > 0)$. Therefore, the utility of the user with index θ when using DAs of quality q valued at $t (t \in \mathbb{R}^+)$ is

$$U(\theta, q, t) = \theta q - \tau q^2 - t. \tag{1}$$

The utility function, $U(\theta, q, t)$, uses a standard functional form in vertical segmentation literature (Chellappa & Shivendu, 2010; Mussa & Rosen, 1978). Henceforth, the terms $U(\theta, q, t)$ and $U(\theta)$ are used interchangeably for brevity. The function is non-monotonic in DAs quality, i.e., the user experiences an increase in utility up to a point with an increase in quality before it decreases. Put another way, the user may not always be better off with higher DAs quality.

Too much data or features can be overwhelming and difficult for users to process. The inherent search/integration costs (e.g., delays, opportunity cost, etc.) associated with information overload eschews the benefits of using DAs (Branco et al., 2016). Therefore, there exists a quality at which each user gets all relevant insights, and additional quality does not bring any additional benefit. For instance, a contractor who does not need specialized transport service (e.g., hazardous goods or temperature-controlled shipments) may not derive much/any utility from access to data on a carrier's certification, equipment, and experience in handling specialized shipments; a simple report with data, such as the rates, service areas, customer satisfaction, would assist/suffice the contractor in compatibility evaluation. Similarly, the blockchain network comes with inherent disutility from transaction costs (e.g., engagement fees) and transaction delays to access and use information (Franke et al., 2023; Holden & Malani, 2022). The burden adds up quickly for users who engage in larger or more frequent transactions, even though the cost and delays depend on specific blockchain networks (e.g., Ethereum, Quorum, etc.) and the transaction size (Harish, Liu, et al., 2023). Therefore, the user may not always be better off

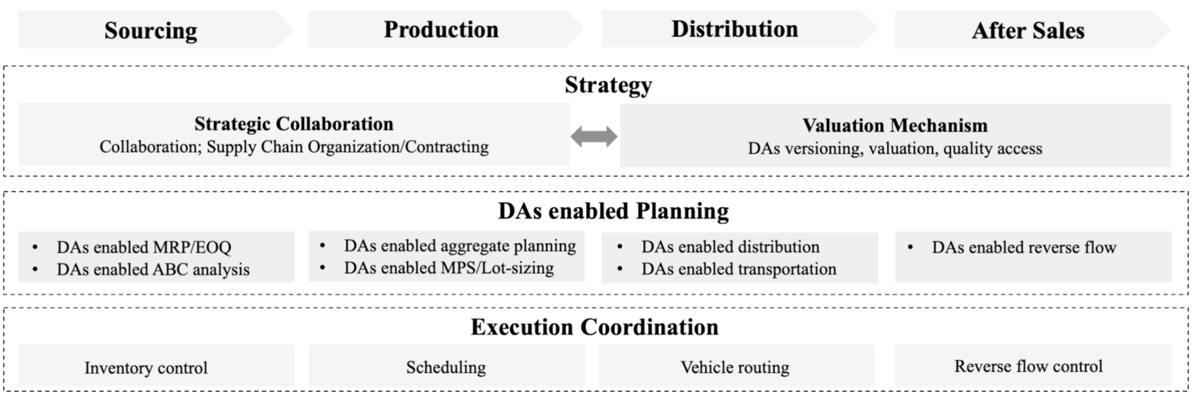

Fig. 3. Integrating valuation mechanism into the supply chain decision matrix.

accessing higher DAs quality.

Another aspect of our model is that the principal (DAs producer) must decide on the highest quality of DAs to produce and maintain in the blockchain network, along with versioning and valuation decisions. We endogenize the decision on highest quality to produce by introducing a fixed cost which is quality dependant. This is the cost of setting up the resources or technology to create the DAs of the highest quality. For instance, the carrier that intends to share real-time tracking services may invest in a smart container that can collect and share information, such as order status, location, temperature, and security, or it may use a simple smartphone to share the order status and location updates. It is up to the carrier to determine what level of investment (cost commitment) will produce the highest quality DAs suitable for the users it serves. This study assumes a convex cost structure/function for the DAs quality and is given by cq, where $c \geq 0$. The convex cost structure is commonly used in digital and information goods literature with varying extents of convexity (Boehm et al., 2000; Jones & Mendelson, 2011). It reflects the common belief that cost-efficient decisions precede costlier decisions when incrementally adding features or functions to improve quality.

Once the DAs with the necessary list of features is created, the principal can create versions of lower quality to serve users. We consider zero versioning/degrading cost, although we relax this constraint later in Section 5. In the following subsections, we characterize the versioning results under full information and compare them with those under information asymmetry.

4.1. *Digital asset provisioning under full information*

The model has the following sequence of events as shown in Fig. 4. The principal decides on the highest-quality DAs to produce. Once the highest quality is determined, he creates lower-quality DAs versions and sets their corresponding valuation. To decide on the highest-quality DAs to create/produce, the principal observes the next-stage decision on versions for user types, with the corresponding valuation, followed by backward induction.

Under complete information, the principal perfectly knows the user's type, which allows it to garner maximum surplus from individual types. The solution under full information is identical to the welfare-maximizing solution, but with the principal deriving the entire surplus. Let the principal produce DAs of the highest quality level, q_M, and serve the user of type, θ, with a version of DAs with quality, $q(\theta)$. By the nonmonotonic concave nature of our utility function, the users have a satiation point where they experience maximum benefit from the quality of DAs. The optimal quality that maximizes the utility function is given by

$$q^*(\theta) = \underset{q}{\operatorname{argmax}}\left[\theta q - \tau q^2\right] = \frac{\theta}{2\tau}, \tag{2}$$

and the corresponding valuation that assists full surplus extraction derives from

$$U(\theta) = \theta q(\theta) - \tau q^2(\theta) - t(\theta) = 0, \tag{3}$$

which means that the optimum valuation $t^*(\theta) = \theta^2/4\tau$. Recall that by valuation, we mean the number of tokens the principal charges while granting access to a specific piece/version of DAs. Interestingly, it does not make sense for the principal to create DAs of quality higher than $\overline{q} = \overline{\theta}/2\tau$ even in the absence of any cost to produce the highest quality. This represents the quality at which the highest type user (s) extract utmost benefit from using DAs.

However, with associated costs to quality improvement, it's not obvious/apparent whether the principal can deliver the same quality to users. When q_M is the highest available quality, the user type which extracts the maximum surplus at this quality is given by $\theta_M = 2\tau q_M$, where $\theta_M \in [\underline{\theta}, \overline{\theta}]$. Furthermore, given $(\partial/\partial\theta)(q^*(\theta)) > 0$, it becomes clear that the user types $\theta \in (\theta_M, \overline{\theta}]$ will receive DAs of quality q_M, which is inferior to their first-best quality. The DAs valuation to extract the maximum surplus from these users is given by $t^*(\theta) = \theta q_M - \tau {q_M}^2$. The resulting objective function of the DAs producer is given by

$$\Pi = \max_{q_M}\left\{\int_{\underline{\theta}}^{\theta_M(q_M)} \frac{\theta^2}{4\tau} f(\theta)d\theta + \int_{\theta_M(q_M)}^{\overline{\theta}} \left[\theta q_M - \tau {q_M}^2\right] f(\theta)d\theta - c{q_M}^2\right\}. \tag{4}$$

Using Fubini's theorem and pointwise maximization, we solve the maximization problem in (4) to produce the optimal values, θ_M^* and ${q_M}^*$, in the following lemma (refer to the appendix for details).

Lemma 1. *θ_M^* is the solution to $\overline{\theta} - \theta_M = A(\overline{\theta}) - A(\theta_M) + c\theta_M/\tau$, where $A(\theta) = \int_{\underline{\theta}}^{\theta} F(x)dx$. The principal serves the users such that $q^*(\theta) = \theta/2\tau \ \forall\theta \in [\underline{\theta}, \theta_M^*]$ and $q_M^* = \theta_M^*/2\tau \ \forall\theta \in [\theta_M^*, \overline{\theta}]$.*

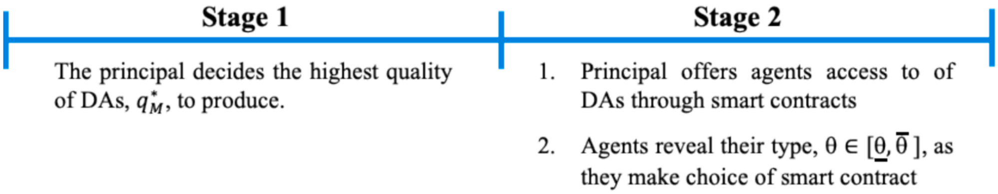

Fig. 4. Sequence of events in valuation of digital assets.

All proofs are in the appendix.

The results above have some interesting properties. When $c = 0$, $\theta_M^* = \overline{\theta}$ (from solving the problem in (4)), i.e., all the user types get their first best quality or the version of DAs $q^*(\theta)$ that maximizes their utility. That is, when there exists no cost associated with quality production, the principal can provide participants with tailored access to DAs according to their needs or roles in the supply chain. In this case, the highest quality of DAs that the principal produces is $\overline{\theta}/2\tau$. For instance, the contractor gets detailed shipment information, such as the expected pickup and delivery time, routes, and potential delays, to make his choice of carrier, whereas a manufacturer may access a more simplified report or subset of information that gives the expected pickup time to plan its production and meet demand.

However, when $c > 0$, the use types greater than θ_M^* receive DAs of quality q_M, which is inferior to their first best quality. The rationale is that when there exists a non-negligible or any finite cost, then $\theta_M^* < \overline{\theta}$ as the function $A(\theta)$ is superlinear in θ. Therefore, the size of the user segment that gets access to a type customized or the individualized versions of DAs is less compared to the scenario with $c = 0$. Put another way, given the finite cost of producing DAs, the principal will not serve the higher user types with their first-best version.

Interestingly, $\tau = 0$ and $c = 0$ fail to produce interior solutions. It is fairly intuitive that a strict increase in the user's utility with quality $\tau = 0$, together with the absence of any cost to produce quality ($c = 0$), results in an infinite quality/valuation for all user types. Even when $c > 0$ and $\tau = 0$, the solution is to produce the best quality and provide the *same* quality to all users at diverse valuations.

Note that replacing the stylized quadratic function of utility with a higher-order polynomial will not affect the qualitative implications of this study. The higher polynomial functions generate a lower surplus per user for a particular quality level; the quality level that produces the highest surplus and the breakeven quality of a given user type becomes lower.

We dedicate the following sub-section to examine the impact of various factors on the DAs versioning strategy. We incorporate information asymmetry, i.e., the DAs producer does not perfectly observe individual users' preferences (or value) for the quality of DAs, to produce more practical results compared to the full-information scenario.

4.2. *Digital asset provisioning under information asymmetry*

When the principal is not entirely knowledgeable of individual users' marginal value for the DAs quality, it must set up a menu of versions and valuation to elicit truth revelation through the users' self-selection of suitable smart contracts. One way for the DAs producer to examine/perceive the value of DAs to a user is through their engagement level, i.e., to track the size and frequency of their transactions in the blockchain network (Harish et al., 2023b). Similarly, Advertising literature and Online gaming literature, even though in a different context, discuss the role of engagement levels in quantifying the value of goods to individual users (Guo et al., 2019; Sisodia & Sisodia, 2023). However, the engagement levels may not always directly translate to value in supply chains. The actual impact of DAs on the performance of individual supply chain stakeholders (e.g., cost reduction, customer acquisition, etc.) can be challenging to observe or quantify. In this scenario, the principal is aware of the user type distribution, even though the exact type of individual user is unknown. Similar to the full information scenario, the principal decides the quality of DAs to produce and the versions to serve the users.

Notably, the principal may incur an information rent while making the valuation decision to prevent the higher user types from opting for a lower-quality version of DAs. When the principal produces the DAs of the highest quality, $\widehat{q}$, the profit maximization problem, constrained by the individual rationality (IR) and incentive compatibility (IC) constraints, becomes:

$$\max_{\{q(\theta),t(\theta)\}} \int_{\underline{\theta}}^{\overline{\theta}} t(\theta)f(\theta)d\theta - c[\widehat{q}]^2 \tag{5}$$

s.t. $U(\theta) \geq 0 \forall \theta$, (IR).

$U(\theta) \geq U_\theta\left(\acute{\theta}\right) \forall \theta$. (IC).

where $U_\theta\left(\acute{\theta}\right)$ stands for the utility that a user type θ experiences when misreporting her type as $\acute{\theta}$. With the IC condition, the user opts for the version or the valuation-quality pair most suitable for him, i.e., the pair that delivers the maximum utility compared to the rest. Indeed, it should be

$$U(\theta) \geq U_\theta\left(\acute{\theta}\right) \Rightarrow \theta q(\theta) - \tau q^2(\theta) - t(\theta) \geq \theta q\left(\acute{\theta}\right) - \tau q^2\left(\acute{\theta}\right) - t\left(\acute{\theta}\right) \tag{6}$$

for any $\left(\theta, \acute{\theta}\right) \in [\underline{\theta}, \overline{\theta}] \times [\underline{\theta}, \overline{\theta}]$. Similarly, a user of the type $\acute{\theta}$ misreporting herself as θ always results in inferior utility, i.e., we get

$$U_{\acute{\theta}}\left(\acute{\theta}\right) \geq U_{\acute{\theta}}(\theta) \Rightarrow \acute{\theta} q\left(\acute{\theta}\right) - \tau q^2\left(\acute{\theta}\right) - t\left(\acute{\theta}\right) \geq \acute{\theta} q(\theta) - \tau q^2(\theta) - t(\theta). \tag{7}$$

We make two interesting observations about the properties of IC constraints (6) and (7). First, the users always opt for the version of DAs most ideal to serve their purposes/needs, i.e., it eliminates demand cannibalization of any version of DAs. Second, an optimal versioning menu/strategy is always non-decreasing in the user types it serves (refer to the appendix for proof), i.e.,

$$q'(\theta) \geq 0. \tag{8}$$

This leads us to Lemma 2.

Lemma 2. *The smallest/lowest user type index that gets access to DAs, $\check{\theta}^*$, is a solution to $\theta - [(1 - F(\theta))/f(\theta)] = 0$, whereas the smallest/lowest user type index that gets access to the highest quality DAs, $\widehat{\theta}^*$, comes from solving $\theta - [(1 - F(\theta))/f(\theta)] - 2\tau\widehat{q} = 0$.*

All proofs are in the appendix.

Lemma 2 leads us to a menu of DAs qualities set up as smart contracts to serve the users.

Proposition 1. *The principal shares DAs with the users such that*

$$q^*(\theta) = \begin{cases} 0 & for \theta \in \left[\underline{\theta}, \check{\theta}^*\right), \\ \dfrac{\theta - [(1 - F(\theta))/f(\theta)]}{2\tau} & for \theta \in \left[\check{\theta}^*, \widehat{\theta}^*\right), \\ q(\widehat{\theta}^*) & for \theta \in [\widehat{\theta}^*, \overline{\theta}]. \end{cases}$$

Lemma 2 and Proposition 1 are preliminary outcomes in that we have not yet derived/extracted the exact form (what it should be) for the optimal highest quality ($\widehat{q}^* = q(\widehat{\theta}^*)$). First, the principal classifies its users into three segments where the user types $\theta \in \left[\underline{\theta}, \check{\theta}^*\right)$ is not given access to the DAs. This observation aligns with the results of extant segmentation literature on physical goods (with marginal costs of the good) where the vendor does not serve a low-type user segment. However, the result is nonintuitive in the case of digital assets. The principal has zero cost of versioning, meaning the DAs provider could create a version suitable for the low type and extract a surplus equal to $\int_{\underline{\theta}}^{\check{\theta}^*} t(\theta)f(\theta)d\theta$ without incurring any additional cost. Even so, the principal finds it optimal to opt against serving the low-type users.

The rationale is that the principal uses exclusion as a preventive measure to avoid paying information rent to the higher type users. Put another way, the principal excludes a segment of low-type users to prevent the high-types from opting for DAs of lower quality-valuation that is intended for those low-type users. The principal essentially takes the decision not to serve the user segment $\theta \in \left[\underline{\theta}, \check{\theta}^*\right)$ after taking the tradeoff between the surplus of serving the low-type users (as there is no cost of serving them) and the information rent he becomes liable in case they serve the low types. This explains why the information service providers in the market offer custom-feature selection for users. For instance, Supply Chain Dive (SCD, 2023), a supply chain intelligence platform, provides custom subscription plans that offer differential access to various topics, such as logistics, freight, operations and procurement, based on user interest.

For the segment $\theta \in \left[\check{\theta}^*, \widehat{\theta}^*\right)$, the principal introduces a nonlinear quality menu where each user gets access to DAs version $q(\theta)$ corresponding to her type. This observation is consistent with the common industry practice where customers look for custom service/features (e.g., customized reporting and real-time information) according to their willingness to pay on top of a logistics company's basic/standard service offering (e.g., proof of delivery). From inspection, it is clear that the quality menu is decreasing in the user's usage-related cost, τ, i.e., each type gets access to a lower quality as the participation cost increases. For the segment $\theta \in [\widehat{\theta}^*, \overline{\theta}]$, the principal offers a single version of the DAs, the highest quality DAs it creates. For instance, some users may demand/request access to more detailed information/features such as cargo security, temperature monitoring reports, or even carbon emissions. A gap between the user requirements and provider capabilities arises when the carriers are not prepared to deliver such information. Evidence for such concerns is visible in industry forums and discussions where firms commonly receive recommendations or suggestions of workarounds to involve third-party consultants (such as SymphonyIRI) to offer the necessary/desired features or data. This segment depicts the presence of high types who are willing to pay for more data or features than what is on offer from the DAs provider.

Now, we first derive the solutions for the maximum quality of DAs that the principal produces as an initial step to determining the entire quality-valuation schedule. Note that the lowest user type that gets access to DAs $\left(\check{\theta}^*\right)$ experiences zero (net) utility as the principal garners full surplus from such as the user (refer to the appendix for further details); therefore, the expression for $t(\theta)$ becomes

$$t(\theta) = \left[\theta - \tau q(\theta) - \frac{1 - F(\theta)}{f(\theta)}\right] q(\theta). \tag{9}$$

The first two terms on the right side of the expression stand for the valuation or full surplus of the user under complete information. The final term deducts the information rent that the principal incurs when it is unaware of the exact type of user it serves. Combining (9) and (5) with the right integral limits produces the expression given by

$$\max_{\{\widehat{q}\}} \left\{ \int_{\check{\theta}^*}^{\widehat{\theta}^*} \left[\theta - \tau q(\theta) - \frac{1 - F(\theta)}{f(\theta)}\right] q(\theta) f(\theta) d\theta + \int_{\widehat{\theta}^*}^{\overline{\theta}} \left[\theta - \tau\widehat{q} - \frac{1 - F(\theta)}{f(\theta)}\right] \widehat{q} f(\theta) d\theta - c\widehat{q}^2, \right\} \tag{10}$$

where $q(\theta) = (\theta - [(1 - F(\theta))/f(\theta)])/(2\tau)$.Note that Lemma 2 sheds light on the role of the highest-quality $\widehat{q}$ in determining the value of $\widehat{\theta}^*$. Therefore, to conceive $\widehat{\theta}^*$, we derive the optimal solution for the highest quality $\widehat{q}^*$ from the principal's optimization problem in (10). Lemma 3 presents the corresponding result.

Lemma 3. *Under asymmetric information, the optimal highest quality of DAs, $\widehat{q}^*$, that the principal creates is the solution to $\widehat{\theta}^* - [(1 - F(\widehat{\theta}^*))/f(\widehat{\theta}^*)] - 2\tau\widehat{q}^* = 0$ and $\widehat{\theta}^*[1 - F(\widehat{\theta}^*)] = 2\widehat{q}^*[\tau[1 - F(\widehat{\theta}^*)] + c]$ solved simultaneously.*

All proofs are in the appendix.

Lemma 3 defines the lowest high-type user that gets access to the highest quality DAs that the principal creates under information asymmetry. Now, proposition 2 compares this value against the corresponding value under full information from Lemma 2 to discuss the quality distortion.

Proposition 2. *The highest quality of DAs that the principal produces in information asymmetry is inferior compared to the quality in complete information $(q_M^* > \widehat{q}^*)$; the same relationship exists between the optimal quality schedules of these two scenarios.*

Extant segmentation literature shows that the highest user type $(\overline{\theta})$ gets access to the same quality in scenarios with and without information asymmetry. Put another way, the highest type does not experience quality distortion under information asymmetry, even though the lower user types do not get access to DAs, or get access to degraded/lower quality (Srinagesh & Bradburd, 1989). In contrast, other studies, such as (Hahn, 2000) and (Jones & Mendelson, 2011), find that all users undergo quality distortion under information asymmetry. Compared to these works, our study delivers findings that are counter-intuitive and much richer in the understanding it provides. Our results divide the users into three segments where the lowest types do not get access to DAs, the middle types get DAs quality customized to their individual needs (no quality distortion), and the highest types are bunched together and get the same/uniform DAs quality, but is downward distorted compared to the quality under full information case.

Note that the user types that fall in the middle segment get access to DAs versions according to their marginal value for quality. Their quality menu takes a concave form (in user types) under imperfect information compared to its linear form under full information. Therefore, under information asymmetry, the quality and valuation for these users increase in their type at a decreasing rate. Also, note that these observation are is strictly restricted to the case where $\theta_M^* < \widehat{\theta}^*$. This does not eliminate the possibility of the converse being possible (proof of proposition 2 in the appendix provides additional details).

Note that the DAs provisioning strategy is independent of the nature of user type distribution, even though the magnitude of DAs quality made available for use is distribution-dependent. The rationale is that we endogenize the decision on the users to serve (user coverage) as a result of using a general distribution for deriving the DAs quality schedule/menu.

We now use cost parameters c and τ to perform comparative statistics over the magnitude/size of different user segments further to understand the coverage of user types in the model.

Proposition 3. *The magnitude of the user segment that gets customized access to DAs enlarges in the participation costs τ but reduces in the resource costs c. The user coverage (in the quality schedule) remains unaltered in these parameters.*

Proposition 3 provides interesting insights into the differential impact of various costs on providing DAs. First, let us delve into the cost-based comparative statistics of $\breve{\theta}^*$, where $\breve{\theta}^*$ stands for the lowest user type that gets access to a version of DAs. From Lemma 2, it is apparent that $\breve{\theta}^*$ is not dependent on any of the two cost factors. That is, cost parameters have no bearing on the user coverage, which is purely a function of the user type distribution. More specifically, all the users get access to DAs (full user coverage) only when $\underline{\theta} \geq 1/f(\underline{\theta})$. On the other hand, the case with full information always ensures full user coverage, with all types inferior to θ_M^* getting access to their first-best quality.

Now, let us delve into the comparative statistics of θ_M^* and $\widehat{\theta}^*$, where θ_M^* stands for the highest user type that gets access to its first-best DAs quality with full information and $\widehat{\theta}^*$ represents the highest user type that gets second-best DAs quality with information asymmetry. It is quite intuitive that these bounds decrease in c due to its role in determining the highest quality of DAs to produce. Interestingly, these bounds are increasing in τ, meaning more users get access to DAs as the participation cost increases. The rationale is as follows. Firstly, an increase in participation cost decreases each user's DAs quality of choice, leading to an increase in the magnitude of the user segment with customized access to DAs for a given highest quality. Secondly, the increase in participation cost leads to a decrease in the surplus of each user, i.e., the users become less valuable to the principal. Consequently, the principal lowers the (highest) quality of DAs it creates, leading to a decrease in the number of users getting type-customized access to DAs, i.e., a reduction in the smallest user type who gets access to the highest quality DAs. For the two conflicting implications of the increase in τ discussed above, Proposition 3 confirms that the former dominates, leading to an overall increase in the users who get access to type-customized access to DAs (refer to the appendix for the proof).

5. Extensions and discussion

In this section, we first introduce extensions to our model − (a) the impact of versioning cost and (b) off-chaining of digital assets. Then, we delve into the managerial implications of this study.

5.1. Impact of versioning costs

Creating copies of DAs or creating degraded smart contracts with lesser feature/quality access should ideally be costless due to its digital nature. However, it has non-digital elements that bring cost. Extent literature either assumes the cost is zero or absorbs it into the marginal costs (Chen & Seshadri, 2007). Often, these cost stems from the specific post-production activities or investments required to manage user segment corresponding to each version of DAs, such as the support cost (Sundararajan, 2004). For instance, consider the case where information with higher privacy/security requirements (e.g., pricing and cost information, customer details, etc.) is shared only with the highest user types accessing the highest quality. In such situations, the information provider experiences an additional disutility of establishing a private file-sharing network (e.g., Inter-Planetary File Systems (IPFS)), side by side with blockchain technology, for secure data transmission while safeguarding the user interest/requirements. Such costs, commonly known as the segment development cost (Dhebar, 1990), are unique to the version of DAs or the segment it serves. It depends on the size of user segment which accesses the type-customizes DAs.

Note that the versioning cost differs from the marginal cost of supporting an additional user. It is the one-time investment that comes with the creation of each separate version. To provide an additional understanding of the difference between the two costs, we modify the principals' objective function (5) as

$$\max_{\{q(\theta),t(\theta)\}}\left\{\int_{\breve{\theta}}^{\overline{\theta}} t(\theta)f(\theta)d\theta - \int_{\breve{\theta}}^{\widehat{\theta}} \alpha d\theta - c[\widehat{q}]^2\right\}, \tag{11}$$

where α stands for the cost associated with each version of DAs. We know that there are three possible user segments in the quality-valuation schedule for DAs: (a) the segment $\theta \in \left[\underline{\theta}, \breve{\theta}\right]$ where users do not get access to DAs, (b) the segment $\theta \in \left[\breve{\theta}, \widehat{\theta}\right]$ where the users get the DAs version of their choice, and (c) the segment $\theta \in [\widehat{\theta}, \overline{\theta}]$ where the users uniformly get a single version of DAs, which is the highest quality of DAs that the principal creates for the user of type $\widehat{\theta}$ ($\widehat{q} = q(\widehat{\theta})$).

Similar to our earlier derivation of the quality schedule, we need to take into account the IR and IC constraints to derive the quality menu of the DAs $\{q(\theta), t(\theta)\}$, which is substituted and backward inducted to produce the bounds $\breve{\theta}^*$ and $\widehat{\theta}^*$ that lead to the highest quality of DAs that the principal produces, $\widehat{q}^*$. The users in the region that lies between $\breve{\theta}^*$ and $\widehat{\theta}^*$ gets access to versions of DAs, which amounts to a versioning cost $\int_{\breve{\theta}^*}^{\widehat{\theta}^*} \alpha d\theta$. This leads us to Proposition 4 (refer to the appendix for the proof).

Proposition 4. *User coverage and quality schedule are unaffected by the versioning cost. However, the cost diminishes the quality of DAs that the principal produces and shrinks (trim down) the user segment that gets access to customized versions of DAs.*

Proposition 4 shows that despite the additional cost of creating versions, the principal serves the users as before. It is evident that the $\breve{\theta}^*$ with the cost of creating versions is identical to its value without versioning cost from Lemma 3; since all the user types superior to $\breve{\theta}^*$ gets access to DAs, the user coverage by the principal remains unaltered.

Indeed, the principal offers the same menu of DAs except that the user segment that gets their preferred type-customized versions of DAs diminishes, i.e., $\widehat{\theta}^*$ (no versioning costs) $>$ $\widehat{\theta}^*$ (with versioning costs). Put another way, more high types get a bunched smart contract of uniform quality.

The motivation behind analyzing versioning cost was to differentiate its impact from that of the marginal costs. Proposition 4 successfully delineates the influence of two factors. For DAs, the influence of these cost factors purely depends on the distribution density—if there is *one* user in *each* type, then the cost of creating a version is the same as the marginal cost of serving an additional user. However, when there exist multiple users of the same type, then the principal bears a cost to serving DAs to each additional user of that type, in addition to the one-time investment it makes to support the version for all the users of the same type or the marginal value for DAs quality.

5.2. Off-chaining of digital assets

The technological nature of the user's participation cost allows it to be partially eliminated or moved elsewhere. The literature on systems design provides qualitative discussion on the advantages of using hybrid storage for the provision of DAs, i.e., a combination of on-chain storage (blockchain network) and off-chain storage (e.g., IPFS, cloud storage, etc.) to serve DAs (Harish et al., 2021, 2023a). However, little to no academic literature discusses the economic implications of using a hybrid approach that may bring an opportunity to transfer the participation cost.

We specifically look into the off-chain storage solutions that reduce the participation cost for the users while potentially adding to the cost borne by the principal, i.e., the principal bears the additional cost of maintaining the off-chain storage solution. Traditionally, blockchain storage is plagued by high transaction costs and low throughput (Cryptoslav, 2023; Godbole, 2020). The off-chain storage allows large chunks of information to be off-loaded outside the blockchain network, while smart contracts deliver access rights using *meta*-data (refer to (Harish et al., 2021, 2023a) for working of on-chain and off-chain classification of DAs). This significantly reduces the transaction cost and time the users incur to execute/record blockchain transactions for the DAs they need. For example, the principal may choose to store larger, more frequently accessed/requested data or features in the off-chain storage to ensure high throughput and low costs for seamless use by the users. Similarly, the change in storage solutions may be due to technological advances that allow for larger-scale transactions, the release/disclosure of new features hidden earlier for strategic reasons, among other reasons.

We capture the decrease in disutility using the parameter $\sigma \in [0, 1]$ such that the hybridizing the storage allows users to experience a utility form $U(\theta) = \theta q(\theta) - \tau(1-\sigma)q^2(\theta) - t(\theta)$. Larger values of σ occur when more DAs are off-chained, i.e., moved to off-chain storage from the on-chain storage.

However, the off-chain does not come without its associated costs. The third-party off-chain storage service providers charge the principal for their service. In this study, we use a simple tariff structure where the number of users (size of user segment) and the quality of DAs to serve together determine the amount payable to the service provider. By using parameter $\gamma(\gamma > 0)$ to capture off-chaining cost, we write the principal's objective functions as

$$\max_{\{q(\theta),t(\theta)\}} \left\{ \int_{\underline{\theta}}^{\overline{\theta}} t(\theta)f(\theta)d\theta - \gamma \int_{\underline{\theta}}^{\overline{\theta}} q(\theta)f(\theta)d\theta - c[\widehat{q}]^2 \right\}. \tag{12}$$

Note that we do not integrate one-to-one mitigation, i.e., a decrease in the disutility of the user is not straight away borne by the principal, assuming that the latter may be better suited to handle this cost aspect. Proposition 5 summarizes the results from solving Equation (12) (refer to the appendix for the proof).

Proposition 5. *The principal's decision to (partially) absorb the user's participation cost leads to decreased user coverage, i.e., more users do not get access to DAs. However, the principal improves the (highest) quality of DAs when the hybrid storage sufficiently reduces (compared to the off-chaining cost) the participation costs.*

We started this section with the narrative that "offchaining" demands transfer payment from the principal to the off-chain storage service provider while it diminishes the participation burden at the user's end. Interestingly, our results indicate that such offchaining costs reduce user coverage, i.e., more low-type users are denied access to DAs. Therefore, introducing off-chain storage to relieve the burden on users does not translate to greater participation.

In addition, our results also show that the high-type users benefit from the higher quality DAs made available by the principal only if the offchaining significantly reduces their participation burden. The offchaining cost naturally pushes the principal to create a higher quality of DAs overall, allowing it to serve more high-type users with type-customized versions of DAs, i.e., $\widehat{\theta}^*$ (on-chain) $< \widehat{\theta}^*$ (hybrid). However, whether the individual types who opt for a quality menu get access to a higher or lower quality DAs, i.e., whether offchaining produces smaller or larger values of $q(\theta)$, depends on the relative values of γ and σ.

The economic implications are interesting, primarily the findings that the low-end users do not enjoy the lowered participation cost associated with off-chaining. The principal trims down its market coverage—focusing on high-end users to extract maximum surplus while restricting access to low-end users.

Even though it looks surprising or non-intuitive initially, these findings assert that the principal's monopoly aspects outweigh any benefit from off-chain migration. It aligns with the observations from literature where a hybridization or offchaining is advocated primarily/predominantly when there is large-scale (in terms of frequency or size) movement of transaction or information between supply chain participants. Therefore, offchaining motivates principal to serve high-end users predominantly. The provider can enhance the highest quality of DAs (flagship) made available for use, introduce access restrictions to more low-end users, and set appropriate valuation schedules to avoid cannibalization.

The two extensions enhance the proposed crypto-valuation mechanism as they generate the following implications. Firstly, delineating versioning costs (from marginal costs) tells the sharer/producer of DAs that an associated cost of creating individual versions could adversely affect high-type users. Put another way, non-negligible versioning costs reduce the segment of users who get customized access to DAs, i.e., more high-type users get access to one uniform quality. Secondly, advancements in storage solutions in blockchain-based delivery of DAs are attractive ways of scaling the provisioning strategy; we observe that this may not directly translate to more user coverage, and it depends on the existing tariff structure of the DAs producer. We observe a contraction in user coverage when the producer pays the third-party storage provider for every version-user served. By extending our analysis to cases with hybrid storage (offchaining) and versioning cost, we derive additional insights and demonstrate that the qualitative implications remain mostly valid even with alterations to some modelling assumptions (e.g., changes to supporting storage mechanism).

5.3. Numerical Example: Full and incomplete information

This section validates the previous general solutions by applying them to a numerical example. By simulating different scenarios and recording outcomes, we specifically intend to investigate how various cost factors and user type distribution influence the DAs versioning strategy. In this example, the users have their marginal value for quality $\theta \in [0,1]$, distributed with density function $f(\theta) = e^{-\theta/\beta}/\beta$ and cumulative density $F(\theta) = 1 - e^{-\theta/\beta}$, where $\beta > 0$. Verifying that $f(\theta)$ is unimodal and its hazard function fulfills the monotone hazard rate property is straightforward. Using Lemma 1, we can derive the optimal values for the quality of digital assets and producer surplus under a scenario with complete information, summarized in Table 2. Similarly, we use Lemma 2, Lemma 3, and Proposition 1 to derive corresponding values under a scenario with information asymmetry. We also derive the solutions for scenarios with versioning cost and offchaining through similar approach.

Even though we assign fixed parameter values, as shown in Table 2, the values are altered based on the need while analyzing individual parameters for impact. This approach to parameter setting is consistent with literature investigating similar mechanisms/models (Huang & Sundararajan, 2011; Sundararajan, 2004). We recognize the limitation in the parameter configuration arising from the absence of pilot projects, practical applications, or comparable studies in this domain. However, this research adds to the emerging literature in this field.

5.3.1. Full information vs information asymmetry

The quality schedule inspection in Table 2 indicates that the producer's DAs versioning strategy is quite different in the scenarios with full information (with no cost), full information (with cost), and information asymmetry, which we hereafter address as scenario 1, scenario 2, and scenario 3, respectively, for convenience.

Firstly, we see that scenario 1 and scenario 2 demonstrate full user coverage, whereas a segment of users remains unserved in scenario 3 as $\breve{\theta}^* = \beta$, as shown in Fig. 5 (a). In scenario 3, it is evident that quality access is dependent only on the nature of user distribution (β). Large values of β reduce user coverage.

Secondly, the diminishing DAs quality menu is apparent in Fig. 5 (a). Scenario 1 offers a quality menu allowing users, $\theta \in [\underline{\theta}, \overline{\theta}]$, to choose their desired (or type-customized) DAs quality. In contrast, scenario 2 limits the user segment who gets type-customized DAs access to $\theta \in [\underline{\theta}, \theta_M^*]$ owing to the resource cost associated with quality production. A segment of users, $\theta \in [\theta_M^*, \overline{\theta}]$, is served with one uniform highest quality ($q_M^* = \theta_M^*/2\tau$) under Scenario 2. On the other hand, Scenario 3 additionally leaves a segment of users unserved given by $\theta \in [\underline{\theta}, \breve{\theta}^*]$, as discussed in Proposition 1. Therefore, the quality menu size progressively decreases from Scenario 1 to Scenario 3. In addition, there is visible quality distortion from scenario 1 to scenario 3. The highest quality of DAs offered in Scenario 1 is greater than that in Scenario 2, and that in Scenario 2 is more significant than in Scenario 3, i.e., $\overline{q} > q_M^* > \widehat{q}^*$. This validates Proposition 2.

Similarly, the producer's benefits progressively decrease from Scenario 1 to 3, as shown in Fig. 5 (b). It can be attributed to the combined effects of a decrease in quality offerings and a reduction in the size of the served user segment, as discussed earlier. The derivation of expressions for the DAs producer's surplus under complete and incomplete information scenarios is straightforward from the expression in Table 2. However, we omit those expressions for their algebraic cumbersomeness, which are shown in Fig. 5 and Fig. 6 for changes in various parameters.

5.3.2. Impact of costs factors

The changes in quality schedule as resource cost (c) vary, as shown in Fig. 6 (a). An increase in c results in a strict decrease in $\widehat{q}^*$ and $\widehat{\theta}^*$, thereby decreasing the maximum DAs quality and the size of the quality menu. As the costs increase, the principal loses the quality advantage from eliminating features of DAs, thereby succumbing to losses, as seen in Fig. 6 (d). As in Proposition 4, a change that aligns in the same direction occurs with an increase in versioning cost (α), as shown in Fig. 7 (a). Irrespective of its type, cost factors negatively influence the producer surplus, as illustrated in Fig. 6 (d) and (e). However, in the case of participation cost (τ), though the quality production diminishes, the menu size increases with the increase in τ, as seen in Fig. 6 (b). That is, the producer reduces the number of features (quality) on offer but offers a broader quality menu with custom feature selection to encourage wider user engagement. This, in turn, shifts a portion of high-end user types to the segment that offers type-customized DAs access. These findings align with Proposition 3.

Finally, in the case of off-chaining of digital assets, we see that the parameters σ and γ have opposing influences on the quality schedule, as shown in Fig. 7 (b) and (c). For instance, an increase in σ leads to an increase in quality, whereas an increase in γ leads to a decrease in the highest quality offered by the producer. Similarly, the quality menu contracts in σ, whereas γ does not impart a noticeable change to the quality menu. Interestingly, with increasing γ values, the user coverage contracts progressively. The principal absorbs a portion of the user's participation cost only when it caters to the high-end user types or the premium user segment, reasserting Proposition 5. The relative benefits of entertaining low-end user participation are smaller than the potential losses from information rents, leading to the producer's decision to restrict a fraction of users.

5.3.3. Evolution of user type distribution

The changes in the quality schedule when β increases or the user type distribution gets more spread out are quite interesting, as shown in Fig. 6 (c). An increase in β increases the maximum DAs quality ($\widehat{q}^*$) on offer while reducing user coverage, as shown by an increase in $\widehat{\theta}^*$. User coverage depends only on β, meaning an increase in value brings down the coverage. The economic rationale is that the producer targets high-end users by offering premium features (or DA quality increase), restricting more low-end users from DAs access. This validates Proposition 3, which states that user coverage is only a factor of user type distribution. From the combined effect, the producer surplus first increases and then decreases with an increase in β value, as illustrated in Fig. 6 (f). That is, there exists a user-

Table 2
Optimal versioning for scenarios with and without information asymmetry in the example.

Example: $\tau = 0.5, \beta = 0.3, c = 0.26, \alpha = 0.06, \sigma = 0.8, \gamma = 0.26, f(\theta) = e^{-\theta/\beta}/\beta, F(\theta) = 1 - e^{-\theta/\beta}$; *where* $\theta \in [0,1], \beta > 0$ and $W(.)$ is a Lambert function	
A) Full information ($c = 0$)	$\overline{q} = \overline{\theta}/2\tau$, $q^*(\theta) = \theta/2\tau$
B) Full information ($c > 0$)	$\theta_M^* = -\tau\beta e^{-\overline{\theta}/\beta}/c + \beta W\left(\tau e^{\tau e^{-\overline{\theta}/\beta}/c}/c\right), q_M^* = \theta_M^*/2\tau$
C) Incomplete information	$\breve{\theta}^* = \beta, \widehat{\theta}^* = \beta[\mathrm{W}(\tau/\mathrm{ce}) + 1], \widehat{q}^* = \beta \mathrm{W}(\tau/\mathrm{ce})/2\tau$
D) Versioning cost	$\breve{\theta}^* = \beta, \widehat{\theta}^* = -2\tau^2\alpha/c + \beta W\left(\tau e^{2\tau^2\alpha/\beta c - 1}/c\right) + \beta,\ \widehat{q}^* = [-\beta + \widehat{\theta}^*]/2\tau$
E) Offchaining	$\breve{\theta}^* = \beta + \gamma$, $\widehat{\theta}^* = \beta W\left(\tau[1-\sigma]e^{-[\beta+\gamma]/\beta}/c\right) + \beta + \gamma$, $\widehat{q}^* = [1 - F(\widehat{\theta}^*)]^2/2cf(\widehat{\theta}^*)$

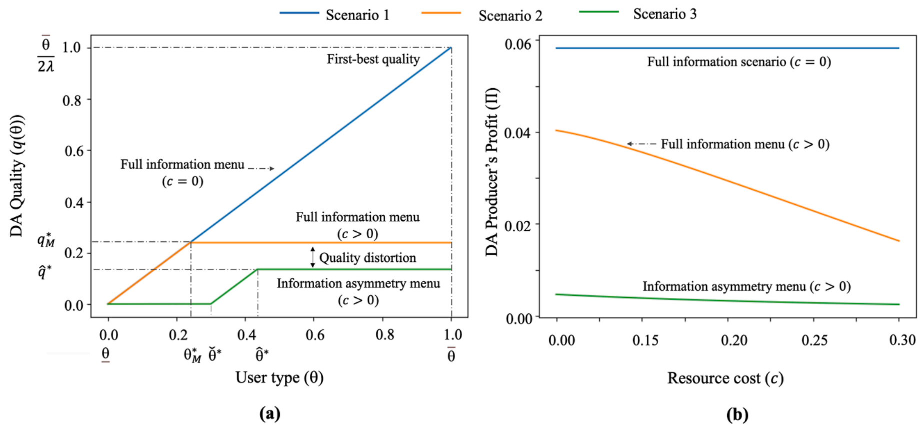

Fig. 5. Comparing optimal solutions in three scenarios: a) DAs quality schedule in different scenarios; b) producer's surplus/profit in different scenarios.

type distribution that allows the DAs producer to extract maximum surplus.

The rationale is simple. Introducing new/shared DAs in the supply chain is typically followed by a large concentration of occasional users who explore the value of DAs to their day-to-day operations, along with a small segment of early adopters who extract significant value through the integration of DAs for decision-making. As the practice matures, the distribution of users between exploration and integration becomes more balanced, gradually leading to more widespread and consistent adoption/integration of DAs across supply chains (Adaryani et al., 2023; Lee & Minner, 2021). Initially, the DAs producer is better off introducing a quality schedule with low barriers for entry, catering to users with lower marginal value for quality. Over time, as the users mature or the perception of value improves, it is optimal to target those high-end users who rely on it for decision-making, thereby improving the supply chain efficiency and responsiveness (Schloetzer, 2012).

5.4. Dicussion and implications

This study offers several insights and recommendations to guide supply chains that leverage DAs sharing for business growth. Firstly, we find that the novel crypto-valuation mechanism drives information sharing and surplus generation by eliminating the concerns related to centralization, differential provision of information, and value capture. By demonstrating an optimal solution, we draw attention to the potential benefits of the mechanism for information providers and users. For instance, a logistics carrier makes real-time tracking information (e.g., order status and estimated pickup time) available through a smart contract. The supplier makes payments in tokens while using the smart contract to extract relevant information to optimize its inventory. This minimizes the storage cost while avoiding potential losses from supply disruptions or stock-outs.

Secondly, we characterize the optimal DAs provisioning strategy (which users get access to DAs and what level of access is offered to each user) under full and incomplete information. Our findings show that a DAs provider should engage in such differential provisioning (or versioning) of DAs only when there are participation costs (e.g., blockchain transaction costs, delays, etc.); otherwise, she should serve one single quality or version to all users. If a user faces participation costs and the smart contract contains features such as carbon emission and a carrier's reputation, the user interested only in the reputation can access a custom smart contract that removes or disables unnecessary features/functions. A supply chain stakeholder may choose a custom contract to serve a unique application, delivering a unique value. To this end, carefully inspecting the various costs influencing user participation is critical to fine-tuning the DAs provisioning strategy. Supply chain managers should know that sharing higher-quality DAs (more features) may not produce better results for users than sharing lower-quality DAs. This explains why various information service providers, such as Bloomberg's Professional Services (Bloomberg, 2023) and Supply Chain Dive (SCD, 2023), offer custom-feature selection or differential access to various supply chain topics/data, such as logistics, freight, operations, and procurement, based on user interests.

Thirdly, we inspect the role of cost factors, user-type distribution, and quality limit on the optimal DAs provisioning strategy. Under information asymmetry, two thresholds need to be established: the exclusion point of low-type users (or the minimum quality of DAs served) and the starting point to serve the maximum quality of DAs (highest level of digitization). Notably, multiple factors (e.g., cost factors and user type distribution, among others) influence the upper threshold compared to the lower one. This is in line with the observations from the industry, where establishing a basic level of digitization is much simpler than adopting sophisticated technology, which brings complexities/challenges in the form of exorbitant upfront costs and stakeholders' skepticism, among others.

Fourthly, our study also highlights the need for supply chain managers to make cost-efficient decisions when faced with increased resource costs. For instance, when met with increased resource costs (e.g., digitization), the managers should eliminate the additional features of exorbitant costs. For instance, the carrier that intends to offer real-time tracking services (for its supply chain stakeholders) may use a simple smartphone to share the order status and location updates instead of investing in a smart container that can collect and share more sophisticated information, such as order status, location, temperature, and security. It is up to the carrier to determine what level of investment (cost commitment) will produce the highest quality DAs suitable for the users it serves.

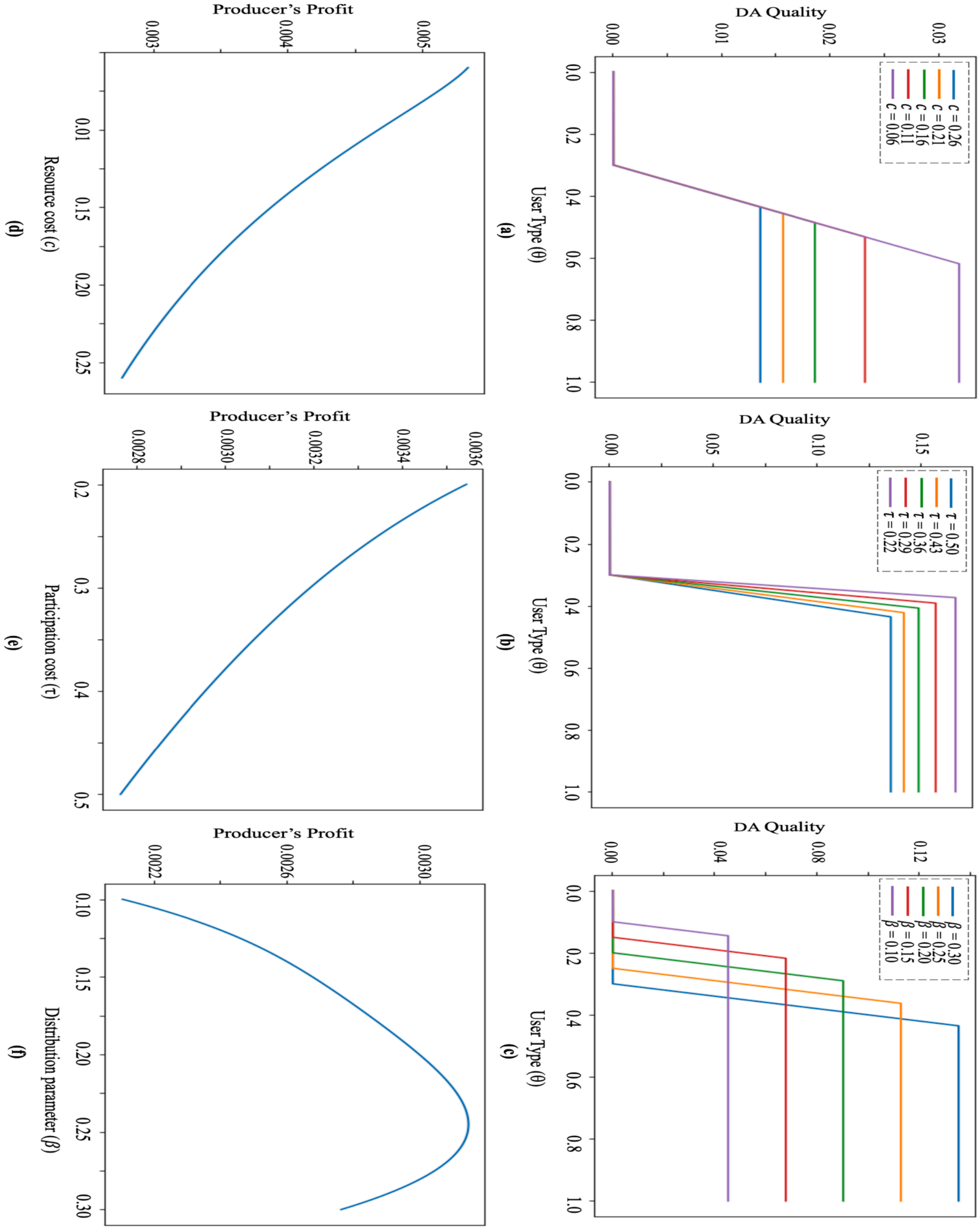

Fig. 6. Impact of parameters on quality schedule and producer surplus: (a) impact of resource cost on quality; (b) impact of participation cost on quality; (c) impact of user type distribution on quality; (d) impact of resource cost on profit; (e) impact of participation cost on profit; f) impact of user type distribution on profit.

Finally, by extending our analysis to cases with hybrid storage (offchaining) and versioning cost, we derive additional insights and demonstrate that the qualitative implications remain mostly valid even with alterations to some modeling assumptions (e.g., changes to supporting storage mechanism). For instance, we see that the impact of versioning cost is similar to that of sharing/resource cost as the user coverage and quality schedules remain unaffected. However, introducing hybrid storage does not necessarily lead to scaling (granting more low-end users access to information). Instead, it leads to the contracting of the user base. More high-end users are granted access to DAs, while more lower-end users are eliminated from the coverage. The implication is that managers should introduce off-chaining solutions only if they intend to serve the higher-end user segment. It aligns with the observations from literature where a hybridization or offchaining is advocated predominantly when there is large-scale (in terms of frequency or size) movement of transaction or information between supply chain participants.

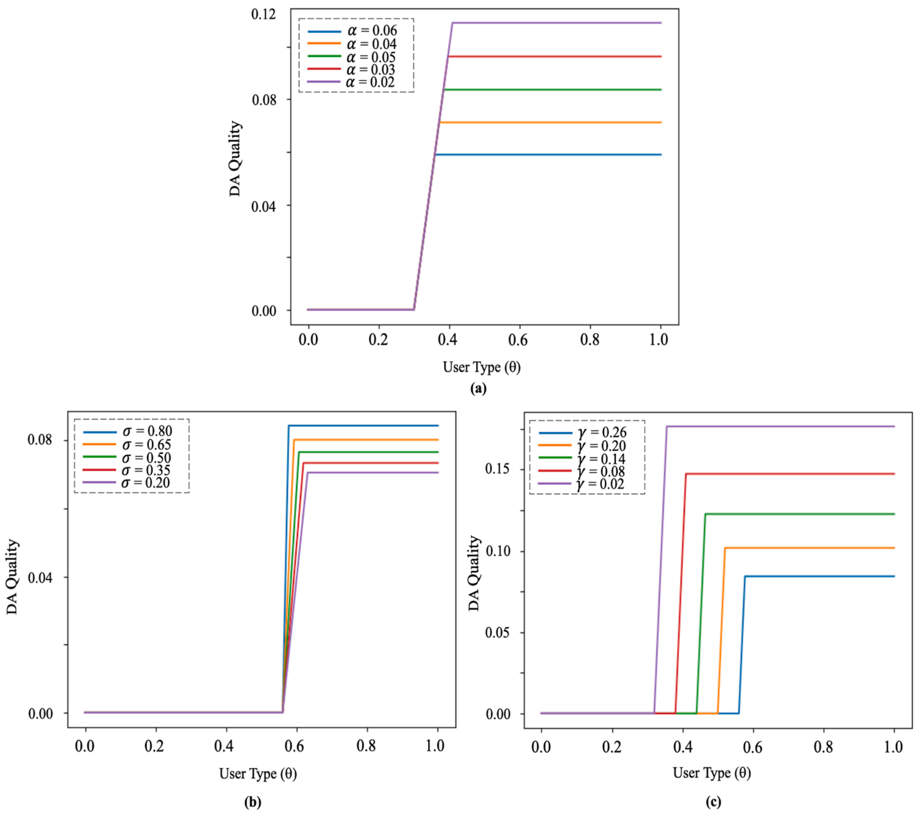

Fig. 7. Impact of parameters on quality schedule: (a) impact of versioning cost; (b) impact of user's participation cost reduction; c) impact of producer's cost absorption.

6. Conclusion

This paper introduces a valuation mechanism to promote the sharing of DAs in supply chains. We incorporate different aspects of DAs while modeling the problem and deliver fresh guidelines for the operators in the supply chain who wish to adopt a provisioning strategy, i.e., decide which users get access to DAs and what level of access is offered to each user. We characterize the optimal DAs provisioning strategy under full and incomplete information. The scenario with full information ensures full user coverage, with one segment of low-end users accessing individualized or customized access to DAs. In contrast, the high-end user segment can access one common version of DAs with all the features. On the other hand, the scenario with incomplete information produces one additional user segment, where the low-end users with the least marginal value for quality are not given access to DAs. We also show the role of the user's marginal value for DAs quality and the cost factors in determining the optimal quality of DAs, i.e., the features each user can access. We then extend the model to incorporate hybrid storage and versioning costs.

6.1. Theoretical contributions

This study contributes to the literature in three aspects. First, this is one of the early attempts to explore the role of DAs sharing and the information sharing they enable to improve the performance of the supply chains. In addition, this study is a natural extension of the existing literature on digitization or technology integration in traditional supply chains. Second, this study contributes to the literature on blockchain applications in supply chain and logistics. We introduce a novel provisioning mechanism of DAs built on blockchain technology to facilitate information sharing for supply chain applications. It uses symbolic (non-monetary) benefits delivered via tokens to motivate contributors to share information. Finally, we develop a DAs-sharing model inspired by extant quality segmentation literature. Despite using a simplistic model and analysis, we incorporate various aspects, such as the user's willingness to pay, the provider's cost of sharing DAs (digitization cost), and the user's participation costs, to fully capture the interaction between the provider and users of DAs. Considering existing research, this study is one of the early attempts to design a value mechanism incorporating reliable information storage, information provision catering to user needs, and non-monetary incentives to promote information sharing in supply chains.

6.2. Future research

Several extensions arise naturally. One would be the role of interdependence in information sharing, i.e., how the consumption of DAs by one stakeholder benefits another stakeholder in the supply chain. For instance, when an e-commerce platform uses the DAs of a logistics company to deliver financing to a merchant, all participants garner direct or indirect benefits. The merchant gets access to finance to expand its business, whereas the logistics company and e-commerce platform benefit from increased sales brought by the merchant. For instance, HSBC partnered with Cainiao to offer trade financing loans to e-commerce merchants in Tmall, an e-commerce platform from Alibaba (Mathias, 2023). Another direction worth exploring is the strategic role of information sharing in the presence of competing participants. It would be interesting to see whether the participants get access to the same information or different versions of information, given that having differential access leads to a competitive advantage of one participant over the other. Extant literature has shown the role of demand cannibalization or encroachment in the selective sharing of information in supply chains with vertical competition (Ha et al., 2023; Wang et al., 2022). However, these studies are limited to sharing demand or point-of-sale information. Therefore, it would be interesting to investigate how the competing participants in the supply chain influence the provisioning of DAs (or information). Finally, the empirical evaluation (e.g., surveys, case studies, controlled experiments, etc.) of the viability and practicality of the theoretical implications of this study remains an area worth exploring. For instance, surveys and questionnaires directed at stakeholders, such as managers, industry experts, or even third-party IT providers, may help gather rich data, both qualitative and quantitative, required to validate the findings. Similarly, a case study or controlled experiment in an industrial setting could be leveraged to investigate technology adoption and DAs sharing dynamics and their impact on participating supply chain stakeholders.

CRediT authorship contribution statement

Arjun Rachana Harish: Writing – original draft, Conceptualization. **Xinlai Liu:** Writing – review & editing, Resources. **Ming Li:** Writing – review & editing, Resources. **Ray Y. Zhong:** Writing – review & editing, Supervision, Resources. **George Q. Huang:** Writing – review & editing, Supervision, Resources.

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.

Acknowledgements

This paper is partially supported by two grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU/15208824, T32-707/22-N) and a RCDTT grant of PolyU, China (No. P0051281).

Appendix. . Proofs and list of Notations

List of Notations

$\theta \in [\underline{\theta}, \overline{\theta}]$	User types definition having a distribution with pdf $f(\theta)$ and cdf $F(\theta)$
$\grave{\theta}$	Misrepresentation of user type whose true value is θ
q	Quality (or features) of DAs
t	Token payment or valuation of DAs
τ	Participation cost parameter for users
c	Cost of creating/sharing the (largest) DAs quality
$U(\theta, q, t)$	User's utility function
$\{q^*(\theta), t^*(\theta)\}$	Optimal menu of Smart contracts or DAs quality-valuation schedule
Full Information	
θ_M^*	Highest user type index that gets customized access to DAs
q_M^*	$q_M^* = q(\theta_M^*)$ – Highest quality DAs available for use
Information Asymmetry	
$\breve{\theta}^*$	Lowest user index that gets access to DAs or the exclusion point for access
$\widehat{\theta}^*$	Highest user type index that gets customized access to DAs
$\widehat{q}^*$	$\widehat{q}^* = q(\widehat{\theta}^*)$ – Highest quality DAs available for use

Proof I: Lemma 1

We rewrite Equation (4) using the valuation and quality analysis in Section 4.1 as

$$\int_{\underline{\theta}}^{\theta_M} \frac{\theta^2}{4\tau} f(\theta)d\theta + \int_{\theta_M}^{\overline{\theta}} \left[\theta\frac{\theta_M}{2\tau} - \tau\left[\frac{\theta_M}{2\tau}\right]^2\right] f(\theta)d\theta - c\left[\frac{\theta_M}{2\tau}\right]^2. \tag{P.1}$$

The integration and simplification of the expression produce

$$\frac{1}{4\tau}\left[\theta_M^2 F(\theta_M) - \int_{\underline{\theta}}^{\theta_M} 2\theta F(\theta)d\theta\right] + \frac{\theta_M}{2\tau}\left[\overline{\theta} - \theta_M F(\theta_M) - \int_{\theta_M}^{\overline{\theta}} F(\theta)d\theta\right] - \frac{\theta_M^2}{4\tau}[1 - F(\theta_M)] - \frac{c\theta_M^2}{4\tau^2}. \tag{P.2}$$

We use the substitution $A(\theta) = \int_{\underline{\theta}}^{\theta} F(x)dx$ and $B(\theta) = \int_{\underline{\theta}}^{\theta} A(y)dy$ to further simplify the above expression as

$$\frac{1}{4\tau}\left[\theta_M{}^2 F(\theta_M) - 2\left[\theta_M A(\theta_M) - A\left(\underline{\theta}\right)\theta\right] + 2\left[B(\theta_M) - B\left(\underline{\theta}\right)\right]\right] + \frac{\theta_M}{2\tau}[\overline{\theta} - \theta_M F(\theta_M) - A(\overline{\theta}) + A(\theta_M)] - \frac{\theta_M{}^2}{4\tau}[1 - F(\theta_M)] - \frac{c\theta_M{}^2}{4\tau^2}. \tag{P.3}$$

If we represent the above expression using a symbol G, then $dG/d\theta_M = (1/(2\tau))[[\overline{\theta} - \theta_M] - [A(\overline{\theta}) - A(\theta_M)] - c\theta_M/\tau]$. That is, the FOC becomes $\overline{\theta} - \theta_M = A(\overline{\theta}) - A(\theta_M) + c\theta_M/\tau$. Now, given $F[\theta_M] \le 1$, $d^2G/d\theta_M{}^2 = -1/(2\tau) + F(\theta_M)/(2\tau) - c/(2\tau^2) < 0$. It reveals the strict concavity of G and the presence of an internal solution.

Notably, when $c = 0$, the FOC reduces to $\overline{\theta} - \theta_M = A(\overline{\theta}) - A(\theta_M)$, whose solution is $\theta_M^* = \overline{\theta}$. No other value of θ can be the solution because this demands $A(\theta)$ to be linear in θ, or $F(\theta) = 1$. The user distribution ceases to exist, and all probability converges to a common point. Since this is not true for the case we are considering, $\theta_M^* = \overline{\theta}$ is a unique solution to the expression $\overline{\theta} - \theta_M = A(\overline{\theta}) - A(\theta_M)$. In addition, since $dG/d\theta_M|_{c>0,\theta_M=\theta} < dG/d\theta_M|_{c=0,\theta_M=\theta} \forall\theta$ we infer that $\theta_M^*|_{c>0} < \theta_M^*|_{c=0}$. Therefore, there exists a unique and internal solution to $\overline{\theta} - \theta_M = A(\overline{\theta}) - A(\theta_M) + c\theta_M/\tau$.

Given $\theta_M^* < \overline{\theta}$, user types with index $\theta > \theta_M^*$ do not obtain their ideal quality of DAs. All user types from θ_M^* and above are given access to quality $\theta_M^*/(2\tau)$. The rest of the users with $\theta \in [\underline{\theta}, \theta_M^*]$ get customized access to their ideal quality of DAs (first-best solution).

Proof II: Proposition 1 & Lemma 2

The principal's (DAs provider) maximization problem is

$$\max_{\{q(\theta),t(\theta)\}} \int_{\underline{\theta}}^{\overline{\theta}} t(\theta)f(\theta)d\theta$$

s.t. $U(\theta) \ge 0$, (IR)

$$U(\theta) \ge U_\theta\left(\hat{\theta}\right) \text{(IC)} \tag{P.4}$$

Let us delve into the IC condition first. The users should maximize their surplus when they reveal their actual type (or reveal truth), θ, as they self-select the quality-valuation smart contract, $\{q(\theta), t(\theta)\}$, most suitable/ideal for them. That is, the IC conditions of users need to be satisfied. If we use $U_\theta\left(\hat{\theta}\right)$ to represent the user of type θ who misrepresents it as $\hat{\theta}$, we should get

$$U(\theta) \ge U_\theta\left(\hat{\theta}\right) \Rightarrow \theta q(\theta) - \tau q^2(\theta) - t(\theta) \ge \theta q\left(\hat{\theta}\right) - \tau q^2\left(\hat{\theta}\right) - t\left(\hat{\theta}\right) \tag{P.5}$$

for any $\left(\theta, \hat{\theta}\right) \in [\underline{\theta}, \overline{\theta}] \times [\underline{\theta}, \overline{\theta}]$.

Similarly, a user of the type $\hat{\theta}$ misreporting herself as θ should experience lower utility from the action, which we write as

$$U_{\hat{\theta}}\left(\hat{\theta}\right) \ge U_{\hat{\theta}}(\theta) \Rightarrow \hat{\theta} q\left(\hat{\theta}\right) - \tau q^2\left(\hat{\theta}\right) - t\left(\hat{\theta}\right) \ge \hat{\theta} q(\theta) - \tau q^2(\theta) - t(\theta). \tag{P.6}$$

Combining (P.5) and (P.6), we get

$$\left[q(\theta) - q\left(\hat{\theta}\right)\right]\left[\theta - \hat{\theta}\right] \ge 0. \tag{P.7}$$

Therefore, $q(\theta)$ is not decreasing when IC constraints are satisfied, i.e.,

$$q'(\theta) \ge 0 \tag{P.8}$$

Additionally, truth revelation through IC constraints implies utility maximization of users. Therefore, $dU_\theta\left(\hat{\theta}\right)/d\hat{\theta}\Big|_{\hat{\theta}=\theta} = 0$ for a user type θ with relevant first-order conditions (FOC), which we simplify to

$$\theta q'(\theta) - 2\tau q(\theta)q'(\theta) - t'(\theta) \geq 0. \tag{P.9}$$

The relevance of Equation (P.9) is dependent on whether $U_\theta\left(\grave{\theta}\right)$ satisfies $d^2U_\theta\left(\grave{\theta}\right)/d\grave{\theta}\Big|_{\grave{\theta}=\theta} < 0$, its second-order condition. With simplification, it becomes

$$\theta q''(\theta) - 2\tau\left[q'^2(\theta) + q(\theta)q''(\theta)\right] - t''(\theta) < 0. \tag{P.10}$$

Equation (P.9), after differentiation w.r.t. θ, can be written as

$$q'(\theta) + \theta q''(\theta) - 2\tau\left[q'^2(\theta) + q(\theta)q''(\theta)\right] - t''(\theta) = 0. \tag{P.11}$$

Combining Equations (P.10) and (P.11), we get $q'(\theta) \geq 0$. Since we already know this from Equation (P.8), we conclude that the second-order conditions are insignificant in producing additional constraints. Additionally, we satisfy the Spence-Mirrlees condition (crossing property) through $\partial^2 U(q,t,\theta)/\partial q\partial\theta = \partial(\theta - 2\tau q)/\partial\theta = 1$. The constant sign indicates that the local ICs are satisfied globally.

Now, let us simplify the objective functions using the ICs. First of all

$$U(\theta) = \theta q(\theta) - \tau q^2(\theta) - t(\theta). \tag{P.12}$$

When differentiated w.r.t θ, we get

$$U'(\theta) = q(\theta) + \theta q'(\theta) - 2\tau q(\theta)q'(\theta) - t'(\theta). \tag{P.13}$$

Combining Equations (P.9) and (P.13), we get

$$U'(\theta) = q(\theta). \tag{P.14}$$

Integrating the above equation between the limits $\underline{\theta}$ and θ produce $U(\theta) - U(\underline{\theta}) = \int_{\underline{\theta}}^{\theta} q(z)dz$. However, the participation constraint of the user of the lowest index is binding, which means $U(\underline{\theta}) = 0$. Therefore, we get

$$U(\theta) = \int_{\underline{\theta}}^{\theta} q(z)dz. \tag{P.15}$$

Combining Equations (P.12) and (P.15), we get $t(\theta) = \theta q(\theta) - \tau q^2(\theta) - \int_{\underline{\theta}}^{\theta} q(z)dz$. Similarly, the principal's objective function becomes

$$\int_{\underline{\theta}}^{\overline{\theta}} \left[\theta q(\theta) - \tau q^2(\theta)\right] f(\theta)d\theta - \int_{\underline{\theta}}^{\overline{\theta}} \left[\int_{\underline{\theta}}^{\theta} q(z)dz\right] f(\theta)d\theta. \tag{P.16}$$

Utilizing Fubini's theorem, we can write

$$\int_{\underline{\theta}}^{\overline{\theta}} \left[\int_{\underline{\theta}}^{\theta} q(z)dz\right] f(\theta)d\theta = \left[\left[\int_{\underline{\theta}}^{\theta} q(z)dz\right] F(\theta)\right]_{\underline{\theta}}^{\overline{\theta}} - \int_{\underline{\theta}}^{\overline{\theta}} F(\theta)q(\theta)d\theta. \tag{P.17}$$

Given $(\overline{\theta}) = 1$ and $F(\underline{\theta}) = 0$, the above equation's right-hand side converges to $\int_{\underline{\theta}}^{\overline{\theta}} [1 - F(\theta)]q(\theta)d\theta$. Thus, Equation (P.16) can be written as

$$\int_{\underline{\theta}}^{\overline{\theta}} \left[\theta - \tau q(\theta) - \frac{1 - F(\theta)}{f(\theta)}\right] q(\theta)f(\theta)d\theta. \tag{P.18}$$

We perform an unconstrained optimization without taking the constraints into account. We later verify whether the solution satisfies the conditions we introduced before. We perform a pointwise maximization where we maximize the integrand in terms of $q(\theta)$, which gives

$$q^*(\theta) = \frac{\theta - (1 - F(\theta))/f(\theta)}{2\tau} \tag{P.19}$$

From (P.19), we can observe that the quality access to users increases in the user type index, θ, until the maximum quality q_M. Therefore, we can conclude that $q^*(\theta)$ is increasing in θ, satisfying the constraint appearing in Equation (P.8). Notably, quality access to the marginal user is 0. If the index of this user is $\check{\theta}^*$, we get

$$\theta - \frac{1 - F(\theta)}{f(\theta)} = 0. \quad (P.20)$$

The solution to (P.20) gives the value of $\breve{\theta}^*$ which is the index of the lowest use type granted access to DAs. Now, let us represent the index of the smallest user type that gets access to the full or highest quality by $\widehat{\theta}^*$. The value of this index derives from solving

$$\widehat{q} = \frac{\theta - (1 - F(\theta))/f(\theta)}{2\tau}$$

$\theta - \frac{1-F(\theta)}{f(\theta)} - 2\tau\widehat{q} = 0$ or (P.21).

From a simple inspection of (P.20) and (P.21), we can see that $\widehat{\theta}^* > \breve{\theta}^*$. Therefore, providing users with differential access to DAs (versions of DAs) is optimal when the users suffer/experience a participation cost.

Proof III: Lemma 3

Taking the Expression (10)'s FOC on $\widehat{q}$ produces

$$\int_{\widehat{\theta}^*}^{\overline{\theta}} \left[\theta - 2\tau\widehat{q}^* - \left[\frac{1 - F(\theta)}{f(\theta)}\right]\right] f(\theta) d\theta = 2c\widehat{q}^* \quad (P.22)$$

The above equation, when simplifies, reduces to

$$\widehat{\theta}^* [1 - F(\widehat{\theta}^*)] = 2\widehat{q}^* [\tau[1 - F(\widehat{\theta}^*)] + c] \quad (P.23)$$

We solve Equations (P.21) (with $\theta = \widehat{\theta}^*$) and (P.23) simultaneously to get $\widehat{\theta}^*$ and $\widehat{q}^*$.

Proof IV: Proposition 2

Proof that the (largest) DAs quality in information asymmetry is inferior to one in complete information: To prove the existence of superior quality under complete information in comparison to information asymmetry, we use $\vartheta(q)$, which is a function of the DAs quality q, to represent the surplus of the principal in complete information (Expression (4)). We get

$$\frac{d\vartheta(q)}{dq}\bigg|_{q=\widehat{q}^*} = \int_{\theta_M}^{\overline{\theta}} [\theta - 2\tau\widehat{q}^*] f(\theta) d\theta - 2c\widehat{q}^* \quad (P.24)$$

Combining the expression of $2c\widehat{q}^*$ from Equation (P.23) with the above expression produces

$$\frac{d\vartheta(q)}{dq}\bigg|_{q=\widehat{q}}^* = \int_{\theta_M}^{\overline{\theta}} [\theta - 2\tau\widehat{q}^*] f(\theta) d\theta - \int_{\widehat{\theta}^*}^{\overline{\theta}} \left[\theta - \frac{1 - F(\theta)}{f(\theta)}\right] f(\theta) d\theta + 2\tau\widehat{q}^* [1 - F(\widehat{\theta}^*)]. \quad (P.25)$$

Given $\widehat{q}^* = \theta_M^*/(2\tau)$, the above expression simplifies to

$$\frac{d\vartheta(q)}{dq}\bigg|_{q=\widehat{q}^*} = \int_{\theta_M}^{\widehat{\theta}^*} [\theta - \theta_M] f(\theta) d\theta + \int_{\widehat{\theta}^*}^{\overline{\theta}} [1 - F(\theta)] d\theta. \quad (P.26)$$

Given $\theta_M^*(\widehat{q}^*) = 2\tau\widehat{q}^*$ and $\widehat{\theta}^*(\widehat{q}^*) = 2\tau\widehat{q}^* + (1 - F(\widehat{\theta}^*(\widehat{q}^*)))/f(\widehat{\theta}^*(\widehat{q}^*))$ (from Lemma 2), we can infer that $\widehat{\theta}^*(\widehat{q}^*) > \theta_M^*(\widehat{q}^*)$. This translates to the term $\int_{\theta_M}^{\widehat{\theta}^*} [\theta - \theta_M] f(\theta) d\theta$ in Equation (P.26) being positive. In addition, the term $\int_{\widehat{\theta}^*}^{\overline{\theta}} [1 - F(\theta)] d\theta$ in the same equation is positive as $F(\theta) < 1$ for $\theta \le \overline{\theta}$. Combining the two observations, we can say that the value of $d\vartheta(q)/dq|_{q=\widehat{q}^*}$ must be positive. Furthermore, we already know the concave nature of the function $\vartheta(q)$ and $d\vartheta(q)/dq|_{q=q_M^*} = 0$, we conclude that $q_M^* > \widehat{q}^*$.

Proof of quality distortion under information asymmetry:

We dedicate the following analysis to show that user access to DAs quality reduces under a scenario with information asymmetry (incomplete information) compared to a scenario with full/complete information. Put another way, the presence of information asymmetry reduces the amount of data units or the number of features that each user taps into for their supply chain applications. The proof comes from the three cases we discuss below.

Case 1 $\theta < min\{\theta_M^*, \widehat{\theta}^*\}$

From Propositions 1 and 2, we know the value of $q^*(\theta)$ under complete and incomplete information, which are $q^*(\theta) = \theta/(2\tau)$ and $q^*(\theta) = (\theta - (1 - F(\theta))/f(\theta))/(2\tau)$ respectively. From simple inspection, we can say that the quality under incomplete information is inferior, given $F(\theta) < 1$.

Case II $\theta > max\{\theta_M^*, \widehat{\theta}^*\}$

All users in this segment get uniform access to q_M^* and $\widehat{q}^*$ with full information and incomplete information, respectively. We know (from proofs) that $q_M^* > \widehat{q}^*$. Therefore, quality distortion is inevitable in information asymmetry.

Case III $min\{\theta_M^*, \widehat{\theta}^*\} \le \theta \le max\{\theta_M^*, \widehat{\theta}^*\}$

When $\theta_M^* < \widehat{\theta}^*$, all users in the segment get access to DAs quality q_M^* in a scenario with complete information and a lower quality $\widehat{q}^*$ with incomplete information. This comes from $q^*(\theta)$ being a function that is increasing in θ (since $(1 - F(\theta))/f(\theta)$ is decreasing in θ). Furthermore, $q_M^* > \widehat{q}^*$. Therefore, it becomes apparent that the information asymmetry delivers inferior quality access compared to the full information scenario.

When $\theta_M^* > \widehat{\theta}^*$, the user type with index $\widehat{\theta}^*$ gets access to DAs of quality $\widehat{q}^*$ under incomplete information. Using the rationale from Case I, the same user gets higher quality access under full information. In addition, the user types with θ greater than $\widehat{\theta}^*$ in information asymmetry gets quality no higher than $\widehat{q}^*$, whereas the quality access increases with θ under a scenario with complete information (since $\theta/(2\tau)$ is increasing in θ). Therefore, we conclude that the users in this range experience quality distortion under information asymmetry compared to a scenario with full information.

Proof V: Proposition 3

To prove the proposition, we introduce the comparative statics of θ_M^*. We first differentiate the expression $\overline{\theta} - \theta_M^* = A(\overline{\theta}) - A(\theta_M^*) + c\theta_M^*/\tau$ (that appear in Lemma 1) w.r.t. c to get

$$-\frac{d\theta_M^*}{dc} + \frac{dA[\theta_M^*]^*}{d\theta_M^*}\frac{d\theta_M^*}{dc} - \frac{\theta_M^*}{\tau} - \frac{c}{\tau}\frac{d\theta_M^*}{dc} = 0 \tag{P.27}$$

With simple rearrangement, we get $(d\theta_M^*/dc)[1 - F[\theta_M^*] + c/\tau] = -\theta_M^*/\tau$. Here, $d\theta_M^*/dc < 0$ when $F[\theta_M^*] \le 1$.

Next, differentiating the same equation (from Lemma 2) w.r.t. τ produces $(d\theta_M^*/d\tau)[1 - F[\theta_M^*] + c/\tau] = c\theta_M^*/\tau^2$, which is a positive value, i.e., $d\theta_M^*/d\tau > 0$.

Now, note that the equation from Lemma 2 is independent of terms c and τ. Hence, analysis of $\breve{\theta}^*$ is straightforward.

Finally, we use Lemma 3 to perform the comparative statics of $\widehat{\theta}^*$. It is known that $\widehat{\theta}^*$ is the solution to the equation $\widehat{\theta}^* - (1 - F(\widehat{\theta}^*))/f(\widehat{\theta}^*) - 2\tau\widehat{q}^* = 0$. With simple inspection, we can conclude that $\widehat{\theta}^*$ increases in τ. On the other hand, $\widehat{\theta}^*$ decreases in c since $\widehat{q}^*$ reduces in c.

Proof VI: Proposition 4

For the proof, we use the same approach without the cost of versioning to determine $\widehat{q}^*$ and $\breve{q}^*$:

$$\widehat{\theta}^* - \frac{1 - F(\widehat{\theta}^*)}{f(\widehat{\theta}^*)} - 2\tau\widehat{q}^* = 0 \quad \breve{\theta}^* - \frac{1 - F\left(\breve{\theta}^*\right)}{f\left(\breve{\theta}^*\right)} = 0 \tag{P.28}$$

The principal's objective function is

$$\int_{\underline{\theta}}^{\overline{\theta}} \left[\theta - \tau q(\theta) - \frac{1 - F(\theta)}{f(\theta)}\right] q(\theta) f(\theta) d\theta - \alpha\left(\widehat{\theta}^* - \breve{\theta}^*\right) - c(\widehat{q}^*)^2 \tag{P.29}$$

$$\alpha > 0$$

The FOC on $\widehat{q}$ for the above objective function produces

$$\int_{\widehat{\theta}^*}^{\overline{\theta}} \left[\theta - 2\tau\widehat{q}^* - \frac{1 - F(\theta)}{f(\theta)}\right] f(\theta) d\theta = \alpha\frac{d\left(\widehat{\theta}^* - \breve{\theta}^*\right)}{d\widehat{q}^*} + 2c\widehat{q}^* \tag{P.30}$$

Now, we differentiate (P.28) w.r.t $\widehat{q}$ to get:

$$\frac{d\widehat{\theta}^*}{d\widehat{q}^*} - \frac{-f^2(\widehat{\theta}^*) - f'(\widehat{\theta}^*)(1 - F(\widehat{\theta}^*))}{f^2(\widehat{\theta}^*)} \cdot \frac{d\widehat{\theta}^*}{d\widehat{q}^*} = 2\tau \tag{P.31}$$

Substituting the above value of $d\widehat{\theta}^*/d\widehat{q}^*$ into the FOC results in

$$\int_{\widehat{\theta}^*}^{\overline{\theta}} \left[\theta - 2\tau\widehat{q}^* - \frac{1 - F(\theta)}{f(\theta)}\right] f(\theta) d\theta = \frac{\alpha\tau}{\left(1 + \left([1 - F(\widehat{\theta}^*)]f'(\widehat{\theta}^*)\right) / \left(2f^2(\widehat{\theta}^*)\right)\right)} + 2c\widehat{q}^* \tag{P.32}$$

We simply the above expression to get

$$\widehat{\theta}^*[1 - F(\widehat{\theta}^*)] = \frac{\alpha\tau}{\left(1 + \left([1 - F(\widehat{\theta}^*)]f'(\widehat{\theta}^*)\right) / \left(2f^2(\widehat{\theta}^*)\right)\right)} + 2\widehat{q}^*[\tau(1 - F(\widehat{\theta}^*)) + c] \tag{P.33}$$

Equations (P.28) and (P.33), when solved simultaneously, produce

$$\widehat{\theta}^* - \frac{(1 - F(\widehat{\theta}^*))[c + \tau(1 - F(\widehat{\theta}^*))]}{cf(\widehat{\theta}^*)} + \frac{2\alpha\tau^2}{c[2 + f'(\widehat{\theta}^*)((1 - F(\widehat{\theta}^*))/f(\widehat{\theta}^*)).1/f(\widehat{\theta}^*)]} = 0 \tag{P.34}$$

From simple inspection, $-(1 - F(\widehat{\theta}^*))[c + \tau(1 - F(\widehat{\theta}^*))]/(cf(\widehat{\theta}^*))$ is increasing in $\widehat{\theta}^*$ since the terms $(1 - F(\widehat{\theta}^*))/f(\widehat{\theta}^*)$ is decreasing. Additionally, from the monotone hazard rate property, we can say that

$$\frac{d((1 - F(\widehat{\theta}^*))/f(\widehat{\theta}^*))}{\widehat{\theta}^*} < 0 \tag{P.35}$$

$$\Longrightarrow \frac{-f^2(\widehat{\theta}^*) - f'(\widehat{\theta}^*)(1 - F(\widehat{\theta}^*))}{f^2(\widehat{\theta}^*)} < 0$$

$$\Longrightarrow \frac{f'(\widehat{\theta}^*)(1 - F(\widehat{\theta}^*))}{f^2(\widehat{\theta}^*)} + 1 > 0$$

$$\Longrightarrow \frac{2\alpha\tau^2}{c\left[2 + f'(\widehat{\theta}^*)\left((1 - F(\widehat{\theta}^*))/f^2(\widehat{\theta}^*)\right)\right]} > 0$$

From simple inspection, left-hand side assumes a larger value when $\alpha > 0$, which confirms the decrease in the value of $\widehat{\theta}^*$ when faced with additional versioning costs.

Proof VII: Proposition 5

The objective function of the principal with off-chaining is given by:

$$\max_{\{q(\theta), t(\theta)\}} \left\{ \int_{\theta}^{\overline{\theta}} t(\theta) f(\theta) d\theta - \gamma \int_{\theta}^{\overline{\theta}} q(\theta) f(\theta) d\theta - c[\widehat{q}]^2 \right\}.$$

s.t.

$$U(\theta) \geq 0$$

(P.36)

$$U(\theta) \geq U\left(\grave{\theta}\right) \forall \grave{\theta} \neq \theta$$

where $\gamma > 0$. Note that we assume that the offchaining cost increases with the quality of DAs (more features) and the number of users given access to DAs. This is generally true, as seen in the literature on digital goods pricing (Huang and Sundararajan, 2011; Sundararajan, 2004). Since the principal bears the off-chaining cost, a user's participation cost/disutility reduces to $\tau(1 - \sigma)q^2(\theta)$, where $0 < \sigma < 1$.

We solve the optimization problem similar to Proposition 2′s proof. Focussing on IC constraint, we simplify (P.36) to

$$\int_{\theta}^{\bar{\theta}} \left[\theta - \tau(1-\sigma)q(\theta) - \frac{1-F(\theta)}{f(\theta)} - \gamma\right] q(\theta)f(\theta)d\theta. \tag{P.37}$$

We perform a pointwise maximization for an unconstrained optimization of the above expression, which gives

$$q^*(\theta) = \frac{\theta - (1-F(\theta))/f(\theta) - \gamma}{2\tau(1-\sigma)} \tag{P.38}$$

Now, we can define the quality menu as follows. The value of $\breve{\theta}^*$, the index of the smallest user type which is granted access to DAs (marginal user who gets 0 quality), is the solution to

$$\theta - \frac{1-F(\theta)}{f(\theta)} - \gamma = 0 \tag{P.39}$$

Note that $\breve{\theta}^*$ with off-chaining is greater than its corresponding value without off-chaining or hybrid storage. Now, the value of $\widehat{\theta}^*$, the index of the smallest user type which is granted access to highest/full-quality DAs, is solution to

$$\widehat{\theta}^* - \frac{1-F(\widehat{\theta}^*)}{f(\widehat{\theta}^*)} - 2\tau(1-\sigma)\widehat{q}^* - \gamma = 0 \tag{P.40}$$

Here, $\widehat{\theta}^* > \breve{\theta}^*$ is straightforward from simple inspection of Equations (P.39) and (P.40). Therefore, providing users with differential access to quality (of DAs) is optimal, even with the additional versioning cost.

The first stage objective function of principal is

$$\int_{\widehat{\theta}^*}^{\bar{\theta}} \left[\theta - 2\tau(1-\sigma)\widehat{q}^* - \frac{1-F(\theta)}{f(\theta)} - \gamma\right] q(\theta)f(\theta)d\theta - c(\widehat{q}^*)^2 \tag{P.41}$$

Its FOC w.r.t $\widehat{q}^*$ produces

$$\int_{\widehat{\theta}^*}^{\bar{\theta}} \left[\theta - 2\tau(1-\sigma)\widehat{q}^* - \frac{1-F(\theta)}{f(\theta)} - \gamma\right] f(\theta)d\theta = 2c\widehat{q}^* \tag{P.42}$$

Which we further simply to

$$(\widehat{\theta}^* - \gamma)[1-F(\widehat{\theta}^*)] = 2\widehat{q}^*[\tau(1-\sigma)(1-F(\widehat{\theta}^*)) + c]. \tag{P.43}$$

We solve Equations (P.40) and (P.43) to produce

$$\gamma = \widehat{\theta}^* - \frac{(1-F(\widehat{\theta}^*))[c+\tau(1-F(\widehat{\theta}^*))(1-\sigma)]}{cf(\widehat{\theta}^*)}\widehat{q}^* = \frac{(1-F(\widehat{\theta}^*))^2}{2cf(\widehat{\theta}^*)} \quad \text{P.44)}$$

We observe that the left-hand side of the initial equation increases in $\widehat{\theta}^*$ (as $(1-F(\widehat{\theta}^*))/f(\widehat{\theta}^*)$ decreases). Similarly, both sides are larger compared to the case without off-chaining where $\sigma = \gamma = 0$. That is, the magnitude of optimal $\widehat{\theta}^*$ with off-chaining is bigger (and $\widehat{q}^*$ is smaller) to the corresponding value for the case without off-chaining when there exists sufficiently big γ or small σ, and vice versa.

References

Adaryani, R.L., Kalantari, K., Asadi, A., Alambeigi, A., Gholami, H., Seifollahi, N., 2023. Information sharing antecedents in the supply chain: a dynamic network perspective. *Operations Management Research* 16 (2), 887–903. https://doi.org/10.1007/s12063-022-00337-w.

Agostinelli, F., McAleer, S., Shmakov, A., Baldi, P., 2019. Solving the Rubik's cube with deep reinforcement learning and search. *Nature Machine Intelligence* 1 (August). https://doi.org/10.1038/s42256-019-0070-z.

Anderson, D. L., & Hau, L. (2000). The Internet-Enabled Supply Chain: From the "First Click" to the "Last Mile".

Bagnoli, M., Bergstrom, T., 2005. Log-concave probability and its applications. *Economic Theory* 26 (2), 445–469. https://doi.org/10.1007/S00199-004-0514-4/METRICS.

Bhargava, H.K., Choudhary, V., 2008. Research Note—When Is Versioning Optimal for Information Goods? *Management Science* 54 (5), 1029–1035. https://doi.org/10.1287/MNSC.1070.0773.

Bloomberg. (2023). *Global Supply Chain Data*. Bloomberg Professional Services. Retrieved 26/11/2024 from https://www.bloomberg.com/professional/dataset/global-supply-chain-data/.

Boehm, B., Abts, C., Chulani, S., 2000. Software development cost estimation approaches - A survey. *Annals of Software Engineering* 10 (1–4), 177–205. https://doi.org/10.1023/A:1018991717352/METRICS.

Branco, F., Sun, M., Villas-Boas, J.M., 2016. Too Much Information? Information Provision and Search Costs. *Marketing Science* 35 (4), 605–618. https://doi.org/10.1287/mksc.2015.0959.

Cachon, G.P., Lariviere, M.A., 2001. Contracting to assure supply: How to share demand forecasts in a supply chain. *Management Science* 47 (5), 629–646. https://doi.org/10.1287/mnsc.47.5.629.10486.

Camdereli, A.Z., Swaminathan, J.M., 2010. Misplaced Inventory and Radio-Frequency Identification (RFID) Technology: Information and Coordination. *Production and Operations Management* 19 (1), 1–18. https://doi.org/10.1111/j.1937-5956.2009.01057.x.

Chatterjee, D., Ravichandran, T., 2013. Governance of Interorganizational Information Systems: A Resource Dependence Perspective. *Information Systems Research* 24 (2), 261–278. https://doi.org/10.1287/isre.1120.0432.

Chellappa, R.K., Shivendu, S., 2010. Mechanism Design for “Free” but “No Free Disposal” Services: The Economics of Personalization Under Privacy Concerns. *Management Science* 56 (10), 1766–1780. https://doi.org/10.1287/MNSC.1100.1210.

Chen, Y.J., Seshadri, S., 2007. Product Development and Pricing Strategy for Information Goods Under Heterogeneous Outside Opportunities. *Information Systems Research* 18 (2), 150–172. https://doi.org/10.1287/ISRE.1070.0119.

Chod, J., Trichakis, N., Yang, S.A., 2022. Platform Tokenization: Financing, Governance, and Moral Hazard. *Management Science* 68 (9), 6411–6433. https://doi.org/10.1287/mnsc.2021.4225.

Chu, L.Y., Shamir, N., Shin, H., 2017. Strategic communication for capacity alignment with pricing in a supply chain. *Management Science* 63 (12), 4366–4388. https://doi.org/10.1287/mnsc.2016.2527.

Cryptoslav, I., 2023. What Is Blockchain Network Congestion? | CoinMarketCap. In. CoinMarketCap.

Dai, T., Tang, C., 2022. Frontiers in Service Science: Integrating ESG Measures and Supply Chain Management: Research Opportunities in the Postpandemic Era. *Service Science* 14 (1), 1–12. https://doi.org/10.1287/serv.2021.0295.

Davies, J., Sharifi, H., Lyons, A., Forster, R., Elsayed, O.K.S.M., 2024. Non-fungible tokens: The missing ingredient for sustainable supply chains in the metaverse age? *Transportation Research Part e: Logistics and Transportation Review* 182, 103412. https://doi.org/10.1016/j.tre.2024.103412.

Dhebar, A.S., 1990. *Cambridge Software Corporation* H. B. S, Case https://www.hbs.edu/faculty/Pages/item.aspx?num=3767.

Duan, L., Kubo, T., Sugiyama, K., Huang, J., Hasegawa, T., Walrand, J., 2014. Motivating Smartphone Collaboration in Data Acquisition and Distributed Computing. *IEEE Transactions on Mobile Computing* 13 (10), 2320–2333. https://doi.org/10.1109/tmc.2014.2307327.

Fang, C., Chi, M., Fan, S., Choi, T.-M., 2024. Who should invest in blockchain technology under different pricing models in supply chains? *European Journal of Operational Research* 319 (3), 777–792. https://doi.org/10.1016/j.ejor.2024.07.006.

Franke, B., Fritz, Q. G., & Stenzel, A. (2023). The (Limited) Power of Blockchain Networks for Information Provision. Management Science(October). https://doi.org/10.1287/mnsc.2023.4718.

Gan, J., Tsoukalas, G., Netessine, S., 2021. Initial coin offerings, speculation, and asset tokenization. *Management Science* 67 (2), 914–931. https://doi.org/10.1287/mnsc.2020.3796.

Godbole, O., 2020. Bitcoin Transaction Fees Decline as Network Congestion Eases - CoinDesk. In *CoinDesk*.

Govindan, K., Jain, P., Kr. Singh, R., & Mishra, R. (2024). Blockchain technology as a strategic weapon to bring procurement 4.0 truly alive: Literature review and future research agenda. Transportation Research Part E: Logistics and Transportation Review, 181, 103352. https://doi.org/10.1016/j.tre.2023.103352.

Guan, X., Chen, Y.J., 2017. The Interplay between Information Acquisition and Quality Disclosure. *Production and Operations Management* 26 (3), 389–408. https://doi.org/10.1111/poms.12651.

Guo, H., Hao, L., Mukhopadhyay, T., Sun, D., 2019. Selling Virtual Currency in Digital Games: Implications for Gameplay and Social Welfare. *Information Systems Research* 30 (2), 430–446. https://doi.org/10.1287/ISRE.2018.0812.

Ha, A.Y., Shang, W., Wang, Y., 2023. Supplier Audit Information Sharing and Responsible Sourcing. *Management Science* 69 (1), 308–324. https://doi.org/10.1287/mnsc.2022.4358.

Ha, A.Y., Tong, S., 2008. Contracting and information sharing under supply chain competition. *Management Science* 54 (4), 701–715. https://doi.org/10.1287/mnsc.1070.0795.

Ha, A.Y., Tong, S., Zhang, H., 2011. Sharing Demand Information in Competing Supply Chains with Production Diseconomies. *Management Science* 57 (3), 566–581. https://doi.org/10.1287/MNSC.1100.1295.

Ha, A.Y., Tian, Q., Tong, S., 2017. Information sharing in competing supply chains with production cost reduction. *Manufacturing and Service Operations Management* 19 (2), 246–262. https://doi.org/10.1287/msom.2016.0607.

Hahn, J.-H. (2000). Monopoly Quality Differentiation with Top-quality Dependent Fixed Costs. In *Keele Department of Economics Discussion Papers (1995-2001)*. Newcastle, UK.: Department of Economics, Keele University.

Harapko, S., 2023. *How COVID-19 impacted supply chains and What Comes Next* EY. Retrieved 26/11/2024 from. https://www.ey.com/en_gl/insights/supply-chain/how-covid-19-impacted-supply-chains-and-what-comes-next.

Harish, A.R., Liu, X.L., Zhong, R.Y., Huang, G.Q., 2021. Log-flock: A blockchain-enabled platform for digital asset valuation and risk assessment in E-commerce logistics financing. *Computers & Industrial Engineering* 151, 107001. https://doi.org/10.1016/j.cie.2020.107001.

Harish, A.R., Liu, X.L., Li, M., Zhong, R.Y., Huang, G.Q., 2023a. Blockchain-enabled digital assets tokenization for cyber-physical traceability in E-commerce logistics financing. *Computers in Industry* 150, 103956. https://doi.org/10.1016/j.compind.2023.103956.

Harish, A.R., Wu, W., Li, M., Huang, G.Q., 2023b. Blockchain-enabled digital asset tokenization for crowdsensing in environmental, social, and governance disclosure. *Computers & Industrial Engineering* 185 (September), 109664. https://doi.org/10.1016/j.cie.2023.109664.

Hayek, F.A., 1945. The Use of Knowledge in Society. *The American Economic Review* 35 (4), 519–530. http://www.jstor.org/stable/1809376.

Holden, R., Malani, A., 2022. An Examination of Velocity and Initial Coin Offerings. *Management Science* 68 (12), 9026–9041. https://doi.org/10.1287/mnsc.2022.4314.

Huang, K.-W., Sundararajan, A., 2011. Pricing Digital Goods: Discontinuous Costs and Shared Infrastructure. *Information Systems Research* 22 (4), 721–738. https://doi.org/10.1287/isre.1100.0283.

Ivanov, D., 2018. Structural Dynamics and Resilience in Supply Chain Risk Management. *International Series in Operations Research & Management Science*. https://doi.org/10.1007/978-3-319-69305-7.

Jiang, L., Hao, Z., 2016. Incentive-driven information dissemination in two-tier supply chains. *Manufacturing and Service Operations Management* 18 (3), 393–413. https://doi.org/10.1287/msom.2016.0575.

Jones, R., Mendelson, H., 2011. Information Goods vs. Industrial Goods: Cost Structure and Competition. *Management Science* 57 (1), 164–176. https://doi.org/10.1287/MNSC.1100.1262.

Kalra, A., & Stecklow, S. (2021). *Amazon copied products and rigged search results, documents show* Reuters. Retrieved 26/11/2024 from https://www.reuters.com/investigates/special-report/amazon-india-rigging/.

Kaplan, D. A. (2018). *The rise, fall and return of RFID*. Supplychaindive. Retrieved 26/11/2024 from https://www.supplychaindive.com/news/RFID-rise-fall-and-return-retail/530608/.

Kapuściński, R., Parker, R.P., 2022. Conveying Demand Information in Serial Supply Chains with Capacity Limits. *Operations Research* 70 (3), 1485–1505. https://doi.org/10.1287/OPRE.2021.2251.

Laffont, J.-J., Martimort, D., 2001. *The theory of incentives I: the principal-agent model*. Princeton University Press.

Lahiri, A., Dey, D., 2012. Effects of Piracy on Quality of Information Goods. *Management Science* 59 (1), 245–264. https://doi.org/10.1287/MNSC.1120.1578.

Lee, H., Özer, Ö., 2007. Unlocking the Value of RFID. *Production and Operations Management* 16 (1), 40–64. https://doi.org/10.1111/j.1937-5956.2007.tb00165.x.

Lee, H.L., Padmanabhan, V., Whang, S., 1997. Information Distortion in a Supply Chain: The Bullwhip Effect. *Management Science* 43 (4), 546–558. https://doi.org/10.1287/mnsc.43.4.546.

Lee, H.L., Whang, S., 2000. Information sharing in a supply chain. *International Journal of Manufacturing Technology and Management* 1 (1), 79. https://doi.org/10.1504/ijmtm.2000.001329.

Leng, M., Parlar, M., 2009. Allocation of cost savings in a three-level supply Chain with demand information sharing: A cooperative-game approach. *Operations Research* 57 (1), 200–213. https://doi.org/10.1287/opre.1080.0528.

Li, M., Li, M., Harish, A.R., Huang, G.Q., 2023. Blockchain-based fine-grained digital twin sharing framework for social manufacturing. *Advanced Engineering Informatics* 58, 102225. https://doi.org/10.1016/j.aei.2023.102225.
Lin, X., Chen, Y.-J., Xiong, H., 2024. Manufacturers' efforts and platform's demand information sharing in eco-friendly actions. *Transportation Research Part e: Logistics and Transportation Review* 192, 103775. https://doi.org/10.1016/j.tre.2024.103775.
Liu, X., Wu, H., Wu, W., Fu, Y., & Huang, G. Q. (2020). Blockchain-Enabled ESG Reporting Chain. 7th International Conference on Sustainable Design and Manufacturing 2020.
Liu, W., Wei, S., Li, K.W., Long, S., 2022. Supplier participation in digital transformation of a two-echelon supply chain: Monetary and symbolic incentives. *Transportation Research Part e: Logistics and Transportation Review* 161, 102688. https://doi.org/10.1016/J.TRE.2022.102688.
Los, J., Schulte, F., Spaan, M.T.J., Negenborn, R.R., 2020. The value of information sharing for platform-based collaborative vehicle routing. *Transportation Research Part e: Logistics and Transportation Review* 141, 102011. https://doi.org/10.1016/j.tre.2020.102011.
Luo, T., Kanhere, S.S., Das, S.K., Tan, H.-P., 2016. Incentive Mechanism Design for Heterogeneous Crowdsourcing Using All-Pay Contests. *IEEE Transactions on Mobile Computing* 15 (9), 2234–2246. https://doi.org/10.1109/tmc.2015.2485978.
Malinova, K., & Park, A. (2023). Tokenomics: When Tokens Beat Equity. Management Science(October). https://doi.org/10.1287/mnsc.2023.4882.
Mathias, G. (2023). HSBC unveils digital trade finance solution in Hong Kong, Singapore, UAE. Retrieved 26/11/2024 from https://ibsintelligence.com/ibsi-news/hsbc-unveils-digital-trade-finance-solution-in-hong-kong-singapore-uae/#.
Meyer, T., Kuhn, M., Hartmann, E., 2019. Blockchain technology enabling the Physical Internet: A synergetic application framework. *Computers & Industrial Engineering* 136, 5–17. https://doi.org/10.1016/j.cie.2019.07.006.
Mishra, R., Kr Singh, R., Daim, T.U., Fosso Wamba, S., Song, M., 2024. Integrated usage of artificial intelligence, blockchain and the internet of things in logistics for decarbonization through paradox lens. *Transportation Research Part e: Logistics and Transportation Review* 189, 103684. https://doi.org/10.1016/j.tre.2024.103684.
Munves, G., 2013. *Wake Up, Retailers! Make Money From Your Big Data*. Retrieved 24/11/2024 from https://chainstoreage.com/news/wake-retailers-make-money-your-big-data. CSA.
Mussa, M., Rosen, S., 1978. Monopoly and product quality. *Journal of Economic Theory* 18 (2), 301–317. https://doi.org/10.1016/0022-0531(78)90085-6.
Niu, Y., Fu, Y., Liu, X., Harish, A.R., Li, M., Huang, G.Q., 2024. Blockchain-based incentive mechanism for environmental, social, and governance disclosure: A principal-agent perspective. *Corporate Social Responsibility and Environmental Management*. https://doi.org/10.1002/csr.2916.
Ren, Z.J., Cohen, M.A., Ho, T.H., Terwiesch, C., 2010. Information sharing in a long-term supply chain relationship: The role of customer review strategy. *Operations Research* 58 (1), 81–93. https://doi.org/10.1287/opre.1090.0750.
Scd, 2023. *Supply Chain News and Analysis*. Supply Chain Dive. Retrieved 26/11/2024 from. https://www.supplychaindive.com/.
Schloetzer, J.D., 2012. Process Integration and Information Sharing in Supply Chains. *The Accounting Review* 87 (3), 1005–1032. http://www.jstor.org/stable/23245638.
Shakhnov, K., Zaccaria, L., & Shakhnov, K. (2023). Utility Tokens, Network Effects, and Pricing Power Utility Tokens, Network Effects, and Pricing Power. (October). https://doi.org/10.1287/mnsc.2023.4917.
Shamir, N., Shin, H., 2016. Public forecast information sharing in a market with competing supply chains. *Management Science* 62 (10), 2994–3022. https://doi.org/10.1287/mnsc.2015.2261.
Shang, W., Ha, A.Y., Tong, S., 2016. Information sharing in a supply chain with a common retailer. *Management Science* 62 (1), 245–263. https://doi.org/10.1287/mnsc.2014.2127.
Sisodia, D., Sisodia, D.S., 2023. A hybrid data-level sampling approach in learning from skewed user-click data for click fraud detection in online advertising. *Expert Systems* 40 (2), e13147–e. https://doi.org/10.1111/EXSY.13147.
Sockin, M., Xiong, W., 2023. A Model of Cryptocurrencies. *Management Science*(october). https://doi.org/10.1287/mnsc.2023.4756.
Srinagesh, P., Bradburd, R.M., 1989. Quality Distortion by a Discriminating Monopolist on JSTOR. *The American Economic Review* 79 (1), 96–105. https://www.jstor.org/stable/1804776.
Sundararajan, A., 2004. Nonlinear Pricing of Information Goods. *Management Science* 50 (12), 1660–1673. https://doi.org/10.1287/mnsc.1040.0291.
Tao, D., Wu, T.-Y., Zhu, S., Guizani, M., 2020. Privacy protection-based incentive mechanism for Mobile Crowdsensing. *Computer Communications* 156, 201–210. https://doi.org/10.1016/j.comcom.2020.03.027.
Tiwari, S., Sharma, P., Choi, T.-M., Lim, A., 2023. Blockchain and third-party logistics for global supply chain operations: Stakeholders' perspectives and decision roadmap. *Transportation Research Part e: Logistics and Transportation Review* 170, 103012. https://doi.org/10.1016/j.tre.2022.103012.
Tsc, 2016. *The Sustainability Consortium*. Retrieved 24/11/2024 from. https://sustainabilityconsortium.org/the-sustainability-consortium-releases-landmark-report-to-drive-more-sustainable-consumer-products-greening-global-supply-chains-from-blind-spots-to-hotspots-to-action/.
Varian, H.R., 1997. Versioning information goods. In: Varian, H.R., Kahin, B. (Eds.), *Internet Publishing and beyond: the Economics of Digital Information and Intellectual Property*. MIT Press.
Wang, Y., Ha, A.Y., Tong, S., 2022. Sharing Manufacturer's Demand Information in a Supply Chain with Price and Service Effort Competition. *Manufacturing and Service Operations Management* 24 (3), 1698–1713. https://doi.org/10.1287/msom.2021.1028.
Wei, X., Nault, B.R., 2013. Experience information goods: "Version-to-upgrade". *Decision Support Systems* 56 (1), 494–501. https://doi.org/10.1016/J.DSS.2012.11.006.
Wei, X., Nault, B.R., 2014. Monopoly versioning of information goods when consumers have group tastes. *Production and Operations Management* 23 (6), 1067–1081. https://doi.org/10.1111/poms.12180.
Zhao, Y., Zhou, H., Leus, R., 2024. Decision timing, information inference, and information sharing: A robust supply chain game with two-way information asymmetry. *Transportation Research Part e: Logistics and Transportation Review* 192, 103807. https://doi.org/10.1016/j.tre.2024.103807.