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Blockchain for supply chain traceability and anticounterfeiting: the oracles' enabling role

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Contents

Introduction

Blockchain is a distributed ledger that records information in multiple copies in several different physical locations (Hastig and Sodhi, 2020). Because of its versatility and extensive impact on multiple aspects of business, it has been defined as a general-purpose technology (De Giovanni, 2020). The literature agrees that blockchain is a ledger of information with peculiar characteristics that ensure the integrity and immutability of the information recorded. However, blockchain needs gateways through which real-world information can be transferred on-chain. These bridges are called oracles. Oracles play a pivotal role because the functionality and benefits promised by blockchain would be nullified if the information entering the chain are not reliable. Studies investigating oracles and their implications are extremely limited in the supply chain literature (Chung et al., 2023; De Giovanni, 2021; Nelaturu et al., 2020). This Ph.D. dissertation aims to investigate the use of blockchain for supply chain traceability and anti-counterfeiting and the oracles enabling role.

This study is divided into three chapters that take inspiration from two interesting blockchain applications. Genuino is a company involved in the certification of match-worn jerseys worn by soccer players in Serie A TIM. Their solution uses blockchain and hardware oracles applied to the jerseys to combat counterfeiting and certify the originality of collectible jerseys (Ruzza, Bernasconi, et al., 2022). Genuino inspired the first chapter. In the first chapter, I present a dynamic game model where a supplier sells chips, called hardware oracles in blockchain language, to a football club. The chips are attached to the player's jerseys before a football match and associated with a non-fungible token (NFT) allowing data collection on the blockchain. The NFT and the data recorded on the blockchain certify the product's originality. In the event of defective chips, the jerseys are sold traditionally without blockchain certification, which still provides lucrative business opportunities for the goods although it is defective. The study compares two pricing mechanisms: smart wholesale pricing, which compensates suppliers based on defect-free rates, and traditional profit sharing, which pays based on digital market sales. Our findings indicate that the smart contract algorithm is economically superior and enables total quality management through smart wholesale pricing. In contrast, our results suggest that profit sharing may only be a viable option when smart wholesale pricing is less effective, and the supplier cannot be adequately incentivized to ensure total quality management. Thus, our dynamic game model demonstrates the potential of blockchain technology to enhance the distribution channel of collectibles and incentivize total quality management through oracles.

Trusty is a company that deals with the certification of supply chains with a focus on the agribusiness sector. It uses a modular solution that allows different initial investments and integrates different technologies and oracles (Ruzza, Morandini, et al., 2022). One of the major applications of Trusty to date is the certification of the chocolate supply chain from the countries of production to the final customer. Trusty inspired the second chapter where I study the blockchain effect on supply chain fairness (Chen et al., 2022b). The cocoa supply chain in Ivory Coast is unfair. Farmers earn an average of $0.5 per day against a minimum wage to be above the poverty threshold set by the World Bank at $2 per day (Amiel et al., 2019). As a result, child exploitation, deforestation to make new plantations, and diseases from the use of chemicals to civil wars in some cases are common phenomena. In this chapter, I develop a system dynamics model based on an empirical study with 3 years of interviews. Thanks to system dynamics I simulate the supply chain without blockchain and with

blockchain to answer two research questions: how does bargaining power asymmetry affect supply chain fairness? What is the blockchain impact on bargaining power asymmetry and supply chain fairness? The results show that bargaining power has a positive effect on supply chain fairness. Blockchain has a positive impact on bargaining power through the price on the field and information asymmetries. Moreover, the blockchain adoption can improve supply chain fairness thanks to its effect on bargaining power. Oracles play a key role because they allow information recording. Trusty use a combination of human oracles and inbound oracles that must be cheap given economic constraints and resilient given environmental conditions.
The third chapter is a quantitative study that combines the insight from Genuino and Trusty and aims to answer two research questions: RQ1: Is there a significant relationship between implementing blockchain technology, supply chain challenges, and business performance? How do they affect each other? RQ2: Which types of blockchain oracles are more efficient in solving supply chain challenges and improving business performance? I collect the data from 156 companies through a survey. The data are analyzed through a Partial Least Squares Path Modeling PLS-PM. I answer the first research questions by demonstrating that Blockchain has a positive impact on supply chain challenges and that supply chain challenges have a positive impact on business performance. However, I do not identify any direct impact of blockchain on business performance, but I do identify a positive and indirect impact of blockchain on business performance through supply chain challenges. I answer the second research question by demonstrating that outbound oracles and human oracles have no significant impact. Conversely, when hardware oracles and inbound oracles are used Blockchain has a higher positive impact on business performance. When hardware oracles, inbound oracles, and software oracles are used, supply chain challenges have a higher positive impact on business performance and blockchain has a higher positive and indirect impact on business performance through supply chain challenges compared to the condition without oracles. Blockchain technology has the potential to revolutionize supply chains, by addressing several challenges and issues that have traditionally hampered their efficiency and effectiveness. By using blockchain technology, businesses can gain greater visibility and control over their supply chain operations, reducing the risk of fraud, errors, and delays.
With this study, I analyzed blockchain and oracles applied to supply chain traceability. This thesis has some peculiarities that make it interesting and capable of contributing to the academic debate on blockchain in the operations and supply chain literature. First, the ideas of the three chapters come from four years of interactions, interviews, and collaborations with Genuino and Trusty. This period allowed me to see the companies grow from startups to structured companies that are a benchmark in their respective industries. I was able to appreciate the technological evolution, difficulties faced, and successful strategies. In addition, I was able to follow from a dual perspective the evolutions of blockchain, which in the last four years has gone from an almost unknown but promising technology to an indispensable tool for numerous business applications. This makes this thesis grounded and able to consider practical, managerial, and social issues. The plurality of sectors analyzed and approaches to technology application gives value to the work. Second, in addition to the sectoral plurality, this thesis was developed with a methodological plurality. Chapter One is a theoretical chapter based on game theory, chapter two uses a mixed method consisting of a qualitative part and a second part with system dynamics simulation, and the third paper is quantitative by applying structural equation modeling. The methodological plurality allowed me to use a pragmatic approach by letting myself be guided by interesting ideas and research questions without any methodological boundary. In each chapter,

the chosen methodology was subordinate to the identified research question and was developed ad hoc. Third, these choices led me to develop an original thesis studying oracles, a phenomenon still understudied in supply chain literature. The main theoretical contributions through which this thesis advances current knowledge are:

- Chapter one: I look at supply chain coordination. Blockchain-based smart contracts allow us to overcome traditional contracts by ensuring better performance in terms of quality and profit. In contrast to traditional contracts where profit-sharing contracts are preferable to wholesale price contracts, when I introduce blockchain I find that smart wholesale price contracts perform better than smart profit-sharing contracts.
- Chapter two: I look at bargaining power and supply chain fairness. I find a relationship between bargaining power and supply chain fairness. Blockchain can improve supply chain fairness through its effect on bargaining power. Blockchain affects the financial resources and information available to supply chain actors.
- Chapter three: I look at the effect of different types of oracles on the relationships between supply chain challenges, blockchain, and business performance. The results show that blockchain has no direct impact on business performance. However, it has an indirect impact on business performance through supply chain challenges. This relationship is confirmed by the positive and significant effect of supply chain challenges on business performance. Furthermore, I show that oracles are not all the same but have a different effect on the above relationships.

The managerial contributions I can derive from this thesis are many and I refer to the chapters for more details. However, here I describe the main ones for each chapter.

- Chapter one: I suggest to managers that the previous knowledge in terms of supply chain coordination with contracts should be revised if they choose to use blackchin-based smart contracts and that in this case, they should prefer a smart wholesale price contract instead of a smart profit-sharing contract.
- Chapter two: I suggest that managers should adopt blockchain when the supply chain is affected by bargaining power asymmetry that leads the supply chain to be e unfair and unsustainable in the long run for the weaker actors in the chain.
- Chapter three: I suggest using blockchain to overcome supply chain challenges rather than for performance improvements because we find that the effect of blockchain on performance is due to overcoming supply chain challenges. Among the oracles studied, hardware oracles and inbound oracles turn out to be more effective so these should be preferred.

Chapter 1

Blockchain and physical oracles in the Collectible Industry

Abstract

This paper presents a dynamic game model using blockchain technology and applied to the collectible industry. One supplier of chips and a football club purchases chips from a supplier to be installed inside t-shirts that will be dressed by the football players. The chips enable the data collection during a football game, which are recorded on the blockchain platform and make then the product original and non-imitable. If the chips used during a football match are defective, the blockchain cannot be activated and the t-shirt are then sold through traditional selling stores.We highlight the value creation through blockchain as well as the optimal quality, pricing, and investments strategies. We compare a smart wholesale price scenarios, which makes payments according to the defect-free rates with a smart profit sharing mechanism, which makes payments according to the sales in the digital market. Our resuls demonstrate that the smart contract algorithm makes firms' economically better off and achieves total quality management when activating transactions according to a smart whole price. Instead, the smart profit sharing turns out to be helpful only when the smart wholesale is inefficient and if total quality management is not fully achieved.

1.1 Introduction

Due to the digital revolution, exchanges in the collectibles industry take place most likely using online platforms (Heitner, 2016; Seideman, 2018), making them easy, quick, and efficient. Even thought, these benefits are counterbalanced by some side effects, of which the spread of counterfeits is surely the most dangerous and challengin. According to an FBI investigation, at least 50 percent of collectibles sold are fakes, a percentage that rises to 90 percent for certain items (The Federal Bureau of Investigation, 2005). The problem is relevant considering the size of the industry, valued at around $400B with an estimated growth of 4% per year (Yahoo Finance, 2022). Among the most popular collectibles are those related to 6-time NBA champion and superstar Michael Jordan that are traded for hundreds of thousands of dollars such as the jersey used in the farewell game sold for over $170,000 (Heitner, 2016). Blockchain technology, through non-fungible tokens (NFT), is frequently used to limit counterfeiting in the collectibles industry. Two strategies are possible: create fully digital collectibles on blockchain such as Dapper Lab, Sorare, and Animoca Brands; create physical-digital collectibles such as Fantastec Swap, Collectable.com, and Genuino. Virtual collectibles have been somehow studied in the literature (Shang et al., 2022; Tan, 2022), while physical-digital collectibles are missing. The peculiarity of physical-virtual collectibles is the need to create a link between the virtual NFT and the physical item. A proven effective solution is the insertion of a chip into the physical object with an oracle function. It allows information registration about the physical object on the blockchain. The chip becomes an integral part of the collectibles and influences its quality by certifying its originality. We have identified a limited number of contributions in the literature that investigate the use of blockchain to limit counterfeiting (Danese et al., 2021;

Li et al., 2021; Pun et al., 2021; Shen et al., 2016). Papers that consider quality have opposite opinions. Some authors show that when blockchain is introduced, product quality decreases because blockchain becomes the quality signal (Shen et al., 2022; Zhang et al., 2012), while others that with blockchain the product quality should increase (Biswas et al., 2022; Cho et al., 2015). Pricing strategies are often associated with quality strategies, and the right pricing strategy could be an effective counterfeiting countermeasure (Shen et al., 2022). However, to our knowledge, there is no paper referring to the collectibles industry. Consequently, our first research question is: How do firms in the collectible industry set their pricing, quality, and blockchain strategies to satisfy the market of digital-physical goods? The manufacturer that produces the collectibles needs to rely on a supplier to purchase the chips. The chips may have defects that have detrimental consequences for the manufacturer in both economic and reputational terms (De Giovanni, 2020; Lee and Li, 2018). When defects occur, the supplier and manufacturer need to activate a reconciliation procedure to restore the product and compensate for the damage (Balachandran and Radhakrishnan, 2005). The product quality and the reconciliation mechanisms are related to contracts used for supply chain collaboration and coordination. Among the most studied in the literature, we can find the wholesale price contract. The wholesale price contract is characterized by the double marginalization issue, which makes it inefficient in many cases (Fan et al., 2017; El Ouardighi, 2014; El Ouardighi and Kim, 2010). Leveraging blockchain technology a new form of wholesale price contract can be developed that we call smart wholesale price contracts (De Giovanni, 2020). In this new contract, the relationship is managed through a blockchain-based smart contract that triggers the payment of chips only when the chips are associated with an NFT resulting compliant with the required quality specifications. Therefore, our second research question is: Do blockchain-based smart wholesale price clauses align the firms' economic targets and total quality management goals? An alternative to wholesale price contact is sharing contracts. Sharing contracts provide better performance because they limit the double marginalization issue (Chen et al., 2012; Ling et al., 2022; Shen et al., 2016). Even with the introduction of blockchain for cryptocurrency payment, asset certification, and information asymmetries reduction, sharing contracts seem preferable to wholesale price contracts (Choi, 2020; Li et al., 2022; Lu et al., 2022). To test their performance in the collectible industry with blockchain, we introduce a smart sharing contract that works as the smart wholesale price contract by triggering the payment and profit-sharing mechanism once the chips are compliant. We then compare the performance of the two contracts. Our third research question is: Should firms in the collectible industry prefer a blockchain based on profit-sharing clauses over a blockchain-based on wholesale price clauses? To answer the identified research questions we develop a dynamic game inspired by the certification process of collectibles match worn jerseys developed by Genuino (Ruzza et al., 2022). We have two players a chip supplier S and a football club F cooperating to prevent counterfeiting. We compare the performance of a w-game in which the relationship is managed through a smart wholesale price contract and a p-game in which a smart profit-sharing contract is used. Both games are played a la Nash. Our results answer the three identified research questions. Greater investment in blockchain is followed by greater investment in quality to ensure compliant chips. Blockchain-equipped products ensure higher profits for both players. In our model, the products that are not certified on blockchain because they are not equipped with chips or equipped with defective chips are sold on the market. The two products do not cannibalize because of the large price difference. The smart wholesale price contract incentivizes the supplier to pursue a total quality management strategy because the blockchain-based smart contract pays the supplier only for compliant goods and prevents any reconciliation procedure. Comparing a smart wholesale price contract and a smart profit-sharing contract we found that the smart wholesale price contract is preferred. This result disagrees with the previous literature. The unexpected result is justified by blockchain implementation for transaction management. Blockchain makes payment only on defect-free products allowing the integration of the business models of the two players without the need for a sharing contract. The paper is organized as follows. Section 2 presents the literature review, section 3 proposes a dynamic game with blockchain with a smart wholesale price contract, section 4 proposes a variant of the game with a smart profit-sharing contract, section 5 compares the two games, section 6 is a sensitivity analysis, section 7 identifies managerial insights, and section 8 concludes the paper.

1.2 Literature Review

1.2.1 Pricing, quality, and blockchain strategy in the collectible industry

The collectible industry is understudied in the marketing and the operations literature (Brint, 2003; Carare and Rothkopf, 2005; Levin et al., 1995). A limited number of authors have recently explored blockchain as a possible technology to limit counterfeiting in the supply chain. Using various, Danese et al. (2021) and Li et al. (2021) analyze how a blockchain system can be designed to prevent counterfeiting in different types of distribution channels. Pun et al., (2021) analyze the blockchain effectiveness in preventing counterfeiting with and without subsidies from the government with a focus on counterfeit quality and consumer mistrust. Shen et al., (2022) looks at the effect of blockchain to limit counterfeiting with a focus on the price and quality of a company's product in the presence of an imitator. However, the fight against counterfeiting is profoundly different if the goods are completely virtual or physical-virtual. In the case of a virtual good, the only technology needed to combat counterfeiting is the blockchain where the dynamics of cost, efficiency, and quality have been studied (Shang et al., 2022; Tan, 2022).

However, when physical objects are the target of counterfeiting, chips that bridge the physical object and the digital world are needed (Ruzza et al., 2021). Chips allow information to be collected and recorded on the blockchain. Their poor quality or malfunctioning can undermine companies' anti-counterfeiting efforts. The literature ignores that the product to be preserved from counterfeiting needs to be equipped with chips that enable such certification. The chips are attached to the product and become an integral part of it. Thus, the quality of the product also depends on the quality of the chip. The papers that consider the quality issue with counterfeiting risk have conflicting opinions about quality. According to Cho et al. (2015) in the case of non-deceptive products, the company should increase the quality and reduce the price, regarding deceptive products, the company should reduce the quality and increase the price. Zhang et al. (2012) find that counterfeiting reduces the branded product price and profit but at the same time increases the quantity sold. Furthermore, counterfeiting creates the incentive to increase the quality of the branded product. If we had blockchain to the equation, Biswas et al., (2022) show that high customer sensitivity to quality encourages the use of blockchain. Other authors find that when blockchain is used against counterfeiting, product quality decreases because the blockchain itself becomes the signaling of quality (Shen et al., 2022). Price strategies are just as important as quality strategies and, in many cases, the two go together (Cho et al., 2015). Producers choose the price trying to limit counterfeiting, but the relationship is also backward as counterfeiting influences the price that the producers should charge (Zhang et al., 2012). Low price sensitivity encourages the parties to use blockchain (Biswas et al., 2022). With blockchain the price is linked to the number of experienced consumers, with few expert consumers blockchain can raise the price (Shen et al., 2022). None of the identified papers refer to the collectible industry and consider chip quality as a key element in combating counterfeiting. For this reason, the first research question is:

RQ1. How do firms in the collectible industry set their pricing, quality, and blockchain strategies to satisfy the market of digital-physical goods?

1.2.2 Wholesale price and total quality management with blockchain

The manufacturer is the company that creates the collectibles. It purchases the chips it needs from a supplier. The chips can meet the quality standard or be defective. Total quality management is a management philosophy with the goal of continuous improvement using the concept of quality from resource acquisition to after-sales service (Kaynak, 2003). However, strategies adopted to increase quality and limit defects such as process inspection and preventive maintenance can only limit the number of defects but cannot make the system perfect (Giri and Dohi, 2007). Lee and Rosenblatt, (1987), are among the first to investigate the effects of defects in imperfect production processes. The study simultaneously considers the problems of determining the optimal amount of production and scheduling inspections to limit defects. More recently, some studies have addressed the situation in which defects are detected before the product is transferred from the supplier to the manufacturer. Liu and Yang, (1996) consider a single-stage production system where production is imperfect and may have defects. The defects could be reworkable or nonreworkable. The authors identify the optimal lot size and develop an algorithm to calculate it to maximize the manufacturer's long-term profits in the presence of defects. Sonntag and Kiesmüller, (2018) build a model in which all defective products are identified before they are brought to market. In this case, the company has the option to rework them, sell them, or eliminate them. Ouyang and Chang, (2013) in addition to the defective products, consider the payment method and the possibility that payment will be delayed. Cunha et al., (2018) consider the possibility that defective products may not necessarily have to be discarded or reworked but, when the defects do not harm their main functions, they may be sold at a discounted price. The results show that the damaged products should be sold as soon as possible.

Other studies consider the possibility that the defects are detected once the product has already been sold to the manufacturer. In this case, image problems and damage to the manufacturer's profits could be created, and a reconciliation procedure between supplier and manufacturer aimed at compensating for the damage should be activated (Powell et al., 2022). Balachandran and Radhakrishnan, (2005) study a supply chain in which the buyer places penalties against the supplier for defective products. The penalty is implemented through a warranty/penalty contract. The penalty imposed can be at most equal to the damage suffered by the buyer. Lee and Li, (2018) suggest the use of inspections, investments, and incentives, and the possible combinations among them, to address the problem of the quality of components provided by suppliers. De

Giovanni, (2020) develops an optimal control model to demonstrate the damage to goodwill that nonconformance quality has. The model shows that failures and defects have a negative impact on goodwill, however, this can be limited through appraisal and prevention strategies.

Quality and compensation procedures are linked to the cooperation and coordination mechanism in a supply chain. The wholesale price contract is among the widest coordination mechanism studied in the literature. El Ouardighi and Kim, (2010) show that coordinated supply chains perform better in terms of quality than uncoordinated ones. The authors consider a wholesale price contract and a revenue-sharing contract. In the literature, the wholesale price contract suffers from the double marginalization problem that makes it less effective than other sharing-based contracts such as revenue-sharing contracts or profit-sharing contracts. The results show that the wholesale price contract is preferable for a duopolistic manufacturer, while the revenue-sharing contract is preferable for a monopolistic supplier. El Ouardighi, (2014) develops a two-stage non-cooperative game in which actors agree on a wholesale price contract or a revenue-sharing contract and collaborate to improve quality over time. The objective is to test whether the wholesale price contract or revenue-sharing contract provides the best performance in terms of pricing, quality, or payoff. The wholesale price contract achieves poor quality and high prices while the optimal revenue-sharing contract ensures cheap but high-quality products. Fan et al., (2017) in a two-echelon supply chain setting with a supplier and a retailer show that when the exchange is regulated with a wholesale price contract an increase in post-sale product liability increases the wholesale price but has no impact on the quality, quantity, and profitability of chain members. Chain members to have a positive impact on quality and profitability should cooperate on quality management.

From the literature reviewed, the wholesale price contract seems to be often ineffective to increase quality and limit defects. However, thanks to blockchain technology a new wholesale price contract called smart wholesale price contract can be designed (De Giovanni, 2020). In a smart wholesale price contract, the reconciliation procedure becomes unnecessary because the contract is based on a smart contract that allows the supplier to be paid automatically once the product quality is good enough. Our research shows no study that analyzes the potential of a smart wholesale price contract to coordinate a supply chain and achieve the minimum quality required. For this reason, the second research question is:

RQ2. Do blockchain-based smart wholesale price clauses align the firms' economic targets and total quality management goals?

1.2.3 Wholesale price and profit sharing with blockchain

Although wholesale price contact is among the most popular, it is not the only tool available for supply chain coordination. In the literature, we can identify some alternatives such as sharing contracts. Ryu and Yücesan, (2010) investigate the coordination problem in a supply chain where the manufacturer and retailer have divergent goals. The authors develop a fuzzy approach to the newsvendor problem where they consider three possible coordination methods: quantity discounts, profit sharing, and buyback. All three coordination methods bring benefits to the supply chain, however, profit sharing turns out to be the solution that brings the most benefits. Chen et al., (2012) examine the coordination mechanisms of a dual-channel supply chain with a retailer and a manufacturer's proprietary channel. The wholesale price contract coordinates the supply chain but benefits only the retailer. While a profit-sharing contract creates a win-win situation that benefits both the manufacturer and the retailer. Shen et al., (2016) look at the fashion industry and analyze coordination in a situation of original equipment manufacturing and original design manufacturing. The results show that if the relationship is managed with a wholesale price contract, the supplier has little incentive to innovate. A profit-sharing contract allows for coordination in both original equipment manufacturing and original design manufacturing. Ling et al., (2022) study the airline industry and the coordination mechanisms between an airline company and an online travel agency. The results show that sharing contracts perform better than wholesale price contracts. Among the sharing contracts, cost-sharing contract performs better than revenue-sharing and profit-sharing contract. Sun et al., (2022) investigate the use of digital showrooming with two strategies: the manufacturer owns a virtual channel but sells the product through a physical retailer; the manufacturer owns the physical channel and distributes the product through an online retailer. A wholesale price contract is effective for coordinating the former situation but is ineffective in the latter. In contrast, a new contract obtained by combining a quantity discount contract and a profit-sharing contract is effective in coordinating both strategies. All the papers analyzed show that sharing contracts are preferable to wholesale price contracts because they limit the problem of double marginalization.

The condition seems similar even when blockchain is introduced. Choi, (2020) analyze supply chain finance creates a standard newsvendor problem with a manufacturer and a retailer. The supply chain is financially supported by blockchain, and cryptocurrency has a lower level of risk and a higher level of profit than a traditional supply chain. The optimal contract to coordinate this supply chain turns out to be the revenue-sharing contract. De Giovanni, (2020) develops a supply chain game with a supplier and a retailer that can be managed through a conventional online platform or blockchain. The results show that the use of a blockchain-based smart wholesale price contract allows the supply chain to achieve a profit-Pareto-improving condition and is an incentive for the use of blockchain by the supplier. However, a smart revenue-sharing contract turns out to be a better solution than both a traditional supply chain based on an online platform and a smart wholesale price contract. Lu et al., (2022) study the use of blockchain to limit counterfeiting in an online platform open to both a supplier and a counterfeiter. When blockchain is used, the authors find that an agency contract performs better on counterfeit reducing than a wholesale price contract. Shi et al., (2022) consider the copycat problem in cross-border consumption and the use of blockchain as a countermeasure. The authors identify the optimal wholesale price with and without blockchain and show that the incentives to use blockchain are not always present. The contracts that have the best performance are the revenue-sharing, the two-part tariff, and the profit-sharing contracts. Fan et al., (2022) create a three-stage supply chain with a supplier, a manufacturer, and a retailer with two possible scenarios with and without blockchain. Blockchain is not convenient all the time but under certain conditions. The appropriate contract for blockchain coordination is the revenue-sharing contract, while the cost-sharing contract is ineffective. Li et al., (2022) explore the use of blockchain to limit information asymmetry in the luxury goods industry. In the model with one manufacturer and two retailers, luxury brands can choose between two types of distribution contracts: wholesale price contracts, and revenue-sharing contracts. When a revenue-sharing contract between chain members is identified, all members benefit from the collaboration. The third research question is:

RQ3. Should firms in the collectible industry prefer a blockchain based on profit-sharing clauses over a blockchain-based on wholesale price clauses?

Table of notations

Notations	Description
c_A	Quality investments efficiency
q_A	Investments in quality
c_u	Production cost
$u(t)$	Quantity to produce (production rate)
$\overline{u}$	Optimal production rate
$Q(t)$	Percentage of defect-free goods
ω	Wholesale price
c_S	Procurement cost
δ	Decay rate (natural decrease of quality)
θ	Contribution of investments in quality to defect free goods
k	Decay rate of inventory
X_1	Inventory
g	Substitute chips
α_B	Market potential for t-shirts with Blockchain
α_N	Market potential for t-shirt without blockchain
β_N	Consumers' sensitivity to price of normal t-shirts
cB	Blockchain investments efficiency
cX	Inventory cost
c_N	Marginal production cost of normal t-shirts
p_N	Selling price of normal t-shirts
η	selling price of t-shirts with blockchain
c_F	Marginal production cost of t-shirts with blockchain

1.3 A dynamic game with Blockchain

This paper models a dynamic in the collectible industry, with a specific focus on the collection of original t-shirts dressed by football players. All notations used to describe the dynamic game are listed and described in Table 1. A football club, given by firm F, uses the blockchain technology to prove that the collectibles are original. Within this sector, the presence of fake and counterfeiting goods has forced firms to adopt ad hoc solutions to avoid such issues. Within the possible options, the blockchain technology is emerging as a valid option to face this problem. Hence, F invests in blockchain technology to implement a system as described in Figure 1; this business model can work only when some chips can be installed inside the t-shirt before the players enter in the groundfield; therefore, player G is responsible to manage the quality of chips, specifically, to be sure that no chip is defective. In fact, when the chips are defective, the whole blockchain model cannot be activated by the IoT systems when the players enter the groundfield and start playing. According to the literature on dynamic models and games, the conformance quality for chips can be modeled as a state variable (see De Giovanni and Zaccour (2022) for a recent survey on this subject), which evolves according to the following motion:

$$\dot{Q}(t) = \theta q_A(t) - \delta Q(t) \tag{1}$$

with $Q \in 0,1]$ and representing the percentage of conform chips that G delivers. When $Q(t) = 0$, all supplied goods are defective and the blockchain will never be activated; in contrast, $Q(t) = 1$ signifies that all supplied chips are conform and the whole business model can be digitalized. To provide the highest possible conformance rate, G invests in quality (e.g., appraisal and prevention), $q(t)$, to acquire the capability $Q(t)$ to make conform goods and according to the scaling parameter, $\theta > 0$. These investments allow the chips to be confom to the standards as well as to prevent the chips for any possible damage, transportation issue, and usage accident (De Giovanni, 2019). However, the production system is subject to a systematic variation of quality, δ, given by maintenance of machines, decreasing performance of operators due to tiring jobs, or eccessive use of machines leading to increasing temperatures and, consequently, underperforming systems (see De Giovanni (2021) for complete overview of such cases liked to systematic variability of production processes). Furthermore, the production facilities are subject to specific causes of variability, which generate defective goods. These require ad hoc investments, namely, investments for failures, since they are costs including both operational failures and market downs (Fine, 1989). Therefore, the causes of specific and systematic system variability lead to a decrease of conformance quality, which is restored by G by investing in $q(t)$.

Along with quality strategies, G also sets the production strategy and decides the production rate, $u(t)$, according to the marginal production costs, c_S, as well as the overall efforts and inputs needed to run the production. The system works with a benchmark, $\overline{u}$, that is an optimal production system setup: any time the optimal production policy deviates from it, G's production is inefficient. The production rate $u(t)$ will feek the stock of chips kept by the football club F, whose motion is studied using the Jorgensen (1987) inventory dynamics while adopting a vendor managed inventory system (De Giovanni et al., 2018). Accordingly, the inventory dynamics take the form:

$$\dot{X}(t) = u(t) - (1+g)D_B(t) - D_N(t) - kX(t) \tag{2}$$

in which $D_B(t)$ is the demand of goods digitalized the blockchain technology, namely, digital goods, while $D_N(t)$ is amount of t-shirt not covered by blockchain, namely, non-digital goods. Indeed, when the chips are conform and the blockchain is activated, the t-shirts become digitalized goods and can be sold in market D_B; in contrast, when the chips are defective, the t-shirts remain non-digitalized and can be sold in a traditional channel since consumers cannot trust and verify the set of information guaranteed by the blockchain technology. Interestingly, when the IoT detect a failing chip in time, this can be substituted either before or during a match and allow the blockchain to remain active and capture even partial information (e.g., only a portion of the entire game). This case is modeled through the parameter g, which represents the higher number of cases due to chips to be substituted. Finally, being physical goods, the chips can be subject to technological obsolescence, damages linked to improper storage, or shocks during the transportation. All these cases imply that the stock of chips available at F's place decreases according to the decay rate δ.

According to the described framework, we model two demand functions, one for digital goods, named B-goods, and one for non-digital goods, named N-goods, with the former being the t-shirt whose chips registered all information on the players and the games by blockchain and the latter being the t-shirts whose chip was not working and for which no information has been registered in the blockchain. Then, the demand functions take the following forms:

$$D_B(t) = \alpha_B Q(t) \tag{3}$$

$$D_N(t) = (\alpha_N - \beta_N p_N)[1 - Q(t)] \tag{4}$$

According to Eq. (3), $\alpha_B Q(t)$ is number of consumers who are potentially interested in purchasing collectibles that are covered by blockchain, when the blockchain system works, e.g., when the chips are conform. Notice that the demand for digital goods does not include any consumers' sensitivity to price since F sells the verified t-shirt on a platform originating a biding among consumers. For example, in the Genuino platform the initial price of a match worn blockchain certified jersey is set by the company at a higher price that the price of traditional worn jersey, which are priced 125 in average in a store. Once the bid start, the costumer knowing that the jersey is match worn and has a special value for collectors, and reling on blockchain to certify its originality push the price up to 7.000 . The bid is managed by the Genuino marketplace and once the bitd is over the winner will have in his wallet the NFT that rapresent the certificate of ownership of the t-shirt, the firm sets the initial price of 299euro for the t-shirt of a soccer player and starts the bid among consumers; knowing that the t-shirt is verified through blockchain, collectors bid for the t-shirt, which can also be sold for 1.600euro. Therefore, the collectors are not sensitive to price in the traditional way the traditional literature has investigated the links between sales and price. Rather, the consumers (collectors in this case) are attracted by the uniqueness and originality of the t-shirt, whose information are verified through the blockchain; the capacity that the blockchain system has to capture and record information depends on the F's investments, $B(t)$, in such technology.

In contrast, the presence of defective chips forces F to sell the non-verified goods through an original e-commerce platform. Hereby, the effects of blockchain are completely lost while consumers purchase only according to the selling price, $p_N(t)$. Therefore, differently from the models presented in the literature of conformance quality, having defective component (e.g., chips) does not imply that products are defective. Rather, their intrinsic value is lower than the digital goods since no information is verified and recorded on the blockchain.

Considering the described framework, we use from now on the superscript $\mathcal{W}$ to indicate the usage of a smart wholesale price mechanism; accordingly, the players' profit functions in the $\mathcal{W}$ −game are given by:

$$J_G^{\mathcal{W}} = \max_{u^{\mathcal{W}}(t), q^{\mathcal{W}}(t)} \int_0^{+\infty} e^{-rt} \left\{ [\omega Q^{\mathcal{W}}(t) - c_S] u^{\mathcal{W}}(t) - c_U \frac{(u^{\mathcal{W}}(t) - \overline{u})^2}{2} - c_A \frac{[q^{\mathcal{W}}(t)]^2}{2} \right\} dt$$

(5)

$$J_F^{\mathcal{W}} = \max_{B^{\mathcal{W}}(t)} \int_0^{+\infty} e^{-rt}\{D_B^{\mathcal{W}}(t)(\eta B^{\mathcal{W}}(t) - c_F) + D_N^{\mathcal{W}}(t)\left(p_N^{\mathcal{W}} - c_N\right) -$$

$$\omega Q^{\mathcal{W}}(t)u^{\mathcal{W}}(t) - c_B \frac{\left[B^{\mathcal{W}}(t)\right]^2}{2} \tag{6}$$

$$-c_X \frac{\left[X^{\mathcal{W}}(t)\right]^2}{2}\}dt \tag{7}$$

subject to Eqs. (1)-(2).

The game is played á la Nash, implying that the players simultaneously select their strategies, specifically, F sets the optimal blockchain investments, $B^{\mathcal{W}}(t)$, and G sets the optimal production rate, $u^{\mathcal{W}}(t)$, and quality investments, $q^{\mathcal{W}}(t)$. These strategies do appear both in the integrand as well as in one of the state variables. The solution to the problem yields the equilibrium feedback strategies $B^{\mathcal{W}*}(Q^{\mathcal{W}}, X^{\mathcal{W}})$, $u^{\mathcal{W}*}(Q^{\mathcal{W}}, X^{\mathcal{W}})$, and $q^{\mathcal{W}*}(Q^{\mathcal{W}}, X^{\mathcal{W}})$, which constitute a feedback Nash equilibrium, which is time consistent. Using these strategies in Eqs. (1)-(2), we will get the inventory $X^{\mathcal{W}*}(t)$, $t \geq 0$, and the conformance quality rate $Q^{\mathcal{W}*}(t)$, $t \geq 0$, with the related decisions $B^{\mathcal{W}*}(Q^{\mathcal{W}*}, X^{\mathcal{W}*})$, $u^{\mathcal{W}*}(Q^{\mathcal{W}*}, X^{\mathcal{W}*})$, and $q^{\mathcal{W}*}(Q^{\mathcal{W}*}, X^{\mathcal{W}*})$.

1.3.1 Optimal solution to the $\mathcal{W}$ −game

In this section, we optimally solve the game we earlier described. We focus on the analysis of the feedback solutions since the optimal decisions will depend on the two state variables given by the conformance quality, $Q^{\mathcal{W}}(t)$, and the inventory, $X^{\mathcal{W}}(t)$. Because the game is played in an infinite time horizon with time-independent parameters, the equilibrium will be stationary since the feedback strategies will not explicitly depend on time t. Therefore, all the results that we display below are analyses at the steady-state. The next proposition characterizes the solution for our game.

Proposition 1 *Let us denote by $V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ and $V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ the players' value funtions. The optimal strategies in the $\mathcal{W}$ −game are given by:*

$$u^{\mathcal{W}*} = \frac{c_U\bar{u} + Q^{\mathcal{W}}\omega - c_S}{c_U} \tag{8}$$

$$q^{\mathcal{W}*} = \frac{\theta\left(S_2^{\mathcal{W}} + 2S_4^{\mathcal{W}}Q^{\mathcal{W}}\right)}{c_A} \tag{9}$$

$$B^{\mathcal{W}*} = \frac{\alpha_B \eta Q^{\mathcal{W}}}{c_B} \tag{10}$$

where $S_2^{\mathcal{W}}$ and $S_4^{\mathcal{W}}$are the coefficients of the conjectured value functions:

$$V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) = S_1^{\mathcal{W}} + S_2^{\mathcal{W}}Q^{\mathcal{W}} + S_3^{\mathcal{W}}X^{\mathcal{W}} + S_4^{\mathcal{W}}Q^{\mathcal{W}^2} \tag{11}$$

$$V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) = F_1^{\mathcal{W}} + F_2^{\mathcal{W}}Q^{\mathcal{W}} + F_3^{\mathcal{W}}X^{\mathcal{W}} + F_4^{\mathcal{W}}Q^{\mathcal{W}^2} + F_5^{\mathcal{W}}X^{\mathcal{W}^2} + F_6^{\mathcal{W}}Q^{\mathcal{W}}X^{\mathcal{W}}$$

Proof. See Appendix A.

According to Eqs. (8)-(10), the optimal strategies depend on the sign of the coefficients of the Riccati equations, specifically. However, since the identified parameters are coupled and linked to each other in a very complex way (see Appendix A), their analysis and interpretation must be supported by a numerical optimization. We start such an analysis by solving the set of Riccati equations linked to the problem. Hence, we search for feasible solutions, that is, solution ensuring positive strategies and payoffs as well as positive inventory and conformance quality such that $Q^{\mathcal{W}} \in [0,1]$. To run a numerical optimization, we fix the parameter values $c_A = 2.5$, $c_U = 1$, $c_B = 0.1$, $c_F = 0.1$, $c_X = 1$, $\overline{u} = 1.5$, $c_S = 0.05$, $\omega = 0.3$, $p_N = 0.75$, $c_N = 0.03$, $\alpha_N = 1$, $b_N = 0.1$, $\eta = 0.1$, $\alpha_B = 1.5$, $g = 0.01$, $\delta = 0.3$, $\theta = 0.3$, $k = 1$, and $r = 0.1$. Accordingly, we obtain various solutions, among which only two are finite and are given by:

• Solution I: $G_1^{\mathcal{W}} = 1.73577, G_2^{\mathcal{W}} = -1.58863, G_3^{\mathcal{W}} 0, G_4^{\mathcal{W}} = 1.71893, F_1^{\mathcal{W}} = 11.1154,$ $F_2^{\mathcal{W}} = -1.90485, F_3^{\mathcal{W}} = -0.281102, F_4^{\mathcal{W}} = -2.5552, F_5^{\mathcal{W}} = -0.238095, F_6^{\mathcal{W}} = -0.238095.$

• Solution II $G_1^{\mathcal{W}} = 0.58952, G_2^{\mathcal{W}} = 1.16366, G_3^{\mathcal{W}} = 0, G_4^{\mathcal{W}} = 0.0667833, F_1^{\mathcal{W}} =$ $5.85392,\ F_2^{\mathcal{W}} = 0.121748, F_3^{\mathcal{W}} = -0.206431, F_4^{\mathcal{W}} = 2.59534, F_5^{\mathcal{W}} = -0.238095, F_6^{\mathcal{W}} =$ $0.100519.$

While Solution I gives non-feasible solutions, Solution II is a good candidate to provide a feasible solution since all positivity assumptions and conditions are met, along with $Q \in [0,1]$. Specifically, it leads to $Q^{\mathcal{W}} = 0.832943$, $X^{\mathcal{W}} = 0.283447$, $u^{\mathcal{W}} = 1.69988$, $q^{\mathcal{W}} = 0.356975$, $B^{\mathcal{W}} = 4.99766$, $D_B^{\mathcal{W}} = 1.24941$, $D_N^{\mathcal{W}} = 0.154528$, $V_G^{\mathcal{W}} = 16.0511$, and $V_F^{\mathcal{W}} = 77.0204$. To show the robustness of this solution, we report a simulation analysis in Appendix C to show that the optimal solution remains feasible even when modifying the various parameter values. Therefore, we will refer to Solution II such as $G_1^{\mathcal{W}*} > 0$, $G_2^{\mathcal{W}*} > 0$, $G_3^{\mathcal{W}*} = 0$, $G_4^{\mathcal{W}*} > 0$, $F_1^{\mathcal{W}*} > 0$, $F_2^{\mathcal{W}*} > 0$, $F_3^{\mathcal{W}*} < 0$, $F_4^{\mathcal{W}*} > 0$, $F_5^{\mathcal{W}*} < 0$, $F_6^{\mathcal{W}*} > 0$.

According to the numerical optimization, the strategies displayed in Eqs. (8)-(10) are all independent of $X^{\mathcal{W}}$ while they are all dependent of $Q^{\mathcal{W}}$. Therefore, both firms should set their optimal production rate, the quality efforts and the blockchain investments independent of the inventory level. This suggests that, within the framework of the collectibles, the firms' strategies should disregard the issues linked to inventory management, since the related costs can be somehow managed between firms. Rather, firms should concentrate on their capacity to manage defect-free goods, exemplified by $Q^{\mathcal{W}}$, since consumers will benefit from the value proposition (purchasing original t-shirts verified by blockchain) only when the goods align with the consumers' expectations, given by chips and IoT systems that recorded all information on the soccer players on the blockchain and can lead to trustworthy collectibles.

Regarding the production rate, it turns out that $\frac{\partial u^{W}}{\partial Q^{W}} = \frac{\omega}{c_U} > 0$; consequently, increasing levels of conformance quality induce G to make and sell more goods to F. In fact, Q^{W} represents the G's capacity to make free-defect chips and, consequently, she has motivations to contribute to the business model by producing more only when having a high capacity to make conform goods. In all cases in which the production output consists of defected items, the production process should be stopped and the production planning revised. Similarly, blockchain investments depend on the G's capacity to make conform chips, through which the blockchain can be activated, e.g., $\frac{\partial B^{W}}{\partial Q^{W}} = \frac{\alpha_B \eta}{c_B} > 0$. In fact, F will not invest in complex and expensive blockchain systems if the chips will be defected or can be easily damaged during a game. Such unfortunate conditions will deter the chips to share information with the hardware oracles and the IoT technology and transfer them to the blockchain system for the recording on the platform. Finally, the appraisal and prevention efforts are independent of the S's capacity to make conform goods; rather, G is called to target $Q = 1$ (100% of chips are defect-free) and balance the quality efforts according to the systematic process variation given by θ, which leads to underperforming batches of chips.

Regarding the value functions reported in Proposition a, note that V_G^{W} can be written as $V_G^{W}(Q^{W}, X^{W}) = S_1^{W} + S_2^{W} Q^{W} + S_4^{W} Q^{W^2}$ since $S_3^{W} = 0$. This implies that the supplier's optimal profits solely depend on the conformace quality. Accordingly, a separation exists between the supplier's performance on conformance quality and the inventory management. In fact, while the excess of inventory generate inefficiencies that can be handled internally and, above all, without losing customers, conformance quality is vital for activating the digital business model, e.g., $\lim_{Q \to 1} D_B^{W} = \alpha_B$ and, consequently, $\lim_{Q \to 1} D_N^{W} = 0$. This trade-off should make firms reflect on the existence of both new and digital markets and rationalize their portfolio of goods accordingly. Differently, the football club's profits depend not only on both dynamics, but also on their interations, which are then addressed in the following proposition by deriving their values at the steady-state (SS).

Proposition 2 *The conformance quality and the inventory at the steady-state are given by:*

$$Q_{SS}^{W} = \frac{\theta^2 S_2^{W}}{\delta c_A - 2\theta^2 S_4^{W}} \quad (12)$$

$$X_{SS}^{W} = \frac{1}{k}\left[\frac{c_U(\overline{u} - \alpha_N + \beta_N p_N) - c_S}{c_U} + Q^{W}\left(\frac{\omega}{c_U} - (1+g)\frac{\alpha_B^2 \eta}{c_B} Q^{W} + (\alpha_N - \beta_N p_N)\right)\right] \quad (13)$$

Proof. A sufficient condition guaranteeing that the expressions in strategies and value functions are players' value functions and strategies is given by:

$$\lim_{t \to \infty} e^{-rt} V_G^{W}(Q^{W}(t), X^{W}(t)) = 0 \text{and} \lim_{t \to \infty} e^{-rt} V_F^{W}(Q^{W}(t), X^{W}(t)) = 0$$

where $(Q^{W}(t), X^{W}(t))$ is the solution of the dynamic system obtained after substituting the strategies inside the state variables. The solution to the system can be written as:

$$X^{\mathcal{W}}(t) = \Delta_1^{X^{\mathcal{W}}} e^{\lambda_1 t} + \Delta_2^{X^{\mathcal{W}}} e^{\lambda_2 t} + X_{SS}^{\mathcal{W}}$$

$$Q^{\mathcal{W}}(t) = \Delta_1^{Q^{\mathcal{W}}} e^{\lambda_1 t} + \Delta_2^{Q^{\mathcal{W}}} e^{\lambda_2 t} + Q_{SS}^{\mathcal{W}}$$

where Δ_1^i, Δ_2^i, with $i = X^{\mathcal{W}}, Q^{\mathcal{W}}$ are constants, $X_{SS}^{\mathcal{W}}$ and $Q_{SS}^{\mathcal{W}}$ are the steady-state values, and λ_j, with $j = 1,2$ are the real eigenvalues of the matrix associated to the system of linear differential equations. The steady-state trajectories make it possible to determine the paths for the strategies, the demand, and the profits. Considering that the functional specifications are quadratic, all sufficient optimality conditions are satisfied when proper bounds are identified. Accordingly, we compute the eigenvalues of the matrix associated to the closed-loop system as:

$$\lambda_1 = \frac{1}{2}\left[\Lambda_2 - \Lambda_3 Q + \sqrt{(\Lambda_2 - \Lambda_3 Q)^2 + 4\Lambda_1 k}\right], \lambda_2 = \frac{1}{2}\left[\Lambda_2 - \Lambda_3 Q - \sqrt{(\Lambda_2 - \Lambda_3 Q)^2 + 4\Lambda_1 k}\right]$$

with $\Lambda_1 = \delta c_A - 2\theta^2 S_4^{\mathcal{W}} > 0$, $\Lambda_2 = \frac{\omega}{c_U} + \alpha_N - \beta_N p_N > 0$ and $\Lambda_3 = 2(1+g)\frac{\alpha_B^2 \eta}{c_B} > 0$. Accordingly, $Q \in \left(\frac{\Lambda_2\Lambda_3 - 2\sqrt{\Lambda_1 \Lambda_3^2 k}}{\Lambda_3^2}, \frac{\Lambda_2\Lambda_3 + 2\sqrt{\Lambda_1 \Lambda_3^2 k}}{\Lambda_3^2}\right)$.It is straightforward to see that one eigenvalue is negative while the other one is positive. Under this assumption, the steady state is a saddle point. The initial conditions on the goodwill lying on the stable subspace associated to the negative eigenvalue allow the system to converge to the steady state as time approaches infinity. □

Proposition 3 *The the demand for both digital and non-digital goods are given by:*

$$D_{B_{SS}}^{\mathcal{W}} = \frac{\alpha_B^2 \eta}{c_B} Q^{\mathcal{W}^2} = \frac{\alpha_B^2 \eta}{c_B}\left(\frac{\theta^2 S_2^{\mathcal{W}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{W}}}\right)^2 \tag{14}$$

$$D_{N_{SS}}^{\mathcal{W}} = (\alpha_N - \beta_N p_N)(1 - Q^{\mathcal{W}}) = \frac{(\alpha_N - \beta_N p_N)(\theta^2 S_2^{\mathcal{W}} - \delta c_A + 2\theta^2 S_4^{\mathcal{W}})}{\delta c_A - 2\theta^2 S_4^{\mathcal{W}}} \tag{15}$$

Proof. Substitute Eq. (12) Eqs. (3)-(4)) to get Eqs. (14)-(15). □

Considering that $Q^{\mathcal{W}} \in (0,1]$, both the demand for digital and non-digital goods, $D_{B_{SS}}^{\mathcal{W}}$ and $D_{N_{SS}}^{\mathcal{W}}$, are always positive. Interestingly, $D_B^{\mathcal{W}}$ increases in a quadratic way with respect to $Q^{\mathcal{W}}$, implying that $\frac{\partial D_B^{\mathcal{W}}}{\partial Q^{\mathcal{W}}} = \frac{2\alpha_B^2 \eta}{c_B} Q^{\mathcal{W}} > 0$ and $\frac{\partial^2 D_B^{\mathcal{W}}}{\partial Q^{\mathcal{W}^2}} = \frac{2\alpha_B^2 \eta}{c_B} > 0$; also, considering that $Q^{\mathcal{W}} \leq 1$, a marginal increase of conformance quality leads to small increase $D_B^{\mathcal{W}}$. In contrast, increasing levels of conformance quality lead to linear reduction in the sales for non-digital goods, resulting $\frac{\partial D_N^{\mathcal{W}}}{\partial Q^{\mathcal{W}}} = -(\alpha_N - \beta_N p_N) < 0$ and $\frac{\partial^2 D_N^{\mathcal{W}}}{\partial Q^{\mathcal{W}^2}} = 0$. Accordingly, aiming a total quality management turns out to be a real chance to continuosly increase sales by developing the market of digital goods. Finally, the optimal solution ensures that $X^{\mathcal{W}} > 0$ along with $\frac{\partial X^{\mathcal{W}}}{\partial Q^{\mathcal{W}}} =$

$\frac{1}{k}\left[\frac{\omega+c_U(\alpha_N-\beta_N p_N)}{c_U}-\frac{2(1+g)\alpha_B^2\eta}{c_B}Q^{\mathcal{W}}\right]\gtreqless 0 \Leftrightarrow Q^{\mathcal{W}}\lesseqgtr\frac{c_B[\omega+c_U(\alpha_N-\beta_N p_N)]}{2c_U(1+g)\alpha_B^2\eta}$ and $\frac{\partial^2 X^{\mathcal{W}}}{\partial Q^{\mathcal{W}2}}=-\frac{2(1+g)\alpha_B^2\eta}{kc_B}<0.$
Therefore, low conformance quality can bring inventory to increase depending on the sales in the non-digital market while high conformance quality leads to decreasing levels of inventory due to high sales in the digital market.

1. 4 A Dynamic game with Blockchain and smart profit sharing mechanism

This section introduces a variant of the previous $\mathcal{W}$-model in which the blockchain activates a smart profit sharing contract; therefore, we name it $\mathcal{P}$-model. Accordingly, F creates a smart contract that manages the financial transactions not only through a traditional wholesale parameter but also through a smart profit sharing clause. Specifically, the blockchain enables G to grant a reward that links to the F's marginal profits from selling digital goods, given by $\eta B(t)-c_F$. The blockchain acts through the smart clause $\phi\in(0,1)$: when $\phi\sim 0$ (~ 1), G receives a low (high) share of the F's profits. This smart clause fully depends on the G's performance exemplified by the conformance quality Q. Therefore, the blockchain can act on both the wholesale price as well as the profit sharing mechanism to engage G in pursuing a total quality management approach. Accordingly, the firms' profit functions modifiy as follows:

$$J_G^{\mathcal{P}}=\max_{u^{\mathcal{P}}(t),q_A^{\mathcal{P}}(t)}\int_0^{+\infty}e^{-rt}\{[\omega Q^{\mathcal{P}}(t)-c_S]u^{\mathcal{P}}(t)+\phi D_B^{\mathcal{P}}(t)(\eta B^{\mathcal{P}}(t)-c_F)-c_U\frac{\left(u^{\mathcal{P}}(t)-\overline{u}\right)^2}{2}-c_A\frac{\left[q^{\mathcal{P}}(t)\right]^2}{2}\}dt \tag{16}$$

$$J_F^{\mathcal{P}}=\max_{B^{\mathcal{P}}(t)}\int_0^{+\infty}e^{-rt}\{(1-\phi)D_B^{\mathcal{P}}(t)(\eta B^{\mathcal{P}}(t)-c_F)+D_N^{\mathcal{P}}(t)(p_N-c_N)-\omega Q^{\mathcal{P}}(t)u^{\mathcal{P}}(t)-c_B\frac{\left[B^{\mathcal{P}}(t)\right]^2}{2}-c_X\frac{\left[X^{\mathcal{P}}(t)\right]^2}{2}\}dt \tag{17}$$

subject to Eqs. (1)-(2).

The $\mathcal{P}$-game is also played á la Nash; consequently, F sets the optimal blockchain investments, $B(t)$, while sharing a portion of his profits to S, who sets the optimal production rate, $u(t)$, and quality investments, $q(t)$. The solution to the problem yields the equilibrium feedback strategies $B^{\mathcal{P}*}(Q^{\mathcal{P}},X^{\mathcal{P}})$, $u^{\mathcal{P}*}(Q^{\mathcal{P}},X^{\mathcal{P}})$, and $q^{\mathcal{P}*}(Q^{\mathcal{P}},X^{\mathcal{P}})$, which constitute a time consistent feedback Nash equilibrium. Using these strategies in Eqs. (1)-(2), we will get the inventory $X^{\mathcal{P}*}(t)$, $t\geq 0$, and the conformance quality rate $Q^{\mathcal{P}*}(t)$, $t\geq 0$, with the related decisions $B^{\mathcal{P}*}(Q^{\mathcal{P}*},X^{\mathcal{P}*})$, $u^{\mathcal{P}*}(Q^{\mathcal{P}*},X^{\mathcal{P}*})$, and $q^{\mathcal{P}*}(Q^{\mathcal{P}*},X^{\mathcal{P}*})$.

1.4.1 Optimal solution to the $\mathcal{P}$ −game

To optimally solve the $\mathcal{P}$ −game, we use the same procedure employed when solving the $\mathcal{W}$ −game. That is, we focus on feedback solutions since the optimal strategies depend on the two state variables $Q(t)$ and $X(t)$ wihle the equilibrium results stationary since the feedback strategies do no explicitly depend on time t. The next proposition characterizes the solution for the $\mathcal{P}$ −game.

Proposition 4 *Let us denote by $V_G^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}})$ and $V_F^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}})$ the players' value funtions. The optimal strategies in the $\mathcal{P}$ −game are given by::*

$$u^{\mathcal{P}*} = \frac{c_U\bar{u} + Q^{\mathcal{P}}\omega - c_S}{c_U} \tag{18}$$

$$q^{\mathcal{P}*} = \frac{\theta\left(S_2^{\mathcal{P}} + 2S_4^{\mathcal{P}}Q^{\mathcal{P}}\right)}{c_A} \tag{19}$$

$$B^{\mathcal{P}*} = \frac{\alpha_B\eta Q^{\mathcal{P}}(1-\phi)}{c_B} \tag{20}$$

where $S_2^{\mathcal{P}}$ and $S_4^{\mathcal{P}}$ are the coefficients of the conjectured value functions:

$$V_S^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}}) = S_1^{\mathcal{P}} + S_2^{\mathcal{P}}Q^{\mathcal{P}} + S_3^{\mathcal{P}}X^{\mathcal{P}} + S_4^{\mathcal{P}}Q^{\mathcal{P}^2} \tag{21}$$

$$V_F^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}}) = F_1^{\mathcal{P}} + F_2^{\mathcal{P}}Q^{\mathcal{P}} + F_3^{\mathcal{P}}X^{\mathcal{P}} + F_4^{\mathcal{P}}Q^{\mathcal{P}^2} + F_5^{\mathcal{P}}X^{\mathcal{P}^2} + F_6^{\mathcal{P}}Q^{\mathcal{P}}X^{\mathcal{P}} \tag{22}$$

Proof. See Appendix B. ☐

According to Eqs. (18)-(20), the optimal strategies depend on the sign of the coefficients of the Riccati equations. However, as for the $\mathcal{W}$ −game, the identified parameters are highly coupled and interconnected (see Appendix B); therefore, their analysis and interpretation must be supported by numerical optimization. We followed the same procedure explained for the solution of the $\mathcal{W}$ −game as well as the same parameter values. Furthermore, we include the parameter $\phi = 0.01$ as resulting from the $\mathcal{P}$ −game. According to the various solutions we obtain, two of them are finite and are given by:

- Solution I: $G_1^{\mathcal{P}} = 2.17458$, $G_2^{\mathcal{P}} = -1.72381$, $G_3^{\mathcal{P}} = 0$, $G_4^{\mathcal{P}} = 1.66193$, $F_1^{\mathcal{P}} = 15.1919$, $F_2^{\mathcal{P}} = -2.96642$, $F_3^{\mathcal{P}} = -0.283939$, $F_4^{\mathcal{P}} = -2.68789$, $F_5^{\mathcal{P}} = -0.238095$, $F_6^{\mathcal{P}} = 0.184491$.

- Solution II $G_1^{\mathcal{P}} = 0.753259$, $G_2^{\mathcal{P}} = 1.23336$, $G_3^{\mathcal{P}} = 0$, $G_4^{\mathcal{P}} = 0.12378$, $F_1^{\mathcal{P}} = 6.83795$, $F_2^{\mathcal{P}} = 0.518426$, $F_3^{\mathcal{P}} = -0.204817$, $F_4^{\mathcal{P}} = 2.72747$, $F_5^{\mathcal{P}} = -0.238095$, $F_6^{\mathcal{P}} = 0.102181$.

While Solution I gives non-feasible outcomes, Solution II is a good candidate to provide a feasible solution since all positivity assumptions and conditions are met, along with $Q^{\mathcal{P}} \in [0,1]$. Precisely, solution II gives $Q^{\mathcal{P}} = 0.961272$, $X^{\mathcal{P}} = 0.246231$, $u^{\mathcal{P}} = 1.73838$, $q_A^{\mathcal{P}} = 0.411974$, $B^{\mathcal{P}} = 5.70996$, $D_B^{\mathcal{P}} = 1.44191$, $D_N^{\mathcal{P}} = 0.038233$, $V_S^{\mathcal{P}} = 20.5323$, and $V_F^{\mathcal{P}} = 98.1592$. To show the robustness of this solution, we report a simulation analysis in Appendix C to show that the optimal solution remains feasible even when modifying the various parameter values. Therefore, we will refer to Solution II such as $G_1^{\mathcal{P}*} > 0$, $G_2^{\mathcal{P}*} > 0$, $G_3^{\mathcal{P}*} = 0$, $G_4^{\mathcal{P}*} > 0$, $F_1^{\mathcal{P}*} > 0$, $F_2^{\mathcal{P}*} > 0$, $F_3^{\mathcal{P}*} < 0$, $F_4^{\mathcal{P}*} > 0$, $F_5^{\mathcal{P}*} < 0$, $F_6^{\mathcal{P}*} > 0$.

According to Proposition ???, we observe that the structure of the G's strategies is the same of the $\mathcal{W}$ −game, indicating that G does not modify the quality of his behaviors when F proposes a smart profit sharing contract. However, our optimization results demonstrate that the value of the state variables as well as the values of the Riccati's coefficients change considerably when shifting from a smart wholesale price mechanism to a smart profit sharing mechanism. The role of ϕ is analyzed afterwards in Section 4, when comparing the $\mathcal{W}$ −game and the $\mathcal{P}$ −game. Note that, the same applies for both the state variables, , as well as both market sales, , whose result from the $\mathcal{P}$ −game are summarized in the following proposition.

Proposition 5 *The conformance quality and the inventory at the steady-state in the $\mathcal{P}$ −game are given by:*

$$Q_{SS}^{\mathcal{P}} = \frac{\theta^2 S_2^{\mathcal{P}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{P}}} \tag{23}$$

$$X_{SS}^{\mathcal{P}} = \frac{1}{k}\left[\frac{c_U(\overline{u} - \alpha_N + \beta_N p_N) - c_S}{c_U} + Q^{\mathcal{P}}\left(\frac{\omega}{c_U} - (1+g)\frac{\alpha_B^2 \eta (1-\phi)}{c_B} Q^{\mathcal{P}} + (\alpha_N - \beta_N p_N)\right)\right] \tag{24}$$

Proof. A sufficient condition guaranteeing that the expressions in strategies and value functions are players' value functions and strategies is given by:

$$\lim_{t\to\infty} e^{-rt} V_G^{\mathcal{P}}(Q^{\mathcal{P}}(t), X^{\mathcal{P}}(t)) = 0 \text{and} \lim_{t\to\infty} e^{-rt} V_F^{\mathcal{P}}(Q^{\mathcal{P}}(t), X^{\mathcal{P}}(t)) = 0$$

where $(Q^{\mathcal{P}}(t), X^{\mathcal{P}}(t))$ is the solution of the dynamic system obtained after substituting the strategies inside the state variables. The solution to the system can be written as:

$$X^{\mathcal{P}}(t) = \Sigma_1^{X^{\mathcal{P}}} e^{\mu_1 t} + \Sigma_2^{X^{\mathcal{P}}} e^{\mu_2 t} + X_{SS}^{\mathcal{P}}$$

$$Q^{\mathcal{P}}(t) = \Sigma_1^{Q^{\mathcal{P}}} e^{\mu_1 t} + \Sigma_2^{Q^{\mathcal{P}}} e^{\mu_2 t} + Q_{SS}^{\mathcal{P}}$$

where Σ_1^i, Σ_2^i, with $i = X^{\mathcal{P}}, Q^{\mathcal{P}}$ are constants, $X_{SS}^{\mathcal{P}}$ and $Q_{SS}^{\mathcal{P}}$ are the steady-state values, and μ_j, with $j = 1,2$ are the real eigenvalues of the matrix associated to the system of linear differential equations. The steady-state trajectories make it possible to determine the paths for the strategies, the demand, and the profits. As for the $\mathcal{W}$-game, the functional are quadratic and all sufficient optimality conditions are satisfied since proper bounds can be identified. Accordingly, we compute the eigenvalues of the matrix associated to the closed-loop system as:

$$\mu_1 = \frac{1}{2}\left[\Lambda_2 - \Lambda_4 Q + \sqrt{(\Lambda_2 - \Lambda_4 Q)^2 + 4\Lambda_1 k}\right], \mu_2 = \frac{1}{2}\left[\Lambda_2 - \Lambda_4 Q - \sqrt{(\Lambda_2 - \Lambda_4 Q)^2 + 4\Lambda_1 k}\right]$$

with $\Lambda_1 = \delta c_A - 2\theta^2 S_4^{\mathcal{P}} > 0$, $\Lambda_2 = \frac{\omega}{c_U} + \alpha_N - \beta_N p_N > 0$ and $\Lambda_4 = 2(1+g)\frac{\alpha_B^2 \eta(1-\phi)}{c_B} > 0$.

Accordingly, $Q^{\mathcal{P}} \in \left(\frac{\Lambda_2\Lambda_4 - 2\sqrt{\Lambda_1 \Lambda_4^2 k}}{\Lambda_4^2}, \frac{\Lambda_2\Lambda_4 + 2\sqrt{\Lambda_1 \Lambda_4^2 k}}{\Lambda_4^2}\right)$.It is straightforward to see that one eigenvalue is negative while the other one is positive. Under this assumption, the steady state is a saddle point. The initial conditions on the goodwill lying on the stable subspace associated to the negative eigenvalue allow the system to converge to the steady state as time approaches infinity. □

Proposition 6 *The demand for both digital and non-digital goods in the $\mathcal{P}$ −game are given by:*

$$D_{B_{SS}}^{\mathcal{P}} = \frac{\alpha_B^2 \eta(1-\phi)}{c_B} Q^{\mathcal{P}^2} = \frac{\alpha_B^2 \eta(1-\phi)}{c_B}\left(\frac{\theta^2 S_2^{\mathcal{P}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{P}}}\right)^2 \quad (25)$$

$$D_{N_{SS}}^{\mathcal{P}} = (\alpha_N - \beta_N p_N)(1 - Q^{\mathcal{P}}) = (\alpha_N - \beta_N p_N)\left[\frac{\theta^2 S_2^{\mathcal{P}} - \delta c_A + 2\theta^2 S_4^{\mathcal{P}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{P}}}\right] \quad (26)$$

Proof. Substitute Eq. (23) Eqs. (3)-(4)) to get Eqs. (25)-(26).

We analyze the implications of the smart profit sharing parameter in the next section, by comparing the solutions of the $\mathcal{W}$ −game and the $\mathcal{P}$ −game.

1. 5 Comparison between the $\mathcal{W}$ −game and the $\mathcal{P}$ −game

To compare the solutions in the $\mathcal{W}$ −game and in the $\mathcal{P}$ −game, we first have to fix an evidence resulting from the numerical optimization results:

Lemma 1 *For any given value of ω, the Riccati coefficients in the $\mathcal{P}$ −game result higher than those of the $\mathcal{W}$ −game.*

From the numerical optimization displayed in the section 3.1 and 4.1, one can notice that the Riccati coefficients of the feasible solutions turn out to be $S_i^{\mathcal{P}} \geq S_i^{\mathcal{W}}$ and $F_j^{\mathcal{P}} \geq F_j^{\mathcal{W}}$ $\forall\, i = 1..5$ and $j = 1..7$. Once we fix these results in Lemma 1, one can easily compare the solutions of the two games.

Proposition 7 *For any fixed value of ω, the adoption of a smart profit sharing mechanism leads to higher levels of conformance quality than the smart wholesale price mechanism when $\phi < \overline{\phi}$.*

Proof. Using the results of Lemma 1 (e.g., $\frac{\partial S_2^{\mathcal{P}}}{\partial \phi} > 0$ and $\frac{\partial S_4^{\mathcal{P}}}{\partial \phi} > 0$), it results that $\frac{\partial Q^{\mathcal{P}}}{\partial \phi} = \frac{\partial S_2^{\mathcal{P}}}{\partial \phi}\frac{\theta^2}{\delta c_A - 2\theta^2 S_4^{\mathcal{W}}} + \frac{\partial S_4^{\mathcal{P}}}{\partial \phi}\frac{2\theta^4 S_2^{\mathcal{W}}}{(\delta c_A - 2\theta^2 S_4^{\mathcal{W}})^2} > 0$ for $\forall \phi \in (0, \overline{\phi})$: $Q^{\mathcal{P}} \leq 1$. □

According to Proposition 5, complementing the smart wholesale price with a smart profit sharing mechanism always leads to higher stock of quality when the blockchain technology does not modify ω in any of the transactions as well as when $\phi < \overline{\phi}$. This result depends on the profit formation process for G, whose economic outcomes also vary according to the performance in the F's digital market. Such a mechanism amplifies the incentives for G to seek for the highest possible stock of conformance quality. Interestingly, the results of Proposition 5 are bounded by $Q^{\mathcal{P}} \leq 1$, according to which G makes defect-free chips. Then, the smart contract should adjust $\phi \in (0, \overline{\phi})$ since any $\phi \geq \overline{\phi}$ makes the game not feasible. In managerial terms, smart sharing profits that exceed $\overline{\phi}$ do not allow F to further improve the quality, which is bounded to 1. Therefore, the players can benefit from a smart profit sharing mechanism when the stock of conformance quality is low since it accelerates the accumulation process. Otherwise, in case of $Q^{\mathcal{W}} = 1$, firms have no incentives to implement a blockchain through smart profit sharing mechanism; rather, they would only focus on a smart wholesale price mechanism.

Proposition 8 *For any fixed value of ω, the adoption of a smart profit sharing mechanism leads to higher investments in quality (appraisal and prevention) and blockchain, as well as higher production rates than the smart wholesale price mechanism when $\phi < \overline{\phi}$. Under the same conditions, the adoption of a smart profit sharing mechanism leads to higher (lower) sales of digital (non-digital) goods than the smart wholesale price mechanism.*

Proof. Using the results of Lemma 1 (e.g., $\frac{\partial S_2^{\mathcal{P}}}{\partial \phi} > 0$ and $\frac{\partial S_4^{\mathcal{P}}}{\partial \phi} > 0$) as well as the results of Proposition 5 (e.g., $\frac{\partial Q^{\mathcal{P}}}{\partial \phi} > 0$), one can easily show that:

- $\frac{\partial u^{\mathcal{P}}}{\partial \phi} = \frac{\omega}{c_U} > 0$;

- $\frac{\partial q^{\mathcal{P}}}{\partial \phi} = \frac{\theta}{c_A}\left[\frac{\partial S_2^{\mathcal{P}}}{\partial \phi} + 2\left(\frac{\partial S_4^{\mathcal{P}}}{\partial \phi} Q^{\mathcal{P}} + \frac{\partial Q^{\mathcal{P}}}{\partial \phi} S_4^{\mathcal{P}}\right)\right] > 0$;

- $\frac{\partial B^{\mathcal{P}}}{\partial \phi} = \frac{\partial Q^{\mathcal{P}}}{\partial \phi}\frac{\alpha_B \eta (1-\phi)}{c_B} - \frac{\alpha_B \eta Q^{\mathcal{P}}}{c_B} > 0$;

• $\frac{\partial D_B^{\mathcal{P}}}{\partial \phi} = -\frac{\alpha_B^2 \eta}{c_B} Q^{\mathcal{P}2} + \frac{2\alpha_B^2 \eta(1-\phi) Q^{\mathcal{P}}}{c_B} \frac{\partial Q^{\mathcal{P}}}{\partial \phi} > 0;$

• $\frac{\partial D_N^{\mathcal{P}}}{\partial \phi} = -\frac{\partial Q^{\mathcal{P}}}{\partial \phi} (\alpha_N - \beta_N p_N) < 0.$

According to Proposition 6, the smart contract inside the blockchain should be developed with smart clauses including both the smart wholesale price mechanism as well as the smart revenue sharing mechanism to engage the firms to put more efforts into the business model development. On the one hand, as emerged from Proposition 5, G has incentives to invest more in appraisal and prevention, $q^{\mathcal{P}}$, to achieve the highest possible conformance quality, $Q^{\mathcal{P}}$, which guarantees margins from the digital goods; considering the increasing economic attractiveness of such a business model, G is inclined to make more chips since the business model works, hence increasing the production rate, $u^{\mathcal{P}}$. Within our framework, the higher number of chips can be linked to new business developments and opportunities like, for example, make the players changing their t-shirts at any time-break to increase the number of digital t-shirts to be sold. As a response to these actions, F invests in blockchain system, $B^{\mathcal{P}}$, to make sure that the system adequately works and includes all technologies required to record the players' information: the success of the whole business model depends of the conformance quality on the operational hand, as well as from the blockchain system on the technological hand. Finally, the selling outcome of the profit sharing mechanism suggest a progressive increase of the digital market, $D_B^{\mathcal{P}}$, and a decrease of the physical market, $D_N^{\mathcal{P}}$.

However, these result remain valid when $\phi \in (0, \overline{\phi})$, which ensures $Q^{\mathcal{P}} \leq 1$; when $\phi > \overline{\phi}$, F continues to invest in blockchain while G invests more in production while $Q^{\mathcal{P}}$ is bounded. Therefore, such investments can harm the firms' margins since the operational improvements vanish. Using the results in Propositions 5 and 6, one can easily check that the inventory at the steady state in a smart profit sharing mechanism are lower than the inventory in a smart wholesale price mechanism, only when ω is fix and $\phi < \overline{\phi}$.

Proposition 9 *For any fixed value of ω, the adoption of a smart profit sharing mechanism leads to higher profits for both firms than the smart wholesale price mechanism, when $\phi < \overline{\phi}$.*

Proof. Use the results displayed in Lemma 1 as well as in Propositions 5 and 6, to check that $V_G^{\mathcal{P}} > V_G^{\mathcal{W}}$ and $V_F^{\mathcal{P}} > V_F^{\mathcal{W}}$ for any fix value of ω and $\phi < \overline{\phi}$.

Note that the results in Propositions 5-8 are valid when Lemma 1 holds, that is, when the blockchain technology smartly set the sharing parameter, $\phi < \overline{\phi}$, while keeping ω fixed. However, F can setup the blockchain to act on both contractual terms when managing the transactions. Modifying ω can have important implications for the whole business model, starting from the conformance quality. As we have seen so far, the conformance quality guarantees the survival of the whole business model. Therefore, as displayed in Figure 1, we identified two regions:

- $\Omega^{\mathcal{P}}$ is the region inside which $Q^{\mathcal{W}} < Q^{\mathcal{P}} \leq 1$; hence, the $\mathcal{P}$-game is feasible inside $\Omega^{\mathcal{P}}$ and the propositions 5-7 hold;

- $\Omega^{\mathcal{W}}$ is the region inside which $Q^{\mathcal{W}} \leq 1$ and $Q^{\mathcal{P}} > 1$; hence, the $\mathcal{P}$-game is not feasible inside $\Omega^{\mathcal{P}}$ and the blockchain technology can only detect the best ω to manage the transactions through the $\mathcal{W}$-game.

$\Omega^{\mathcal{P}}$ identifies all cases in which both the games remain feasible since $Q \leq 1$ in both games; also, it correspondes to all cases in which $Q^{\mathcal{P}} > Q^{\mathcal{W}}$. One can observe that the blockchain can smartly adjust the contractual terms in these two directions to guarantee total quality management. On the one hand, increasing the smart wholesale parameter leads to increasing levels of conformance quality. On the other hand, complemeting the wholesale price with a smart profit sharing allows F to better engage G in reaching the highest possible quality levels. Note that the results obtained in Propositions 5 and 6 give an clear information: the blockchain should aim at performing from a total quality management perspective, which signify aiming at $Q = 1$. While this is the ultimate operational target, Figure 1 shows that that F has two possible options to get this target:

1. transfer to G the highest possible wholesale price, e.g., $\omega = \overline{\omega}$;

2. codify the blockchain to search for the best combination (ω, ϕ) and maximize the stock of Q.

In the first case, the blockchain only runs a smart wholesale price payment, which is the only possible option since the smart profit sharing mechanism is not feasible. In fact, it results that $Q^{\mathcal{P}} > 1$, leading to a non-feasible solution and imposing the transaction to be managed by a smart wholesale price clause. In the second case, the blockchain searches for the best pairs (ω, ϕ) to seek total quality management. Therefore, as Figure 2 displays, three possible regions can be identified:

- Region $\Omega^{\mathcal{W}}$, which corresponds to the case in which $\omega = \overline{\omega}$ and $\phi = 0$. In this region, any $\phi > 0$ leads to an unfeasible solution for the $\mathcal{P}$ $-$game since $Q^{\mathcal{P}} > 1$. Therefore, the smart contract in the blockchain will always manage the transactions by using a smart wholesale price contract;

- Region $\Omega_1^{\mathcal{P}}$, which corresponds to pairs (ω, ϕ) according to which the smart wholeprice must be complemented by ad hoc values of smart profit sharing; otherwise, the $\mathcal{P}$ $-$game turns out to be not feasible;

- Region $\Omega_2^{\mathcal{P}}$, which corresponds to pairs (ω, ϕ) according to which the wholesale price is too low to guarantee Pareto-improving cases; accordingly, the smart wholesale price contract must always be complemented by a smart profit sharing contract. In such cases, the smart sharing can take the maximum values.

Although Figure 2 shows how the blockchain should adjust the contractual terms to manage the transactions, its analysis should be integrated with the comparison of the profits. From Figure 2, one clear result emerges: for any fix wholesale price, any marginal increase of the smart profit sharing improves the operational performance given by quality, production, and inventory, when $\phi < \overline{\phi}$. However, performing the best operational performance, e.g., conformance quality, is a necessary but not a sufficient condition to ensure higher profits for firms. This statement becomes evident from the analysis of Table 2, which presents some pairs (ϕ, ω) that guarantee $Q = 1$.

ϕ	ω	V_G	V_F
	0.34175	25.0619	99.9741
.01	0.3085	20.5295	96.5231
.02	0.275	16.2520	93.6826
.03	0.2409	12.161	90.9272
.04	0.20645	8.29427	88.1666
.05	0.17135	4.61304	84.9019

Table 2. Combinations (ω, ϕ) that ensure $Q = 1$

As the analysis of V_G and V_F in Table 2 demonstrates, the row corresponding to $\Omega^{\mathcal{W}}$ with the pair ($\phi = 0, \omega = \overline{\omega} = 0.34175$), which implies $V_G^{\mathcal{W}} = 25.0619$ and $V_F^{\mathcal{W}} = 99.9741$, leads to the highest profits for both firms with respect to all other possible profits obtainable inside $\Omega^{\mathcal{P}}$. In fact, all other combinations including smart wholesale and smart profit sharing ensure lower profits than the sole presence of smart wholesale mechanism. Note that, according to Figure 2, any $\phi > 0$ with $\omega = \overline{\omega}$ makes the smart profit mechanism not feasible. Accordingly, the following Claim can be left:

Claim 1 *When using blockchain to regulate transactions in a dynamic framework, the firms should prefer a smart wholesale price mechanism to a profit sharing mechanism.*

Our finding takes important positioning with respect to the whole literature in coordination developed in dynamic games, according to which the shift from a wholesale price to a sharing mechanism leads to Pareto-improving situation and, consequently, to coordination. This result is disconfirmed when the transactions are managed through a blockchain. In fact, differently from the traditional wholesale price contracts, the smart wholesale price contracts activate the payment according to the firms' performance, specifically, according to the conformance quality. In a traditional transaction involving conformance quality, the company that is responsible for conformance quality gets payed according to either the sales or the production rate (e.g., El Ouardighi and Kim, 2012). Within our framework, the transactions are regulated by the blockchain that transfers money to G - who is responsible for conformance quality - according to the defect-free rate, that is, according to G's capacity to make conform chips. In the latter case, F can satisfy the market for digital goods. This happens because the blockchain already responsibilizes G in performing the highest possible conformance quality by using a simple smart wholesale mechanism. In fact, the main purpose of proposing a sharing agreement in a traditional transaction is to integrate the firms' business models and make all firms responsible for the whole business model success. With our analysis, we discover that the sharing mechanisms can be avoided when the wholesale agreements are regulated through a blockchain since such integration is achieved without using a profit sharing clause.

1.6 Sensitivity analysis

This section provides a full sensitivity analysis on all the models' parameter values, as displayed in the Appendix B. Starting from the benchmark solution, whose parameter values are given in Section 4, we change each single parameter values as dispayed in the main colon of Table B, whose Δ have been set according to the reaction of the optimal solutions with respect to changes in a certain parameters. For example, small changes in c_B (step 0.05) have huge effects on the V_F while c_U require high changes (step 0.5) to get visible the changes in V_F. For each modified parameter, we obtain and show the related changes in terms of the state variables Q and X, the control variables u, q_A, and B, the sales D_N and D_B, and the profits V_F and V_S. According to the sensitivity analysis, we can derive additional information from the optimal solution. To pursue an effective discussion and save notations, we grouped the subscripts as follows: $\lambda\{A, U, S\}$, $\psi\{B, X, F, N\}$.

Claim 2 *Increasing levels of the marginal cost for quality investments (c_A), production process (c_U), and the product raw material for chips (c_S) imply that:*

a) Conformance quality, Q, decreasese, resulting $\frac{\partial Q}{\partial c_\lambda} < 0$;

b) Inventory stock, X, increase in c_A, resulting $\frac{\partial X}{\partial c_A} < 0$, while decreasing in c_U and c_S, as $\frac{\partial X}{\partial c_U} < 0$ and $\frac{\partial X}{\partial c_S} < 0$.

c) The demand for both digital and non-digital goods decrease, resulting $\frac{\partial D_F}{\partial c_\lambda} < 0$ and $\frac{\partial D_N}{\partial c_\lambda} < 0$;

d) The control variables take lower values, resulting $\frac{\partial u}{\partial c_\lambda} < 0$, $\frac{\partial q_A}{\partial c_\lambda} < 0$, and $\frac{\partial B}{\partial c_\lambda} < 0$;

e) The players' profits decrease, resulting $\frac{\partial V_F}{\partial c_\lambda} < 0$ and $\frac{\partial V_S}{\partial c_\lambda} < 0$.

When we analyze the marginal cost for quality investments, production material and process, we can see that their conformance quality always decreases accordingly. This is due to the investments in quality, which are very expensive; therefore, firms have an attempt to decrease the amount of monitoring activities and controls to ensure free defect batches. Rather, they prefer to face possible consequences coming from the defects, which are given hereby in terms of sales of traditional goods rather then in terms of penalties. In fact, defective chips will still lead to a sales in the original (non-digital) market, although they prevent business for digital goods. When the cost of the raw materials for the chip as well as the production costs take high values, G has less budget available to keep full control of the production, resulting in an lower conformance quality.

When the costs of production and procurement increase, the supply chain has an attempt to reduce the inventory because of the high economic value absorbed by the stock. In contrast, increasing marginal cost of quality leads the supply chain to increase the inventory since the production of high quality chips is fundamental to guarantee the economic sustainability of the business model. Therefore, the inventory policy entails numerous operational tradeoffs to be carefully evaluated.

Overall, these three cost categories have at the tremendous effect for the demand of all types of products, digital and non-digital; this turns out to be true also for the players' strategies, leading to less production, lower investments in quality, and basic blockchain technologies. Similarly, the firm's profits decrease in each of these three cost categories. On the one hand, F as a low willingness to invest in blockchain technology because they operations run by G in terms of quality and production are of low level; on the other hand, G can perceive the scarce attitude by F to invest in blockchain technology, highlighting lower needs to invest in quality to guarantee high conformance as well as in production to ensure the continuous replenishment of inventory.

Claim 3 *Increasing levels of the marginal cost for blockchain (c_B), inventory (c_X), production raw materials for digital (c_F) and non-digital goods (c_N) lead to:*

a) Conformance quality, Q, is constant, resulting $\frac{\partial Q}{\partial c_\psi} = 0$;

b) Inventory stock, X, remain constant, as $\frac{\partial X}{\partial c_\psi} = 0$;

c) The demand for both digital and non-digital goods remain constant, resulting $\frac{\partial D_F}{\partial c_\psi} = 0$ and $\frac{\partial D_N}{\partial c_\psi} = 0$;

d) The production and the quality investments remain constant, resulting $\frac{\partial u}{\partial c_\psi} = 0$ and $\frac{\partial q_A}{\partial c_\psi} = 0$; however, the blockchain investments remain constant in the costs for inventory, and raw materials, resulting $\frac{\partial B}{\partial c_X} = \frac{\partial B}{\partial c_F} = \frac{\partial B}{\partial c_N} = 0$. Instead, the blockchain investments result decreasing in c_B, as $\frac{\partial B}{\partial c_B} < 0$;

e) The G's profits are constant in all the marginal costs, c_ψ, resulting $\frac{\partial V_G}{\partial c_\psi} = 0$; in contrast, F's profits decrease in all the marginal costs, c_ψ, resulting $\frac{\partial V_F}{\partial c_\psi} < 0$.

Interestingly, the marginal cost for blockchain (c_B), inventory (c_X), production raw materials for digital (c_F) and non-digital goods (c_N) do not have any effect on the state variables at the steady-state as well as on both demand functions. Therefore, neither the operations management outcomes or the marketing outcomes are influenced by the marginal costs. This is also reflected in production rates and quality investments that are constant with respect these cost categories; the only exception is represented by the blockchain investments, which decrease in the marginal cost of blockchain. Therefore, when high investments in the digital technology translate into high penalties for the F's profit function, the interest for blockchain and the chances offered by the digital marketplace decrease accordingly.

Claim 4 *Increasing levels of the wholesale price (ω), the price of non-digital goods (p_N), and the* *margins on digital goods (η) imply that:*

a) Conformance quality, Q, increases in the wholesale price, resulting $\frac{\partial Q}{\partial \omega} > 0$, while it remains constant in p_N and η, resulting in $\frac{\partial Q}{\partial p_N} = \frac{\partial Q}{\partial \eta} = 0$;

b) Inventory stock, X, decreases in ω (e.g., $\frac{\partial X}{\partial \omega} < 0$), increases in p_N (e.g., $\frac{\partial X}{\partial p_N} < 0$), and remains constant in η (e.g., $\frac{\partial X}{\partial \eta} = 0$).

c) The demand for both digital and non-digital goods entail a trade-off in ω since $\frac{\partial D_B}{\partial \omega} > 0$ and $\frac{\partial D_N}{\partial \omega} < 0$,while both are constant in η (e.g., $\frac{\partial D_B}{\partial \eta} = \frac{\partial D_N}{\partial \eta} = 0$). In contrast, increasing levels of p_N lead to D_N (e.g., $\frac{\partial D_N}{\partial p_N} < 0$), while D $_B$ remains constant (e.g.,$\frac{\partial D_N}{\partial p_N} < 0$);

d) The control variables increase in ω (e.g., $\frac{\partial u}{\partial \omega} < 0$, $\frac{\partial q_A}{\partial \omega} > 0$, and $\frac{\partial B}{\partial \omega} > 0$) while they remain constant in p_N (e.g., $\frac{\partial u}{\partial p_N} = \frac{\partial q_A}{\partial p_N} = \frac{\partial B}{\partial p_N} = 0$); the latter result is confimed for increasing values of η relatively to u and qA (e.g.,$\frac{\partial u}{\partial \eta} = \frac{\partial q_A}{\partial \eta} = 0$), while the investments in blockchain increase in η (e.g.,$\frac{\partial B}{\partial \eta} > 0$).

e) The F's profits turn out to be increasing in all the three parameters (e.g., $\frac{\partial V_F}{\partial p_N} > 0$, $\frac{\partial V_F}{\partial \omega} > 0$, and $\frac{\partial V_F}{\partial \eta} > 0$). Instead, the G's profits increase only according to ω (e.g., $\frac{\partial V_G}{\partial \omega} > 0$) while remaining constant in η and p_N (e.g., $\frac{\partial V_G}{\partial p_N} = \frac{\partial V_G}{\partial \eta} = 0$).

Considering that G's margins are fully dependent on the wholesale price, it targets to reach the highest possible conformance quality rate, Q. Considering that this target is not influenced by the F's strategies (e.g., the conformance depends only on the G's efforts), G seeks to achieve it without being affected by the F's margins. In contrast, increasing values of the wholesale price penalize the F's purchasing strategy, because of the lower production rate. Therefore, the inventory decreases according to the wholesale price while it increases in the non-digital product price, which brings the demand down. Although the margin of digital good can be attractive, there is no effect on the inventory kept in stock since its behavior is constant at the steady-state. The demand for the two goods contrast when the wholesale price increases, signaling that F pushes for the market according to the supply chain efficiency. When the wholesale price is sufficiently high, G reduces the production rate since a few amount of goods sold can guarantee sufficient revenues. Differently, the quality efforts along with the blockchain technology investments increase: the first to guarantee to get paid by ensuring high conformance; the second to push for the market for digital goods. In general, the market for the non-digital goods is considered to be a "secondary" market since the players' strategies do not change in the non-digital goods' marginal gains.

Claim 5 *Increasing levels of both the market potential (α_N) and the customer sensitivity to price (β_N) for non-digital goods, as well as the market potential for digital goods (α_B) imply that:*

a) Conformance quality, Q, remains constant in α_B, α_N, and β_N (e.g., $\frac{\partial Q}{\partial \alpha_N} = \frac{\partial Q}{\partial \beta_N} = \frac{\partial Q}{\partial \alpha_B} = 0)$;

b) Inventory stock, X, decreases in α_N and α_B (e.g., $\frac{\partial X}{\partial \alpha_N} < 0$ and $\frac{\partial X}{\partial \alpha_B} < 0)$, while it increases in β_N (e.g., $\frac{\partial X}{\partial \beta_N} > 0)$;

c) The demand for both digital goods is constant with respect to α_B, α_N, and β_N (e.g., $\frac{\partial D_B}{\partial \alpha_N} = \frac{\partial D_B}{\partial \beta_N} = \frac{\partial D_B}{\partial \alpha_B} = 0)$; in contrast, the demand for non-digital goods increases in both α_B amd α_N (e.g., $\frac{\partial D_N}{\partial \alpha_N} > 0$ and $\frac{\partial DN}{\partial \alpha_B} > 0)$, and decreases in β_N $(e.g., \frac{\partial D_N}{\partial \beta_N} > 0)$;

d) The quality investments and the production rate remain constant in α_B, α_N, and β_N (e.g., $\frac{\partial u}{\partial \alpha_N} = \frac{\partial q}{\partial \alpha_N} = \frac{\partial u}{\partial \alpha_B} = \frac{\partial q}{\partial \alpha_B} = \frac{\partial u}{\partial \beta_N} = \frac{\partial q}{\partial \beta_N} = 0)$; in contrast, the blockchain investmennts only increase in the digital goods' market potential (e.g., $\frac{\partial B}{\partial \alpha_N} > 0$ and $\frac{\partial B}{\partial \alpha_B} = \frac{\partial B}{\partial \beta_N} = 0)$;

e) The F's profits turn out to be increasing in all α_B and α_N (e.g., $\frac{\partial V_F}{\partial \alpha_N} > 0$ and $\frac{\partial V_F}{\partial \alpha_B} > 0$), while being decreasing in the consumers' sensitivity to price β_N (e.g., $\frac{\partial V_F}{\partial \beta_N} < 0)$. Instead, the G's profits constant in α_B, α_N, and β_N (e.g., $\frac{\partial V_G}{\partial \alpha_N} = \frac{\partial V_G}{\partial \alpha_B} = \frac{\partial V_G}{\partial \beta_N} = 0$).

The market parameters α_B, α_N, and β_N do not influence the G's conformance quality path, given that the quality investments do not interact with the two markets. In fact, G's business is guaranteed by selling the chips made, independent of which market will ask for them. This result is also reflected in a production strategy that follows the G's profits rather than the F's profits. Intuitively, market changes occuring in both the digital and the non-digital goods will make the modify the inventory accordingly; for example, the increasing market potentials and, consequently, sales lead to decreasing availability of chips at the steady-state. The digital market attractivness pushes F to invest more in blockchain, since new injections considerably stimulate both the market and the profits.

Claim 6 *Increasing levels of the quality efficiency (θ), the defect rate during the match (g), the decay factor for quality (δ), and the discount factor (r) imply that:*

a) Conformance quality, Q, remains constant in g (e.g., $\frac{\partial Q}{\partial g} = 0$), increases in θ (e.g., $\frac{\partial Q}{\partial \theta} > 0$), and decreases in both r and δ (e.g., $\frac{\partial Q}{\partial r} < 0$ and $\frac{\partial Q}{\partial \delta} < 0$);

b) Inventory stock, X, increases in both r and δ (e.g., $\frac{\partial X}{\partial r} > 0$ and $\frac{\partial X}{\partial \delta} > 0$), and decreases in both θ and g (e.g., $\frac{\partial X}{\partial \theta} < 0$ and $\frac{\partial X}{\partial g} < 0$);

c) The demand for digital goods remains constant in g (e.g., $\frac{\partial D_B}{\partial g} = 0$), increases in θ (e.g., $\frac{\partial D_B}{\partial \theta} > 0$), and decreases in both r and δ (e.g., $\frac{\partial D_B}{\partial r} < 0$ and $\frac{\partial D_B}{\partial \delta} < 0$); all these results are reversed regarding the demand for non-digital goods, except for g since it also results constant (e.g., $\frac{\partial D_B}{\partial g} = 0$).

d) The triple strategies $\Omega\{u, q, B\}$ remains constant in g (e.g., $\frac{\partial \Omega}{\partial g} = 0$), increases in θ (e.g., $\frac{\partial \Omega}{\partial \theta} > 0$), and decreases in both r and δ (e.g., $\frac{\partial \Omega}{\partial r} < 0$ and $\frac{\partial \Omega}{\partial \delta} < 0$); all these results are reversed regarding the demand for non-digital goods, except for g since it also results constant (e.g., $\frac{\partial D_B}{\partial g} = 0$);

e) The F's profits increases in θ (e.g., $\frac{\partial V_F}{\partial \theta} > 0$ and $\frac{\partial V_G}{\partial \theta} > 0$), and decreases in both r and δ (e.g., $\frac{\partial V_F}{\partial r} < 0$, $\frac{\partial V_F}{\partial \delta} < 0$, $\frac{\partial V_G}{\partial r} < 0$, and $\frac{\partial V_G}{\partial \delta} < 0$); in contrast, V_G remains constant in g (e.g., $\frac{\partial V_G}{\partial g} = 0$), which instead leads to increasing V_F (e.g., $\frac{\partial V_F}{\partial g} > 0$).

Interestingly, since the damages occurring to chips during the match cannot be controlled by G, the conformance quality dynamics does not modify according to g over time, driven by constant quality investments. In contrast, favorable conditions for quality (high quality efficiency and low decreasing quality) push G to invest more in quality and achieve high conformance quality standards. Furthermore, such favorable conditions for quality lead to a general decrease of inventory, leading to a better management of stocks that requires F to properly handle the trade-offs induced by the demand for digital and non-digital goods. In general, operations management policies (exemplified by quality management and inventory management in this research) contrasting effects when it turns out to satisfy these two demand types. Indeed, the management of such trade-off followed by favorable operational conditions allows both players to easily increase their profits.

Intuitively, increasing values of the interest rate r generate decreasing discount factors, leading to decreasing appealingness of the business model followed by decreasing investments in quality, production and blockchain technology and, consequently, decreasing players' profits. Finally, variations of the inventory obsolescence, k, will not influence the at all results. Consequently, the firms should set their strategies without being preoccupied of the possible deterioration of chips.

1.7 Managerial implications

The blockchain technology has important implications for all business models in which the detection of the true quality is problematic while the traditional tracking systems fail due to the missing connection with the eco-system. The blockchain technology, adequately supported by Internet-of-Things technologies, allow one to connect the physical objects sparced in the eco-system on digital blockchain platforms and record information of any kind, even the information linked to conformance quality and total quality management. In this sense, one main advantage that the blockchain offers is the activation of payments that are based on the real quality performance of suppliers rather than to the traditional contractual terms. In the past, a seller and a buyer were used to sign a contract relatively to the supply of a certain amount of goods; once the buyer had finalized the transfer to the seller, the latter would send the goods to the buyer. Then, if the buyer experieced defects when receiving the goods, a reconciliation procedure should be activated with considerable administrative and penalty costs associated to the defective items. Nowadays, this approach has been overcomed and substituted by the smart contracts activated by the blockchain. Hereby, the buyer does not make the transaction when the seller send the goods; rather, the blockchain activates the payment to the seller only after that the buyer checked the goods and the related quality; the seller gets paid by the smart contracts managed by the blockchain only for the defect-free items sent to the buyer. Indeed, Internet-of-Things technology is needed to ensure the correct verification processes and the true behaviors of agents.

In this paper, we replicate this mechanism within the framework of collectibles in which a supplier of chips allow a football club to carry out a digital business by selling original t-shirts dressed by soccer players during certain matches. The conformance of chips guarantees that the digital market can be served; otherwise, the t-shirt can be sold to a traditional market, losing *de facto* all business opportunities offered by the digital transformation. In fact, the blockchain algorithm can be set to pay the supplier of chips according to the defect-free rate. Hence, we evaluate two types of smart clause: a smart wholesale price and a smart profit sharing mechanism. The analysis of these two options are very important for managers and practitioners since the blockchain offers genuine oppurtunities to effectively use them in a digitalized environment. Accordingly, the following managerial insights can be left:

• The smart wholesale price responsibilizes the suppliers to pursue the maximum possible conformance quality; in fact, the smart clause developed in the blockchain pays the supplier only for the defect-free items. This option is very appealing in all business applications since the buyers do not need to activate any atypical procedure to manage the defective items, for which the suppliers still have the full responsibility. The smart process pursued through the blockchain pushes the suppliers to manage efficiently the operations (e.g., production planning and inventory management) and seek to achieve total quality management by maximizing the defect-free rates. The latter becomes the only way to be paid by the blockchain.

• One of the biggest opportunities that companies - especially in industries like the collectible industry - have nowadays is to parallely develop and manage the traditional market as well as the digital market. Our findings demonstrate how these two markets can co-exist without cannibalizing each other since the price of the two goods are not economically comparable. For example, according to the the Genuino Marketplace the Dusan Vlahovic certified jersey worn in the Atalanta-Fiorentina Serie A match on 11th september 2021 can be bought for a starting price of 3.050 while the non-digital version can be bought in the store for 125 . Therefore, our study offers genuine opportunities to make a reflection on the opportunities to sell gods (t-shirts in our framework) with defective chips in traditional markets. However, considerind the huge difference existing between the prices of digital goods and non-digital goods, the suppliers of chips should be highly penalized when supplying defective items; within our framework, we designed a smart wholesale price that does not make any payment to the supplier for defective items, although the foodtball club can continue to sell them in the traditional market.

• To encourage the supplier to perform total quality management, the firms can also complement a smart wholesale mechanism with smart profit sharing mechanism, which is based on the profits that the football club obtains by selling digital goods. The presence of a smart profit sharing offers a dual incentive to the supplier to perform total quality management. In principle, when the smart wholesale price takes either low or medium levels, complementing the blockchain with profit sharing clauses can contribute to the success of the whole business model.

• When the blockchain can smartly modify the wholesale price and the profit sharing, the smart contract favors the adoption of wholesale price mechanisms rather than the profit sharing mechanisms. This result is opposite with respect to the adoption of these mechanisms in traditional negotiations and depends on the adoption of blockchain thinking. In fact, the profit sharing agreement helps in integrating the firms' strategies and to make their business models interdependent. Such interdependency is already embedded in the smart wholesale price contract since the supplier is paid according to the defect-free rate. This different approach in managing transactions makes the profit sharing less appealing than the wholesale price and reveals the differences between traditional and digital transactions: what it is appealing in traditional transactions (e.g., a profit sharing agreement) can be not economically and operationally feasible in digital frameworks.

1. 8 Conclusions

This paper proposes a dynamic game in which the blockchain can be used within the collectibles industry to verify and record information on soccer matches and the related players with the objective to prove that some collectibles t-shirts are original and have been really dressed by soccer teams' players. The blockchain technology, jointly with IoT technology sparse over the soccer field, allow the t-shirts to become digitalized and record information through a chip. The collectors can access to all information regarding the t-shirts by using the chips and related tags. Because their digitalized t-shirts go to that market of collectors, a bid is initiated on online platforms on such original products. Within our game, we focus on the key ingredients of the business models which are represented by the supplier of chips and the blockchain technology. In fact, the blockchain technology is per se not sufficient to make the business model successful since the chips must be free of defects; otherwise, the IoT cannot transfer information to be recorded on the blockchain platform.
We then model an original framework in which the collectibles are proved to be originally through the blockchain technology. When this proof cannot be made because the chip is defected, the t-shirt can still be sold either in traditional e-commerce platforms or in physical stores at the price that is set by the market. Our results show that the investments in blockchain technology are followed by higher investments in quality to guarantee high free defect of the chips. Because the supplier of chips gets encouragement by the presence of blockchain, it also makes more products and ensures high production rates. This entails a certain trade-off between the market for the digitalized goods and the market for non-digitalized goods. In fact, since both

players gain substantially increase their profits by selling digitalized goods, the traditional market has a lower availability of nondigital t-shirts to be purchased. Consequently, although the blockchain technology allows to extract more economic value from the ecosystem, we discovered that it might create social problems for customers who cannot afford the price of collective goods, who then have low availability of t-shirts and chances to purchase traditional goods from classical e-commerce platforms or physical stores. Therefore, firms investing in digital technologies like blockchain and IoT should adopt a more holistic view of the whole problem and avoid the creation of social issues for the most fragile social clusters and fulfill the requirements of a responsible digital transformation.

Afterwards, we develop a smart profit sharing agreement inside the blockchain system, to complement the smart wholesale price clause. The presence of such a dual mechanism offers more incentives to the supplier to perform a high free-defect rate. In fact, the blockchain pays the supplier according to the defect free rate, which is directly linked to the smart wholesale price and indirectly to the sales of digital goods. Our analysis demostrates that if the wholesale price is fixed, the smart profit sharing can be helpful to achieve a total quality management and increase the profits of both firms. However, if the blockchain acts on both smart clauses (the wholesale and profit sharing) simultaneously, the algorithm prefers to make transactions according the smart wholesale price only while fully disregarding the profit sharing agreements. This result, which is completely opposite with respect to the literature of supply chain coordination that sponsors and favors the adoption of sharing mechanisms, depends on the way the blockchain works. In fact, the blockchain makes payments to the supplier according to the defect-free rate, implying that the firms' business models are already integrated and interdependent even without a profit sharing agreement, which results not preferable. Therefore, the effectiveness of a profit sharing agreement over a wholesale price mechanism fails when it is adopted to manage digital transactions through blockchain.

This paper is not free of limitations which are listed here in order to inspire future research in the same field. This paper models a dynamic game between a supplier of chips and a soccer club; future research can add more players within this analysis since the supply chain of the sport sector is composed various stakeholders involving sponsors, suppliers of t-shirts, and community surrounding the sport facilities. Furthermore, this framework requires an enrichment of both the fair and the unfair competition: the fair competition comes from the presence of other types of gadgets that can be available in the sport industry, which can complement the sales of t-shirts; the unfair competition comes from the presence of fake goods, which can increase due to the absence of normal t-shirts available in the market. The latter point can entail a challenging trade-off to be analyzed since, in principle, the blockchain seeks to reduce the presence of fake goods in the market, while the shortage of traditional t-shirts can lead to increasing the amount of fake goods and the consumers' availability in purchasing them due to unaffordable prices of digitalized goods. Although the blockchain technology is in rapid evolution and expansion, the current platforms and the existing algorithms behind the smart contracts still consume lots of energy, causing increasing amount of environmental damages. Future research should then address the trade-off between economic, social, and environmental performance linked to the blockchain technology. Finally, more research is needed to ensure that the collectors will not speculate from their purchases by authorizing future transfers and transactions only by using ad hoc blockchain platforms, to absorb all market externalities existing in the collectibles industry.

Table 1: tabella versione 1

parameters		states		controls			demand		payoff	
name	values	Q	X	U	q_A	B	demand B	demand N	S	F
benchmark		0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	77.0204
$c_A = 2.5$	3	0.674739	0.329326	1.65242	0.289174	4.04843	1.01211	0.300867	11.4816	54.619
	3.5	0.567039	0.360559	1.62011	0.243017	3.40223	0.850559	0.400489	8.4031	44.1455
	4	0.488988	0.383193	1.5967	0.209566	2.93393	0.733482	0.472686	6.18837	38.9734
$c_U = 1$	1.5	0.796748	0.230935	1.62602	0.341463	4.78049	1.19512	0.188008	14.97	74.3184
	2	0.780086	0.206762	1.59201	0.334323	4.68052	1.17013	0.20342	14.4791	73.0864
	2.5	0.770506	0.192862	1.57246	0.330217	4.62303	1.15576	0.212282	14.1987	72.3815
$c_B = 0.1$	0.15	0.832943	0.283447	1.69988	0.356975	3.33177	1.24941	0.154528	16.0511	35.3928
	0.2	0.832943	0.283447	1.69988	0.356975	2.49883	1.24941	0.154528	16.0511	14.579
	0.25	0.832943	0.283447	1.69988	0.356975	1.99906	1.24941	0.154528	16.0511	2.09076
$c_F = 0.1$	0.2	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	64.5263
	0.3	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	52.0322
	0.4	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	39.538
$c_X = 1$	1.5	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	75.0119
	2	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	73.0033
	2.5	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	70.9948
$\overline{u} = 1.5$	1.55	0.861665	0.325117	1.7585	0.369285	5.16999	1.2925	0.12796	17.4446	79.1899
	1.6	0.890387	0.366788	1.81712	0.381594	5.34232	1.33558	0.101392	18.8938	81.3817
	1.65	0.919109	0.408458	1.87573	0.393904	5.51465	1.37866	0.0748242	20.3986	83.5958
$c_S = 0.05$	0.1	0.80422	0.241776	1.64127	0.344666	4.82532	1.20633	0.181096	7.3384	74.8733
	0.11	0.798476	0.233442	1.62954	0.342204	4.79086	1.19771	0.18641	5.63254	74.4466
	0.12	0.792732	0.225108	1.61782	0.339742	4.75639	1.1891	0.191723	3.9389	74.0207
$\omega = 0.3$	0.31	0.870879	0.281154	1.71997	0.373234	5.22528	1.30632	0.119436	18.0023	81.6669
	0.32	0.910081	0.279278	1.74123	0.390035	5.46048	1.36512	0.0831754	20.0775	86.813
	0.33	0.95064	0.277833	1.76371	0.407417	5.70384	1.42596	0.0456576	22.2853	92.5076
$p_N = 0.75$	1.25	0.832943	0.2918	1.69988	0.356975	4.99766	1.24941	0.146175	16.0511	83.4875
	1.75	0.832943	0.300152	1.69988	0.356975	4.99766	1.24941	0.137822	16.0511	89.1124

	2.25	0.832943	0.308505	1.69988	0.356975	4.99766	1.24941	0.12947	16.0511	93.895
$c_N = 0.03$	0.13	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	75.4752
	0.53	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	69.294
	0.83	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	64.6582
$\alpha_N = 1$	1.5	0.832943	0.199918	1.69988	0.356975	4.99766	1.24941	0.238057	16.0511	85.0532
	2	0.832943	0.116389	1.69988	0.356975	4.99766	1.24941	0.321586	16.0511	92.3884
	2.5	0.832943	0.0328605	1.69988	0.356975	4.99766	1.24941	0.405114	16.0511	99.0258
$\beta_N = 0.1$	0.2	0.832943	0.295976	1.69988	0.356975	4.99766	1.24941	0.141999	16.0511	75.7553
	0.5	0.832943	0.333564	1.69988	0.356975	4.99766	1.24941	0.104411	16.0511	71.8659
	0.8	0.832943	0.371152	1.69988	0.356975	4.99766	1.24941	0.066823	16.0511	67.8351
$\eta = 0.4$	0.5	0.832943	0.283447	1.69988	0.356975	6.24707	1.24941	0.154528	16.0511	147.267
	0.7	0.832943	0.283447	1.69988	0.356975	8.7459	1.24941	0.154528	16.0511	334.591
	1	0.832943	0.283447	1.69988	0.356975	12.4941	1.24941	0.154528	16.0511	732.655
$\alpha_B = 1.5$	1.55	0.832943	0.241383	1.69988	0.356975	5.16424	1.29106	0.154528	16.0511	86.1721
	1.6	0.832943	0.199319	1.69988	0.356975	5.33083	1.33271	0.154528	16.0511	95.4243
	1.65	0.832943	0.157256	1.69988	0.356975	5.49742	1.37436	0.154528	16.0511	104.777
$g = 0.01$	0.02	0.832943	0.270953	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	77.3668
	0.1	0.832943	0.170999	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	79.5755
	0.15	0.832943	0.108529	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	80.4486
$\delta = 0.3$	0.35	0.60961	0.348213	1.63288	0.304805	3.65766	0.914414	0.361111	9.20208	47.8229
	0.4	0.467537	0.389414	1.59026	0.267164	2.80522	0.701305	0.492529	5.02444	37.908
	0.45	0.370921	0.417433	1.56128	0.238449	2.22553	0.556382	0.581898	2.27193	35.0119
$\theta = 0.7$	0.71	0.861181	0.275257	1.70835	0.363879	5.16709	1.29177	0.128407	16.8727	81.8972
	0.73	0.919745	0.258274	1.72592	0.377977	5.51847	1.37962	0.0742363	18.5822	92.8587
	0.75	0.981203	0.240451	1.74436	0.392481	5.88722	1.4718	0.0173872	20.3846	105.593
$k = 1$	1.5	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	77.0204
	2	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	77.0204
	2.5	0.832943	0.283447	1.69988	0.356975	4.99766	1.24941	0.154528	16.0511	77.0204
$r = 0.1$	0.2	0.644152	0.338196	1.64325	0.276065	3.86491	0.966228	0.329159	3.24658	12.8128
	0.3	0.525129	0.372712	1.60754	0.225055	3.15078	0.787694	0.439255	1.15309	4.56841
	0.4	0.443231	0.396463	1.58297	0.189956	2.65939	0.664847	0.515011	0.517449	2.30539

1.9 Appendix A

Let us denote by $V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ and $V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ the supplier's and the football club's value functions associated to the $\mathcal{W}$ −game, respectively. Then, $\partial_Q V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ and $\partial_Q V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ are the derivatives with respect to the state function $Q^{\mathcal{W}}$ and $\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ and $\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ are the derivatives with respect to the state function $X^{\mathcal{W}}$. The HJB equations are given by:

$$rV_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) = [\omega Q^{\mathcal{W}} - c_S]u^{\mathcal{W}} - c_U \frac{(u^{\mathcal{W}} - \overline{u})^2}{2} - c_A \frac{(q^{\mathcal{W}})^2}{2} + \\ + \partial_Q V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})[\theta q^{\mathcal{W}} - \delta Q^{\mathcal{W}}] + \\ + \partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})[u^{\mathcal{W}} - kX^{\mathcal{W}} - \alpha_B(1+g)Q^{\mathcal{W}} - (\alpha_N - \\ \beta_N p_N)(1 - Q^{\mathcal{W}})] \tag{27}$$

$$rV_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) = D_B^{\mathcal{W}}(\eta B^{\mathcal{W}} - c_F) + D_N^{\mathcal{W}}(p_N^{\mathcal{W}} - c_N) - \omega Q^{\mathcal{W}} u^{\mathcal{W}} - c_B \frac{(B^{\mathcal{W}})^2}{2} - \\ c_X \frac{(X^{\mathcal{W}})^2}{2} \\ + \partial_Q V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})[\theta q^{\mathcal{W}} - \delta Q^{\mathcal{W}}] + \\ + \partial_X V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})[u^{\mathcal{W}} - kX^{\mathcal{W}} - \alpha_B(1+g)Q^{\mathcal{W}} - (\alpha_N - \\ \beta_N p_N)(1 - Q^{\mathcal{W}})] \tag{28}$$

Deriving $V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ with respect to $u^{\mathcal{W}}$ and $q^{\mathcal{W}}$ as well as $V_F^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})$ with respect to $B^{\mathcal{W}}$, we obtain a system of equation, whose resolution gives the following optimal strategies:

$$u^{\mathcal{W}*} = \frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) - c_S + c_U \overline{u} + Q^{\mathcal{W}} \omega}{c_U} \tag{29}$$

$$q^{\mathcal{W}*} = \frac{\theta \ \partial_Q V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})}{c_A} \tag{30}$$

$$B^{\mathcal{W}*} = \frac{\alpha_B \eta Q^{\mathcal{W}}}{c_B} \tag{31}$$

Substituing the optimal controls in the HBJs we obtain:

$$rV_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) = [\omega Q^{\mathcal{W}} - c_S]\left(\frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) - c_S + c_U \overline{u} + Q^{\mathcal{W}} \omega}{c_U}\right) - \\ c_U \frac{\left(\left(\frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}}) - c_S + c_U \overline{u} + Q^{\mathcal{W}} \omega}{c_U}\right) - \overline{u}\right)^2}{2} \tag{32} \\ -c_A \frac{\left(\frac{\alpha_B \eta Q^{\mathcal{W}}}{c_B}\right)^2}{2} + \partial_Q V_G^{\mathcal{W}}(Q^{\mathcal{W}}, X^{\mathcal{W}})\left[\theta \frac{\alpha_B \eta Q^{\mathcal{W}}}{c_B} - \delta Q^{\mathcal{W}}\right] +$$

$$+\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})\begin{bmatrix}\left(\frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})-c_S+c_U\overline{u}+Q^{\mathcal{W}}\omega}{c_U}\right)-kX^{\mathcal{W}}-\alpha_B(1+g)Q^{\mathcal{W}}\\-(\alpha_N-\beta_N p_N)(1-Q^{\mathcal{W}})\end{bmatrix} \quad (33)$$

$$rV_F^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})=\alpha_B Q(t)\left(\eta\frac{\alpha_B\eta Q^{\mathcal{W}}}{c_B}-c_F\right)+(\alpha_N-\beta_N p_N)[1-Q(t)]-$$
$$\omega Q^{\mathcal{W}}\left(\frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})-c_S+c_U\overline{u}+Q^{\mathcal{W}}\omega}{c_U}\right)$$
$$-c_B\frac{\left(\frac{\alpha_B\eta Q^{\mathcal{W}}}{c_B}\right)^2}{2}-c_X\frac{(X^{\mathcal{W}})^2}{2}+\partial_Q V_F^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})\left[\theta\frac{\alpha_B\eta Q^{\mathcal{W}}}{c_B}-\delta Q^{\mathcal{W}}\right]+$$
$$+\partial_X V_F^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})\begin{bmatrix}\left(\frac{\partial_X V_G^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})-c_S+c_U\overline{u}+Q^{\mathcal{W}}\omega}{c_U}\right)-kX^{\mathcal{W}}\\-\alpha_B(1+g)Q^{\mathcal{W}}-(\alpha_N-\beta_N p_N)(1-Q^{\mathcal{W}})\end{bmatrix} \quad (34)$$

Inserting the optimal strategies inside the HJBs in Eqs. (27) and (28), we can conjecture the expressions that satisfy the HJB equations associated with G and F as follows:

$$V_G^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})=S_1^{\mathcal{W}}+S_2^{\mathcal{W}}Q^{\mathcal{W}}+S_3^{\mathcal{W}}X^{\mathcal{W}}+S_4^{\mathcal{W}}Q^{\mathcal{W}^2} \quad (35)$$
$$V_F^{\mathcal{W}}(Q^{\mathcal{W}},X^{\mathcal{W}})=F_1^{\mathcal{W}}+F_2^{\mathcal{W}}Q^{\mathcal{W}}+F_3^{\mathcal{W}}X^{\mathcal{W}}+F_4^{\mathcal{W}}Q^{\mathcal{W}^2}+F_5^{\mathcal{W}}X^{\mathcal{W}^2}+F_6^{\mathcal{W}}Q^{\mathcal{W}}X^{\mathcal{W}}$$

where the coefficients of the value functions $S_i^{\mathcal{W}}$, $i=1..4$ and $F_i^{\mathcal{W}}$, $i=1..6$ are determined by identification. Using the constant terms $K_1=\overline{u}+\beta_N p_N-\frac{c_S}{c_U}-\alpha_N$, $K_2=\left(\frac{\omega}{c_U}-\alpha_B(1+g)+\alpha_N-\beta_N p_N\right)c_A c_U$, $K_3=c_A c_U(p_N-c_N)(\alpha_N-\beta_N p_N)$, $K_4=K_3+c_A(c_S-c_U\overline{u})\omega+c_A c_U\alpha_B c_F$, $K_5=c_A(r+2\delta)$, After substituting the value functions and the related derivatives in the HJBs, the coefficients can be easily obtained by solving the following ten algebraic Ricatti equations.

$$c_A S_3^{\mathcal{W}^2}+2c_U c_A K_1 S_3^{\mathcal{W}}+2c_U c_A\theta^2 S_2^{\mathcal{W}^2}-2c_U c_A r S_1^{\mathcal{W}}+c_A c_S(c_S-2c_U\overline{u})=0 \quad (36)$$
$$-(k+r)S_3^{\mathcal{W}}=0 \quad (37)$$
$$K_2 S_3^{\mathcal{W}}+c_U\left(2\theta^2 S_4^{\mathcal{W}}-c_A(r+\delta)\right)S_2^{\mathcal{W}}+c_A(c_U\overline{u}\omega-c_S\omega)=0 \quad (38)$$
$$2c_U c_B\left(2\theta^2 S_4^{\mathcal{W}}-c_A(r+2\delta)\right)S_4^{\mathcal{W}}+c_A c_B\omega^2=0 \quad (39)$$
$$c_U\theta^2 S_2^{\mathcal{W}}F_2^{\mathcal{W}}-rc_U c_A F_1^{\mathcal{W}}+\left(c_U c_A K_1+S_3^{\mathcal{W}}\right)F_3^{\mathcal{W}}+K_3=0 \quad (40)$$
$$c_U\theta^2 S_2^{\mathcal{W}}F_6^{\mathcal{W}}+2c_A F_5^{\mathcal{W}}\left(S_3^{\mathcal{W}}+c_U K_1\right)-c_A c_U(k+r)F_3^{\mathcal{W}}=0 \quad (41)$$
$$-2(2k+r)F_5^{\mathcal{W}}-c_X=0 \quad (42)$$
$$\left(2c_U\theta^2 S_2^{\mathcal{W}}F_4^{\mathcal{W}}-c_A\omega S_3^{\mathcal{W}}+K_2 F_3^{\mathcal{W}}\right)c_U c_A+c_A\left[K_1 c_U+S_3^{\mathcal{W}}\right]F_6^{\mathcal{W}}+c_U\left(2\theta^2 S_4^{\mathcal{W}}-\right.$$

$K_5)F_2^{\mathcal{W}} + K_4 = 0$ (43)

$$-c_U F_6^{\mathcal{W}}\left(c_A(\delta + k + r) - 2\theta^2 S_4^{\mathcal{W}}\right) - 2F_5^{\mathcal{W}} K_2 = 0 \tag{44}$$

$$-2c_A c_U c_B F_6^{\mathcal{W}} K_2 - 2c_A c_U F_4^{\mathcal{W}}\left(K_5 - 4\theta^2 S_4^{\mathcal{W}}\right) + c_A(\alpha_B^2 c_U \eta^2 - 2c_B\omega^2) = 0 \tag{45}$$

To get the coefficients in analytical form, one can solve the system of Riccati equations fixing $S_3^{\mathcal{W}} = 0$ and $F_5^{\mathcal{W}} = -\frac{c_X}{2(2k+r)} < 0$ from Eqs. (48) and (53), respectively. Then, use the constant terms $M_1 = c_A c_B \omega^2$, $M_2 = 4c_U c_B \theta^2$ and $M_3 = -2c_A c_U c_B(r + 2\delta)$, in Eq. (39) to derive $S_4^{\mathcal{W}}$ as follows:

$$S_4^{\mathcal{W}} = \frac{-M_3 \pm \sqrt{-4M_1M_2 + M_3^2}}{2M_2} \tag{46}$$

Since $M_3 < 0$, both solutions for $S_4^{\mathcal{W}} > 0$. When substituting these solutions of $S_4^{\mathcal{W}}$ inside Eq. (38) and solving with respect to $S_2^{\mathcal{W}}$, one gets $S_2^{\mathcal{W}}$ as a function of $S_4^{\mathcal{W}}$, specifically, $S_2^{\mathcal{W}} = f_1\left(S_4^{\mathcal{W}}\right)$, where $f_1\left(S_4^{\mathcal{W}}\right) = \frac{c_A(c_U(\overline{u}\omega - \alpha_B c_F \phi) - c_S\omega)}{[c_A(r+\delta) - 2\theta^2 S_4^{\mathcal{W}}]c_U}$, which results to be positive considering that the denominator of $Q_{SS}^{\mathcal{W}} = \frac{\theta^2 S_2^{\mathcal{W}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{W}}}$ is also positive. However, to guarantee positive values for $Q_{SS}^{\mathcal{W}}$, one should use the negative root of $S_4^{\mathcal{W}}$.
Considering that $S_3^{\mathcal{W}} = 0$, Eq. (36) reduces to $2c_U c_A \theta^2 S_2^{\mathcal{W}^2} - 2c_U c_A r S_1^{\mathcal{W}} + c_A c_S(c_S - 2c_U\overline{u}) = 0$. Solving it with respect to $S_1^{\mathcal{W}}$ gives $S_1^{\mathcal{W}}\left[f_1\left(S_4^{\mathcal{W}}\right)\right] = \frac{c_A c_S(c_S - 2c_U\overline{u}) + 2c_U c_A \theta^2 \left[f_1\left(S_4^{\mathcal{W}}\right)\right]^2}{2c_U c_A r}$.
Once $S_4^{\mathcal{W}}$ is correctly derived, one can easly obtain the other coefficients as follows:

- Substitute in Eq. (44) to obtain the equation $-c_U F_6^{\mathcal{W}}\left(c_A(\delta + k + r) - 2\theta^2 S_4^{\mathcal{W}}\right) + \frac{c_X K_2}{2k+r} = 0$, which can be solved with respect to $F_6^{\mathcal{W}}$ and see that $F_6^{\mathcal{W}} = f_2\left(S_4^{\mathcal{W}}\right)$. Specifically $f_2\left(S_4^{\mathcal{W}}\right) = \frac{c_X K_2}{(2k+r)c_U(c_A(\delta+k+r) - 2\theta^2 S_4^{\mathcal{W}})}$ which is positive since both the numerator and the denoninator are positive.

- Substitute $F_6^{\mathcal{W}} = f_2\left(S_4^{\mathcal{W}}\right)$ inside Eq. (45) and solve with respet to $F_4^{\mathcal{W}}$ to obtain $F_4^{\mathcal{W}} = f_3\left(S_4^{\mathcal{W}}, f_2\left(S_4^{\mathcal{W}}\right)\right) = f_4(S_4^{\mathcal{W}})$, where $f_4\left(S_4^{\mathcal{W}}\right) = = \frac{c_A(\alpha_B^2 c_U \eta^2 - 2c_B\omega^2) - 2c_A c_U c_B f_2(S_4^{\mathcal{W}})K_2}{2c_A c_U(K_5 - 4\theta^2 S_4^{\mathcal{W}})}$.

- Substitute $S_3^{\mathcal{W}} = 0, F_5^{\mathcal{W}} = -\frac{c_X}{2(2k+r)}$, $S_2^{\mathcal{W}} = f_1\left(S_4^{\mathcal{W}}\right)$ and $F_6^{\mathcal{W}} = f_2\left(S_4^{\mathcal{W}}\right)$ inside Eq. (41), which reduced to $c_U\theta^2 f_1\left(S_4^{\mathcal{W}}\right) f_2\left(S_4^{\mathcal{W}}\right) - \frac{c_X c_A c_U K_1}{(2k+r)} - c_A c_U(k + r)F_3^{\mathcal{W}} = 0$. Solving with respect to $F_3^{\mathcal{W}}$, it results that $F_3^{\mathcal{W}} = f_5(f_1\left(S_4^{\mathcal{W}}\right), f_2\left(S_4^{\mathcal{W}}\right)) = f_6\left(S_4^{\mathcal{W}}\right)$; in particular, $f_6\left(S_4^{\mathcal{W}}\right) = -\frac{c_X c_A K_1 - (2k+r)\theta^2 f_1(S_4^{\mathcal{W}}) f_2(S_4^{\mathcal{W}})}{c_A(k+r)(2k+r)}$.

- Substitute $S_2^{\mathcal{W}} = f_1\left(S_4^{\mathcal{W}}\right), F_4^{\mathcal{W}} = f_4\left(S_4^{\mathcal{W}}\right), S_3^{\mathcal{W}} = 0, F_6^{\mathcal{W}} = f_2\left(S_4^{\mathcal{W}}\right)$ and $F_3^{\mathcal{W}} = f_6\left(S_4^{\mathcal{W}}\right)$ inside Eq. (43). Solving it with respect to $F_2^{\mathcal{W}}$, it results that $F_2^{\mathcal{W}} = f_7\left(S_4^{\mathcal{W}}, f_1\left(S_4^{\mathcal{W}}\right), f_4\left(S_4^{\mathcal{W}}\right), f_6\left(S_4^{\mathcal{W}}\right)\right) = f_8\left(S_4^{\mathcal{W}}\right)$

where $f_8\left(S_4^{\mathcal{W}}\right)=\frac{K_4+\left(2c_U\theta^2 S_2^{\mathcal{W}} f_4\left(S_4^{\mathcal{W}}\right)+K_2 f_6\left(S_4^{\mathcal{W}}\right)\right)c_U c_A+c_A K_1 c_U f_2\left(S_4^{\mathcal{W}}\right)}{c_U\left(K_5-2\theta^2 S_4^{\mathcal{P}}\right)}$.

- Substitute $F_3^{\mathcal{W}}=f_6\left(S_4^{\mathcal{W}}\right)$, $S_2^{\mathcal{W}}=f_1\left(S_4^{\mathcal{W}}\right)$ and $F_2^{\mathcal{W}}=f_8\left(S_4^{\mathcal{W}}\right)$ inside Eq. (40). Soving it with respect to $F_1^{\mathcal{W}}$, it results that $F_1^{\mathcal{W}}=f_9\left(f_6\left(S_4^{\mathcal{W}}\right),f_1\left(S_4^{\mathcal{W}}\right),f_8\left(S_4^{\mathcal{W}}\right)\right)=f_{10}\left(S_4^{\mathcal{W}}\right)$, where $f_{10}\left(S_4^{\mathcal{W}}\right)=\frac{c_U\theta^2 f_1\left(S_4^{\mathcal{W}}\right)f_8\left(S_4^{\mathcal{W}}\right)+c_U c_A K_1 f_6\left(S_4^{\mathcal{W}}\right)+K_3}{r c_U c_A}$.

1.10 Appendix B

Let us denote by $V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ and $V_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ the supplier's and the football club's value functions associated to the $\mathcal{P}$ −game, respectively. Then, $\partial_Q V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ and $\partial_Q V_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ are the derivatives with respect to the state function $Q^{\mathcal{P}}$ and $\partial_X V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ and $\partial_X V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ are the derivatives with respect to the state function $X^{\mathcal{P}}$. The HJB equations are given by:

$$rV_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})=D_B^{\mathcal{P}}(\eta B^{\mathcal{P}}-c_F)\phi+[\omega Q^{\mathcal{P}}-c_S]u^{\mathcal{P}}-c_U\frac{\left(u^{\mathcal{P}}-\overline{u}\right)^2}{2}-c_A\frac{\left(q^{\mathcal{P}}\right)^2}{2}+$$
$$+\partial_Q V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})[\theta q^{\mathcal{P}}-\delta Q^{\mathcal{P}}]+$$
$$+\partial_X V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})[u^{\mathcal{P}}-kX^{\mathcal{P}}-\alpha_B(1+g)Q^{\mathcal{P}}-(\alpha_N-\beta_N p_N)(1-Q^{\mathcal{P}})]$$

$$rV_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})=D_B^{\mathcal{P}}(\eta B^{\mathcal{P}}-c_F)(1-\phi)+D_N^{\mathcal{P}}\left(p_N^{\mathcal{P}}-c_N\right)-\omega Q^{\mathcal{P}}u^{\mathcal{P}}-c_B\frac{\left(B^{\mathcal{P}}\right)^2}{2}-c_X\frac{\left(X^{\mathcal{P}}\right)^2}{2}$$
$$+\partial_Q V_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})[\theta q^{\mathcal{P}}-\delta Q^{\mathcal{P}}]+$$
$$+\partial_X V_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})[u^{\mathcal{P}}-kX^{\mathcal{P}}-\alpha_B(1+g)Q^{\mathcal{P}}-(\alpha_N-\beta_N p_N)(1-Q^{\mathcal{P}})]$$

Deriving $V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ with respect to $u^{\mathcal{P}}$ and $q^{\mathcal{P}}$ as well as $V_F^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})$ with respect to $B^{\mathcal{P}}$, we obtain a system of equation, whose resolution gives the following optimal strategies:

$$u^{\mathcal{P}^*}=\frac{\partial_X V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})-c_S+c_U\overline{u}+Q^{\mathcal{P}}\omega}{c_U}$$

$$q^{\mathcal{P}^*}=\frac{\theta\ \partial_Q V_G^{\mathcal{P}}(Q^{\mathcal{P}},X^{\mathcal{P}})}{c_A}$$

$$B^{\mathcal{P}^*}=\frac{\alpha_B\eta Q^{\mathcal{P}}(1-\phi)}{c_B}$$

Inserting the optimal strategies inside the HJBs, we can conjecture the expressions that satisfy the HJB equations associated with G and F as follows:

$$V_G^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}}) = S_1^{\mathcal{P}} + S_2^{\mathcal{P}} Q^{\mathcal{P}} + S_3^{\mathcal{P}} X^{\mathcal{P}} + S_4^{\mathcal{P}} Q^{\mathcal{P}^2}$$

$$V_F^{\mathcal{P}}(Q^{\mathcal{P}}, X^{\mathcal{P}}) = F_1^{\mathcal{P}} + F_2^{\mathcal{P}} Q^{\mathcal{P}} + F_3^{\mathcal{P}} X^{\mathcal{P}} + F_4^{\mathcal{P}} Q^{\mathcal{P}^2} + F_5^{\mathcal{P}} X^{\mathcal{P}^2} + F_6^{\mathcal{P}} Q^{\mathcal{P}} X^{\mathcal{P}}$$

where the coefficients of the value functions $S_i^{\mathcal{P}}, i = 1..4$ and $F_i^{\mathcal{P}}, i = 1..6$ are determined by identification. After substituting the value functions and the related derivatives in the HJBs, the coefficients can be easily obtained by solving the following ten algebraic Ricatti equations.

$$c_A S_3^{\mathcal{P}^2} + 2c_U c_A K_1 S_3^{\mathcal{P}} + 2c_U c_A \theta^2 S_2^{\mathcal{P}^2} - 2c_U c_A r S_1^{\mathcal{P}} + c_A c_S (c_S - 2c_U \overline{u}) = 0 \quad (47)$$

$$-(k + r) S_3^{\mathcal{P}} = 0 \quad (48)$$

$$K_2 S_3^{\mathcal{P}} + c_U \left(2\theta^2 S_4^{\mathcal{P}} - c_A(r + \delta)\right) S_2^{\mathcal{P}} + c_A(c_U(\overline{u}\omega - \alpha_B c_F \phi) - c_S \omega) = 0 \quad (49)$$

$$2c_U c_B \left(2\theta^2 S_4^{\mathcal{P}} - c_A(r + 2\delta)\right) S_4^{\mathcal{P}} + c_A(c_B \omega^2 - 4c_U \alpha_B^2 \eta^2 \phi^2) = 0 \quad (50)$$

$$c_U \theta^2 S_2^{\mathcal{P}} F_2^{\mathcal{P}} - r c_U c_A F_1^{\mathcal{P}} + \left(c_U c_A K_1 + S_3^{\mathcal{P}}\right) F_3^{\mathcal{P}} + K_3 = 0 \quad (51)$$

$$c_U \theta^2 S_2^{\mathcal{P}} F_6^{\mathcal{P}} + 2c_A F_5^{\mathcal{P}} \left(S_3^{\mathcal{P}} + c_U K_1\right) - c_A c_U (k + r) F_3^{\mathcal{P}} = 0 \quad (52)$$

$$-2(2k + r) F_5^{\mathcal{P}} - c_X = 0 \quad (53)$$

$$\left(2c_U \theta^2 S_2^{\mathcal{P}} F_4^{\mathcal{P}} - c_A \omega S_3^{\mathcal{P}} + K_2 F_3^{\mathcal{P}} + \alpha_B c_F \phi\right) c_U c_A + c_A\left[K_1 c_U + S_3^{\mathcal{P}}\right] F_6^{\mathcal{P}} +$$
$$c_U\left(2\theta^2 S_4^{\mathcal{P}} - K_5\right) F_2^{\mathcal{P}} + K_4 = 0 \quad (54)$$

$$-c_U F_6^{\mathcal{P}} \left(c_A(\delta + k + r) - 2\theta^2 S_4^{\mathcal{P}}\right) - 2F_5^{\mathcal{P}} K_2 = 0 \quad (55)$$

$$-2c_A c_U c_B F_6^{\mathcal{P}} K_2 - 2c_A c_U F_4^{\mathcal{P}} \left(K_5 - 4\theta^2 S_4^{\mathcal{P}}\right) + c_A(\alpha_B^2 c_U \eta^2 (1 - \phi)^2 - 2c_B \omega^2) = 0$$
(56)

To get the coefficients in analytical form, one can solve the system of Riccati equations fixing $S_3^{\mathcal{P}} = 0$ and $F_5^{\mathcal{P}} = -\frac{c_X}{2(2k+r)} < 0$ from Eqs. (48) and (53), respectively. Then, use the constant terms $N_1 = c_A(c_B \omega^2 - 4c_U \alpha_B^2 \eta^2 \phi^2)$, $N_2 = 4c_U c_B \theta^2$ and $N_3 = -2c_A c_U c_B (r + 2\delta)$, in Eq. (50) to derive $S_4^{\mathcal{P}}$ as follows:

$$S_4^{\mathcal{P}} = \frac{-N_3 \pm \sqrt{-4N_1 N_2 + N_3^2}}{2N_2} \quad (57)$$

Since $N_3 < 0$, both solutions for $S_4^{\mathcal{P}} > 0$. When substituting these solutions of $S_4^{\mathcal{P}}$ inside Eq. (49) and solving with respect to $S_2^{\mathcal{P}}$, one gets $S_2^{\mathcal{P}}$ as a function of $S_4^{\mathcal{P}}$, specifically, $S_2^{\mathcal{P}} = f_1(S_4^{\mathcal{P}})$, where $f_1(S_4^{\mathcal{P}}) = \frac{c_A(c_U(\overline{u}\omega - \alpha_B c_F \phi) - c_S \omega)}{[c_A(r+\delta) - 2\theta^2 S_4^{\mathcal{P}}] c_U}$, which results to be positive considering that the denominotor of $Q_{SS}^{\mathcal{P}} = \frac{\theta^2 S_2^{\mathcal{P}}}{\delta c_A - 2\theta^2 S_4^{\mathcal{P}}}$ is also positive. However, to guarantee positive values for $Q_{SS}^{\mathcal{P}}$, one should use the negative root of $S_4^{\mathcal{P}}$.

Considering that $S_3^{\mathcal{P}} = 0$, Eq. (47) reduces to $2c_U c_A \theta^2 S_2^{\mathcal{P}^2} - 2c_U c_A r S_1^{\mathcal{P}} + c_A c_S(c_S - 2c_U \overline{u})$. Solving it with respect to $S_1^{\mathcal{P}}$ gives $S_1^{\mathcal{P}}[f_1(S_4^{\mathcal{P}})] = \frac{c_A c_S(c_S - 2c_U\overline{u}) + 2c_U c_A \theta^2 [f_1(S_4^{\mathcal{P}})]^2}{2c_U c_A r}$.

Once $S_4^{\mathcal{P}}$ is correctly derived, one can easly obtain the other coefficients as follows:

- Substitute in Eq. (55) to obtain the equation $-c_U F_6^{\mathcal{P}}(c_A(\delta + k + r) - 2\theta^2 S_4^{\mathcal{P}}) + \frac{c_X K_2}{2k+r} = 0$, which can be solved with respect to $F_6^{\mathcal{P}}$ and see that $F_6^{\mathcal{P}} = f_2(S_4^{\mathcal{P}})$. Specifically $f_2(S_4^{\mathcal{P}}) = \frac{c_X K_2}{(2k+r)c_U(c_A(\delta+k+r) - 2\theta^2 S_4^{\mathcal{P}})}$ which is positive since both the numerator and the denoninator are positive.

- Substitute $F_6^{\mathcal{P}} = f_2(S_4^{\mathcal{P}})$ inside Eq. (56) and solve with respet to $F_4^{\mathcal{P}}$ to obtain $F_4^{\mathcal{P}} = f_3\left(S_4^{\mathcal{P}}, f_2(S_4^{\mathcal{P}})\right) = f_4(S_4^{\mathcal{P}})$, where $f_4(S_4^{\mathcal{P}}) = = \frac{c_A(\alpha_B^2 c_U \eta^2 (1-\phi)^2 - 2c_B \omega^2) - 2c_A c_U c_B f_2(S_4^{\mathcal{P}}) K_2}{2c_A c_U(K_5 - 4\theta^2 S_4^{\mathcal{P}})}$.

- Substitute $S_3^{\mathcal{P}} = 0, F_5^{\mathcal{P}} = -\frac{c_X}{2(2k+r)}$, $S_2^{\mathcal{P}} = f_1(S_4^{\mathcal{P}})$ and $F_6^{\mathcal{P}} = f_2(S_4^{\mathcal{P}})$ inside Eq. (52), which reduced to $c_U \theta^2 f_1(S_4^{\mathcal{P}}) f_2(S_4^{\mathcal{P}}) - \frac{c_X c_A c_U K_1}{(2k+r)} - c_A c_U (k+r) F_3^{\mathcal{P}} = 0$. Solving with respect to $F_3^{\mathcal{P}}$, it results that $F_3^{\mathcal{P}} = f_5(f_1(S_4^{\mathcal{P}}), f_2(S_4^{\mathcal{P}})) = f_6(S_4^{\mathcal{P}})$; in particular, $f_6(S_4^{\mathcal{P}}) = -\frac{c_X c_A K_1 - (2k+r)\theta^2 f_1(S_4^{\mathcal{P}}) f_2(S_4^{\mathcal{P}})}{c_A(k+r)(2k+r)}$.

- Substitute $S_2^{\mathcal{P}} = f_1(S_4^{\mathcal{P}})$, $F_4^{\mathcal{P}} = f_4(S_4^{\mathcal{P}})$, $S_3^{\mathcal{P}} = 0$, $F_6^{\mathcal{P}} = f_2(S_4^{\mathcal{P}})$ and $F_3^{\mathcal{P}} = f_6(S_4^{\mathcal{P}})$ inside Eq. (54). Solving it with respect to $F_2^{\mathcal{P}}$, it results that $F_2^{\mathcal{P}} = f_7\left(S_4^{\mathcal{P}}, f_1(S_4^{\mathcal{P}}), f_4(S_4^{\mathcal{P}}), f_6(S_4^{\mathcal{P}})\right) = f_8(S_4^{\mathcal{P}})$ where $f_8(S_4^{\mathcal{P}}) = \frac{K_4 + (2c_U \theta^2 S_2^{\mathcal{P}} f_4(S_4^{\mathcal{P}}) + K_2 f_6(S_4^{\mathcal{P}}) + \alpha_B c_F \phi) c_U c_A + c_A K_1 c_U f_2(S_4^{\mathcal{P}})}{c_U(K_5 - 2\theta^2 S_4^{\mathcal{P}})}$.

- Substitute $F_3^{\mathcal{P}} = f_6(S_4^{\mathcal{P}})$, $S_2^{\mathcal{P}} = f_1(S_4^{\mathcal{P}})$ and $F_2^{\mathcal{P}} = f_8(S_4^{\mathcal{P}})$ inside Eq. (51). Soving it with respect to $F_1^{\mathcal{P}}$, it results that $F_1^{\mathcal{P}} = f_9\left(f_6(S_4^{\mathcal{P}}), f_1(S_4^{\mathcal{P}}), f_8(S_4^{\mathcal{P}})\right) = f_{10}(S_4^{\mathcal{P}})$, where $f_{10}(S_4^{\mathcal{P}}) = \frac{c_U \theta^2 f_1(S_4^{\mathcal{P}}) f_8(S_4^{\mathcal{P}}) + c_U c_A K_1 f_6(S_4^{\mathcal{P}}) + K_3}{r c_U c_A}$.

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Chapter 2

Supply chain fairness and bargaining power in agriculture supply chain: the blockchain effect

Abstract

Supply chain fairness is the fair and impartial treatment of all supply chain members without favoritism or discrimination. Many agricultural supply chains in developing countries are characterized by poor conditions of local farmers that preclude supply chain fairness. Blockchain is a technology that through the traceability of agricultural supply chains is used to address this problem. We use an empirical study and simulation with system dynamics to test the impact of blockchain and bargaining power on supply chain fairness. We find that a blockchain is an effective tool for improving supply chain fairness through its impact on bargaining power.

2.1 Introduction

Supply chain fairness is defined as the fair and impartial treatment of all supply chain members without favoritism or discrimination (Chen et al., 2022; Liu et al., 2012). Supply chain fairness is attracting growing interest among consumers. Consumers say they care and are willing to pay more not only for sustainable products but also for products that ensure that the minimum needs of all actors involved in the supply chain are met (Izaret, 2022; Jameson et al., 2022; Kopka et al., 2020). As a result, certifiers to ensure supply chain fairness have emerged and are consolidating their position. For example, Fair Traide is an organization dedicated to certifying that the raw materials used in their branded products have been produced following stringent social sustainability criteria. The products Fair Trade targets mainly involve agricultural products where the raw material is grown in developing countries, such as cocoa, sugar, and cotton. Despite these attempts, much of the global agricultural supply chain remains largely unfair and farmers live below the poverty line while large multinational corporations record increasing profits. If we consider the cocoa supply chain. Cocoa is among the top 5 agricultural commodities traded in global markets with an estimated value approaching $200 billion in 2026 (Voora et al., 2019). Most of the cocoa produced in the world comes from Central Africa with Ivory Coast and Ghana responsible for 60% of global production. All of the cocoa is exported, mainly to Europe and the United States where it is processed into chocolate or semi-finished products. The supply chain is characterized by an hourglass shape. We can identify about five million small local producers, tens of millions of end consumers, and eight companies responsible for more than 75% of processing and export activities (United Nations, 2016). This system is unsustainable for Ivory Coast farmers that earn an average of $0.5 per day against a minimum wage to be above the poverty threshold set by the World Bank at $2 per day (Amiel et al., 2019). As a result, child exploitation, deforestation to make new plantations, diseases from the use of chemicals, to civil wars in many cases are common phenomena. On the other hand, the multinational firms in the middle of the supply chain are global corporations with billions of dollars in profits.

Our study focuses on the supply chain of cocoa from the Ivory Coast to Europe and investigates whether asymmetric bargaining power may be one of the causes of the lack of supply chain fairness. We adopt a resource dependence theory perspective and consider bargaining power as the result of the possession of unique and valuable resources by one of the parties involved in a transaction (Argyres and Liebeskind, 1999; Pfeffer and Salancik, 1978; Cheng et al., 2021). It appears from the literatures that financial resources (Parviziomran and Elliot, 2023; Towner, 2020), information (Chen et al., 2017; Guo, 2023) and relational resources (Matsui, 2022; Sheu and Gao, 2014) are among the resources that most influence bargaining power. Although no one has investigated the effect of bargaining power on supply chain fairness, we find it interesting to investigate this relationship as some studies develop the idea that some resources may influence supply chain fairness (Chen et al., 2022; Choi and Messinger, 2016; Wu and Niederhoff, 2014). In contrast, we argue that resources do not directly influence supply chain fairness but do so through bargaining power. Our first research question is: RQ1: How does bargaining power asymmetry affect supply chain fairness?

Although organizations such as Fair Trade have been operating for dozens of years the problem related to unfair agricultural supply chains is far from being solved. To improve this condition some non-governmental entities and companies are promoting the use of blockchain technology for supply chain traceability and supply chain fairness improvement. Early companies that have addressed this challenge include Cocoblock, Koa, and Trusty. Trusty has developed a patented solution that allows to record more than 30 information on the blockchain including cocoa prices, quality, and quantity even in the absence of an internet connection (Ruzza et al., 2022). The innovation of Trusty lies in the fact that it allows farmers from developing countries, and therefore poorly covered by technological infrastructure, to directly enter information on blockchain. In addition, they can access certain and relevant information such as weather forecasts or price trends. Among the advantages that blockchain provides over traditional certifiers, the literature has identified disintermediation, trust-building among actors, transparency, and ensuring the integrity of the supply chain (Biswas et al., 2023; Nayal et al., 2021). These benefits are driven by blockchain's effect of changing the distribution of resources available to companies involved in the supply chain. Blockchain facilitates access to information to actors who are usually excluded from it or who have access to unreliable information (Casino et al., 2020; Guo et al., 2021; Wang et al., 2021) and allows a different redistribution of financial resources by acting on prices and debt capacity (Agrawal et al., 2022; Bai et al., 2019; Yi et al., 2021). However, it is unclear whether blockchain, acting on resources, could change bargaining power dynamics and influence supply chain fairness. Our second research question is: RQ2: What is the blockchain impact on bargaining power asymmetry and supply chain fairness?

We answer the research questions with a two-step study. First, we conduct an empirical study built on a series of interviews with 3 experts in the field, and 42 reports published by 14 organizations. Based on the evidence from the empirical study, we built a system dynamics model on Vensim to simulate the relationships between variables over time and test our hypotheses. We obtain three main results. First, reducing bargaining power asymmetries between farmers and multinational corporations responsible for cocoa export has a positive effect on supply chain fairness by improving farmers' condition. Second, we introduce blockchain into our model by isolating its effect on information and financial resources. We find that blockchain allows reducing information asymmetries by decreasing bargaining power asymmetries. In addition, blockchain allows farmers to receive a higher price for their product by decreasing bargaining power asymmetries. With blockchain adoption being equal, the effect on bargaining power determined by financial resources is greater than that determined by information. Third, we introduce the combined effect of blockchain on information and financial resources and see that this results in improved supply chain fairness. However, blockchain alone is not sufficient to ensure a level of fairness such that all farmers are outside the poverty line. The rest of the paper is organized as follows: section 2 analyzes the supply chain literature on bargaining power, supply chain fairness and blockchain from a resource dependence theory perspective, section 3 presents the research method, section 4 describes the results, section 5 clarifies the contributions section 6 concludes the paper.

2.2 Literature review

2.2.1 Bargaining power and resource dependence theory perspective

Bargaining power can be defined as the ability of a party to influence the terms and conditions of one or more business relationships in its favor through the possession of unique and valuable resources (Argyres and Liebeskind, 1999; Cheng et al., 2021; Sheu and Gao, 2014). Building from resource dependence theory, bargaining power comes from some firms' ownership of resources that are important and for which control is concentrated (Cheng et al., 2021). Two factors determine the importance of a resource: magnitude which refers to the proportion of input/output that resource represents, criticality which refers to the possibility of continuing operations without that resource (Pfeffer and Salancik, 1978). Supply chain members who are able to control these resources increase their bargaining power and are in a position of dominance over other chain members (Crook and Combs, 2007). Conversely, chain members who are dependent on these resources are at a disadvantage because they have less bargaining power.

Several studies in supply chain literature have explored bargaining power from the resource dependence theory perspective. Below we present some interesting works for this paper by classifying them based on the resource that is most considered. Financial resources seem to have a bidirectional effect on bargaining power. Parviziomran and Elliot, (2023) study how bargaining power affects trade credit. The results show that bargaining power influences the amount of trade credit that supply chain members can accumulate. The relationship can also be in the other direction, Towner, (2020) studies the effect of debt on bargaining power. Analyzing a sample of U.S. hospitals, he finds that higher debt is associated with greater bargaining power. Firms with lower bargaining power are those that benefit most from increased debt. Similarly, Huang et al., (2019) show that bargaining power influences the ability to appropriate benefits from the disposition of the financial resource. The authors study the combined impact of wholesale price decision and bargaining power on supply chain actors' strategies in the presence of credit guaranteed loans. The results show that a decrease in wholesale price decreases the bargaining power of the retailer. The retailer with lower bargaining power has a higher probability of losing from the financing since it is unable to capture the benefits. On the other hand, a supplier with strong bargaining power is less likely to take risks and make financing.

Another resource that has a major impact on bargaining power is information. Guo, (2023) look at information asymmetries and information strategies in a bargaining process. The authors show that the effect of information gathering is symmetrical for buyer and seller. As the bargaining power of the information collector increases, more information is collected. In addition, higher bargaining power may result in lower expected gain due to the counterparty's reduced incentive to collect information. Chen et al., (2017) investigate how bargaining power structures affect performance in a supply chain in the presence of information asymmetry. The results show that the manufacturer benefits from improvements in demand and cost reduction only when it has bargaining power. Moreover, when the retailer has a lot of bargaining power, prices should always be at the high end.

The last resource we consider is the relational resource and refers to the ties between a firm and external entities (Davis and Mentzer, 2008). Sheu and Gao, (2014) show that having more ties represents an advantage in terms of bargaining power. The authors consider the negotiation between supplier and manufacturer in reverse logistics. The authors study how supplier alliances affect bargaining power and the impact of a change in bargaining power on profits. The results show that supplier alliances alter bargaining power and pose a threat to manufacturers. Increasing the bargaining power of one of the parties ensures higher profits from negotiations. Similarly, Matsui, (2022) take the perspective of a retailer in a dual channel supply chain and study whether the retailer should use its bargaining power, if it had it, to negotiate a better wholesale price or accept the one set unilaterally by the manufacturer. The results show that with a single channel it should use bargaining power but in a dual channel the retailer gets higher profits if it accepts the wholesale price set unilaterally by the manufacturer.

It emerges from the analyzed papers that the asymmetry of bargaining power, resulting from the unbalanced control of relevant resources, results in a weak and a strong party in the exchanges within the supply chain. The strong party has the ability to appropriate more of the shared value in the supply chain (Chang et al., 2022). It follows that lower bargaining power represents a disadvantage. The party with greater bargaining power may decide to make shrewd use of the power at its disposal (Crook and Combs, 2007). However, if the stronger party decides to make unwise use of the bargaining power at its disposal, it could create conditions for harassment of the weaker party that would fail to capture sufficient value from the supply chain.

2.2.2 Supply chain fairness

Supply chain fairness is defined as the fair and impartial treatment of all supply chain members without favoritism or discrimination (Chen et al., 2022). In the literature supply chain fairness is often used as a synonym for justice reflecting the economic and social damage resulting from the lack of supply chain fairness (Liu et al., 2012). Supply chain fairness has been measured in the literature through the Rawlsian principle, which uses the utility of the most disadvantaged individual to determine the fairness of an economic system (Jiang et al., 2021). Chen et al., (2022), in a recent theoretical paper, recognize the relevance of supply chain fairness and make a call for studies on the topic. The authors investigate the challenges, benefits, and opportunities of implementing supply chain fairness in supply chains and identify three types of fairness in the literature: distributional, procedural and interactional. They then choose to focus on distributional fairness, which concerns how outcomes are distributed. In this dimension they distinguish fair price, fair trade, and fair pay. Unfair practices occur when distortions occur in the market that may result from a sudden change in demand or supply, limited opportunities for change by workers or trading partners, or information asymmetry. Distributional fairness seems to be the dimension that has attracted the most interest in the literature, and numerous studies have investigated its linkage with various performance measures. Ho et al., (2014) consider one supplier and two retailer supply chain and investigate the role of distributional fairness and peer induced fairness on wholesale and retail price. In the presence of distributional fairness, the supplier will demand a lower wholesale price than the retailer. However, in the case where the exchange does not occur simultaneously but is sequential orderthe second retailer will have a higher wholesale price and a lower profit than the first retailer. This also occurs in the presence of peer induced fairness. Liu et al., (2012) recognize that fairness in a relationship is more relevant if it is perceived by both parties involved. The authors investigate how mutual perceptions of distributive, procedural, interpersonal, and informational fairness drive relational performance and which type of fairness has the greatest influence. The results show that a higher level of mutual perceived fairness results in higher levels of coupling behaviors, which in turn has a positive impact on relational performance. However, in some cases maximizing the utility of a system may bring results that are not necessarily fair (Agnetis et al., 2019). While the fair condition might require utility costs called price of fairness that decrease the overall utility of the system (Agnetis et al., 2019).

Certain conditions favor the presence of supply chain fairness such as concern for the fairness of the parties and the presence of repeated trade. Wu and Niederhoff, (2014) study the impact of fairness concerns on supply chain performance focusing on distributional fairness. The results show that supply chain coordination can be achieved when parties have fairness concerns in the chain. A win-win situation is achieved when demand variability is sufficiently high and seller fairness concern is medium. Choi and Messinger, (2016) in an experimental study investigate the implications of fairness in a supply chain where participants have multiple interactions. The results show that the distribution of profits is very fair in all the settings analyzed, this could be due to the repeated interactions and the tendency of the parties to imitate the behavior of competitors. The retailer appears to be more concerned with respect to the fairness of manufacturers. Oyedijo et al., (2021) study the role of fairness in the relationships of multi-tier sustainable supply chains and how fairness manifests itself at different stages of the relationships. The authors show that fairness is an antecedent of collaboration in multi-tier sustainable supply chains. When fairness is perceived, it has a positive impact on current relationships, facilitating among other things information sharing, and on future relationships.

Chen et al., (2022) argue that unfair practices emerge on supply chains because some firms want to extract more economic value from supply chains than other chain members. Among the reasons that lead to this situation they identify the limited ability to change partners within the chain such as suppliers and the limited flow of information between chain members (Chen et al., 2022; Choi and Messinger, 2016; Wu and Niederhoff, 2014). Information is a resource that influences the bargaining power of chain members. Relationships in the chain are also an intangible supply chain resource. Previous literature has built the conditions to believe that it is not resources themself that influence supply chain fairness but rather it is the bargaining power that comes from the combination of these resources. There may be a relationship between bargaining power and supply chain fairness not yet considered in the literature. From our best knowledge, there have been an extremely limited number of papers that have considered the relationship between bargaining power and supply chain fairness, and none of these have tested it empirically. Du et al., (2014) study the newsvendor problem in a dyadic supply chain where both the supplier and retailer have concerns about fairness. The results show that market size and bargaining power of actors can influence chain performance. However, the authors do not investigate the impact of bargaining power on fairness. Ho et al., (2014) find that when in a seller-buyer relationship one of the parties gives a take-or-leave ultimatum trying to appropriate a larger portion of a limited pie the offer is often rejected as it is deemed unfair. In contrast when bargaining is instituted it is more likely to succeed in reaching an agreement. The presence of bargaining seems to influence supply chain fairness but xthe authors do not investigate the effect of bargaining power. We hypothesize that supply chain fairness might be influenced by the asymmetry of bargaining power of the parties that emerges from the resources they have at their disposal. The asymmetry of power between the parties determines which party is vulnerable (Oyedijo et al., 2021; Wu and Niederhoff, 2014). Our first hypothesis is:

H1: The more the bargaining power asymmetries decrease the more supply chain fairness increase.

2.2.3 Blockchain and resource dependence theory perspective

Recent studies in supply chain literature are exploring the relationship between blockchain and bargaining power with a resource dependence theory perspective. Gruchmann, (2022) in a conceptual paper uses the resource dependence theory perspective to analyze supply network characteristics from a power point of view. The authors find that blockchain, through disintermediation, decentralization, and reduction of information asymmetries, is the technology that could enable decreasing power asymmetries in multilevel supply chains. Kamble et al., (2020) developed a structured literature review on the sustainable performance of agri-food supply chains and the role of information with a resource dependence theory perspective. Among the results the authors show that supply chain visibility and data management, achieved through blockchain, are among the key elements in improving sustainable performance. Rejeb et al., (2021) study the potential of blockchain for supply chain collaboration. It emerges that blockchain can improve supply chain collaboration, and among the main reasons for this finding are improved trust, power dynamics, information sharing, and resources in general. Although these papers give encouraging indications, the effect on bargaining power asymmetries is understudied.

From a recourse dependence theory perspective blockchain can alter the resource structure in a supply chain and thus impact bargaining power. Bargaining power asymmetries between parties can undergo even radical changes. In this section, we categorize the studies that consider blockchain and the resources previously reviewed and present them according to the resource most considered in each paper. From the literature review, information emerges as the most analyzed resource in blockchain studies. Looking at agricultural supply chains we identify two interesting studies. Nayal et al., (2021) identify the lack of integration of small-scale farmers, the lack of strict food quality and safety standards, and the lack of reliable information as the major problems in agricultural supply chains and investigate the use of blockchain as a possible solution to these problems. Their article aims to identify the critical success factors of blockchain in this environment. The proposed model identifies nine factors. Cost, green and lean practices, and internal and external environmental conditions are the most relevant factors for blockchain adoption. Casino et al., (2020) develop a blockchain architecture to create a traceability mechanism in food supply chains. The results show that blockchain creates benefits in trust, quality, efficiency, and resilience of the supply chain. It minimizes operational costs related to traceability and breaks down system boundaries and geographical limitations. In addition, it creates benefits for the regulatory framework as it mobilizes food verification authorities, simplifies, and automates the flow of information, and facilitates regulators' access to traceability information.

If we refer to other sectors, the impacts of blockchain on the information resource seem equally relevant. Guo et al., (2021) consider the application of smart contracts in the clean energy supply chain. The possible benefits of introducing a smart contract are twofold: managing solar uncertainties by excluding the possibility of tampering and reducing the risk of renegotiation between the parties. The results show that smart contracts lead to benefits for both poor and rich households and the government. Lohmer et al., (2020) in a simulation model, analyze the role of collaboration to increase resilience in supply chains. Collaboration translates into information sharing, decision synchronization, resource sharing, collaborative communication, and goal alignment. Blockchain is a technology that, enhancing collaboration, can increase resilience. The results show positive effects of using blockchain but also negative implications such as the deterioration of collaboration. Wang et al., (2021) consider the trust issues toward the provider of 'dirty' data. The authors develop a blockchain-based system architecture where a smart contract is embedded. A smart contract is a possible solution to this problem as it strengthens trust and improves information sharing. The results show that the blockchain-based solution with a voting mechanism solves the trust problem and reduces 'dirty' data by increasing the perceived quality of the service. Manupati et al., (2020) consider the use of blockchain to track the supply chain carbon emissions. They take into account lead times, inventory constraints, regular and extraordinary production rates, costs, and carbon taxation. The results show that the use of blockchain facilitates the flow of information along the supply chain by enabling the traceability and exchange of carbon allowances between actors. It also makes it easier for consumers and producers to comply with government policies. We hypothesize an impact of blockchain on bargaining power through information asymmetries. Specifically, bargaining power asymmetries should decrease as a consequence of improved information flow between supply chain actors.

H2: The more the blockchain adoption increase the more the bargaining power asymmetries decrease because of the blockchain effect on information.

Blockchain can have a direct or indirect impact on financial resources. If we refer to direct impact, we can consider the study by Agrawal et al., (2022) which investigates how blockchain-based smart contracts foster resource sharing, collaboration and utilization in supply chains. The resources considered include financial resources, and the results show that the most significant financial effect is caused by pricing and value capture. Rodríguez-Espíndola et al., (2020) look at the possible benefits of using new technologies on humanitarian supply chains. The results show that blockchain combined with other technologies such as Artificial intelligence and 3D printing can improve information flow, money flow, and decision making. Blockchain also has an indirect effect on financial resources through information asymmetries. Often the lack of financial resources, in the form of granted debt, results from the lack of information to verify the reliability of the borrower. Bai et al., (2019), recognize the relevance of credit for the sustainable economic development of agricultural supply chains and poverty reduction in developing countries. However, credit evaluation is a complex activity based on large amounts of data on environmental factors, farmers' characteristics, creditworthiness, and the relationship between this information. The authors develop a system for assessing farmer creditworthiness in China based on 43 factors. Yi et al., (2021), address the problem faced by farmers, especially small farmers in developing countries, to find finance sourcing for their activities. One emerging solution is platforms that act as an intermediary between banks and farmers. The platform can be a guarantor toward the bank or lend money directly to the farmers. The results of the Stackelberg game show that both conditions have advantages for the farmer. The choice between the two depends on the cost of production and the fee. The credit from the bank without the platform intervention never benefits the farmer. Moreover, a high level of social responsibility leads to an advantage for the whole supply chain in terms of lower interest rates and higher production. It is apparent that blockchain can influence financial resources, which in turn help determine asymmetries in bargaining power.

H3: The more the blockchain adoption increase the more the bargaining power asymmetries decrease because of the blockchain effect on financial resource.

Finally, we hypothesize that blockchain can have a combined impact on information and financial resources. The combined impact is expected to result in greater impact than the single action points we have seen so far. Considering the impact of bargaining power on supply chain fairness we hypothesize the effect of the combined impact of blockchain adoption on supply chain fairness through bargaining power asymmetries. Our third hypothesis is:

H4: The more the blockchain adoption increase the more the supply chain fairness increases because of the blockchain effect on bargaining power asymmetries.

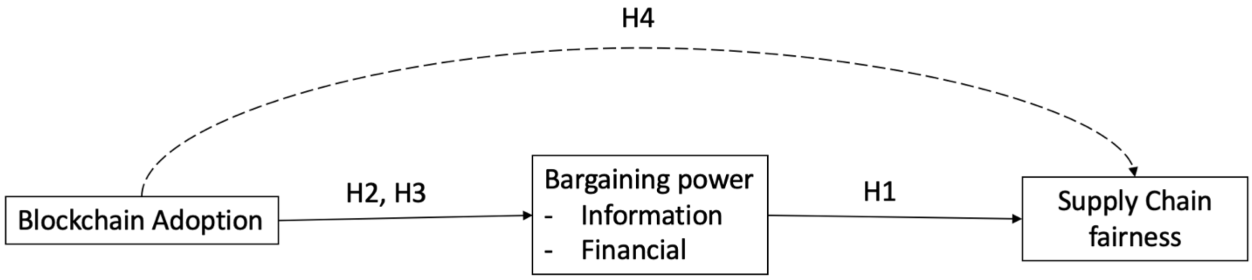


Figure 1: Conceptual model

2.3. Research method

In this study, we focus on the chocolate supply chain because it is one of the most relevant global agricultural supply chains suffering unfairness issues. Because the chocolate supply chain is global, and although the dynamics are similar in each country considered, we chose to focus on the largest producer the Ivory Coast, and the largest importer Europe. Our study is divided into two parts. In the first part, we conducted empirical research aimed at building a system dynamic model, which is the second part of the study.

2.3.1 Part I: Case research and empirical observation

The first step was empirical research to investigate the current supply chain condition and build the system dynamic model in a structured way. We used a combination of documents, interviews, and observations to enable data triangulation. We first performed a keyword search on Google using the keywords "Report Cocoa." From the results, we kept only reports written by NGOs or independent organizations. We identified 42 reports produced by 14 organizations (Table 3). The identified reports range from 2012 to 2022. Starting in November 2021, we conducted 8 semi-structured interviews with 3 experts in the field (Table 4). The selected experts cover the three market areas. Expert number 1 is from Côte d'Ivoire and has been working on chocolate and the living conditions of local people for 10 years. Expert number 2 has been a cocoa supply chain consultant for more than 20 years. Expert number 3 is the CEO and co-founder of a cocoa supply chain traceability company with blockchain technology and maintains relationships with chocolatiers and importers.
Expert number 1 and expert number 2 have made two trips to Ivory Coast (end of 2021 and end of 2022) and shared notes and useful information with us.

	Organization	**Report Title**	**Year**	**Pages**
1	World Cocoa Foundation	WCF Cocoa Livelihoods Program (CLP)	2012	43
2	World Cocoa Foundation	WCF Cocoa Livelihoods Program Annual Report 2014	2014	21
3	World Cocoa Foundation	CocoaAction Progress Report 2015	2015	8
4	World Cocoa Foundation	WCF Cocoa Livelihoods Program 2015 Annual Report	2015	23
5	World Cocoa Foundation	WCF Walmart Foundation Report	2015	7

6	World Cocoa Foundation	Walmart Foundation- Empowering women cocoa farmers in West Africa 2015 Annual Report	2015	12
7	World Cocoa Foundation	Empowering Cocoa Households with Opportunities and Education Solutions (ECHOES)	2015	44
8	World Cocoa Foundation	Qualitative Farmer Economics Study: Final Report	2015	50
9	World Cocoa Foundation	African Cocoa Initiative Final Report	2016	36
10	World Cocoa Foundation	African Cocoa Initiative Learning Report	2017	24
11	World Cocoa Foundation	Report on land tenure & Cocoa production in Ghana	2017	53
12	World Cocoa Foundation	Community Needs Assessment & Action Plan Guide: A Pathway To Sustainable Cocoa Manual	2017	50
13	World Cocoa Foundation	2018 World Cocoa Foundation Learning Meeting Report	2018	18
14	World Cocoa Foundation and World Bank Group	Forest and Climate-Smart Cocoa in Cote d'Ivoire and Ghana	2018	57
15	The Cocoa Barometer Consortium	Cocoa Barometer 2012	2013	17
16	The Cocoa Barometer Consortium	Cocoa Barometer 2015	2016	27
17	The Cocoa Barometer Consortium	Cocoa Barometer 2018	2018	76
18	The Cocoa Barometer Consortium	Cocoa Barometer 2020	2021	118
19	The Cocoa Barometer Consortium	Cocoa Barometer Latin American Baseline 2022	2022	38
20	The Cocoa Barometer Consortium	Cocoa Living Income Compendium	2022	19
21	The Cocoa Barometer Consortium	Transparency and Accountability Toward building trust in the cocoa sector's sustainability efforts	2022	15
22	International Cocoa Initiative	Annual Report 2012	2013	55
23	International Cocoa Initiative	Annual Report 2013	2014	20
24	International Cocoa Initiative	Annual Report 2014	2015	20
25	International Cocoa Initiative	Annual Report 2015	2016	28
26	International Cocoa Initiative	Annual Report 2016	2017	28
27	International Cocoa Initiative	Annual Report 2017	2018	32
28	International Cocoa Initiative	Annual Report 2018	2019	32
29	International Cocoa Initiative	Annual Report 2019	2020	32
30	International Cocoa Initiative	Annual Report 2020	2021	39
31	International Cocoa Initiative	Annual Report 2021	2022	40
32	World Bank Group	Eliminating Deforestation from the Cocoa Supply Chain	2017	61
33	IDDRI	Agricultural value chains facing the biodiversity challenge: the cocoa-chocolate example	2019	42
34	Cocoa of Excellence Program Biodiversity International	International stakeholders' consultations on the development and validation of proposed international standards on cocoa quality and flavor assessment	2017	42
35	The Rainforest Alliance	Cocoa Certification Data Report 2021	2022	58
36	KIT	Demystifying the cocoa sector in Côte d'Ivoire and Ghana	2017	232
37	Fair Labor Association	Sustainable Management of Nestlé's Cocoa Supply Chain in the Ivory Coast—Focus on Labor Standards	2012	67
38	International Institute for Sustainable Development	Global Market Report: Cocoa	2019	12
39	Statista	Cocoa Report 2022	2022	34
40	United Nations	Cocoa industry: Integrating small farmers into the global value chain	2016	49
41	European Union	Traceability and transparency of cocoa supply chains in Côte d'Ivoire and Ghana	2021	44
42	NORC at the University of Chicago	Assessment of Effectiveness of Cocoa Industry Interventions in Reducing Child Labor in Cocoa Growing Areas of Côte d'Ivoire and Ghana	2020	81

		Final report		

Table 1: Report collected and analyzed

Expert	Date	Time
Expert 3 first round	15/10/2021	55 min
Expert 3 first round	08/11/2021	50 min
Expert 1 first round	16/12/2021	45 min
Expert 2 first round	23/12/2021	80 min
Expert 3 second round	12/07/2022	40 min
Expert 1 second round	28/11/2022	70 min
Expert 2 second round	29/11/2022	90 min

Table 2: Interviews collected and analyzed

The cocoa supply chain is long and extremely complex. There are dozens of actors involved from producer to final consumer. Here we focus on the main actors and for simplicity we avoid considering intermediaries who perform activities with limited or no added value. The main actors considered in our model are farmers who grow and supply cocoa to exporters. Exporters are mainly involved in the export of cocoa but often also in processing activities into semi-finished products. Once the cocoa arrives in Europe, it is sold to other companies that produce the final product, which can take many forms including chocolate bars, cocoa powder, chocolates, and cocoa butter. Our model stops at when cocoa is sold to the final processor. Cocoa, especially that produced in Central Africa which accounts for 70 percent of world production, is an agricultural commodity. Organic cocoa is the only cocoa that differs in quality and represents less than 5% of total production in Ivory Coast to date. For this reason, in our model we treat the product as undifferentiated and make no distinction on cocoa quality. However, we can make a distinction between certified and non-certified product. In fact, processors are interested in having the guarantee that the product meets the minimum criteria imposed by the European Food Safety Act because. They are therefore willing to pay more for cocoa for which they have more information. The whole chain relies on the flow of cocoa from the Ivory Coast to Europe and the flow of money in the reverse direction. The flow of money is supported by financiers who lend the money, today mainly to exporters.

World Bank data show that this supply chain is deeply unfair and farmers live well below the poverty line. Common problems among the farmers and their families include lack of education, child labor, lack of health care and food, deforestation to make way for new irregular plantations, and disease due to pesticide use. In contrast, exporters are often multinational companies with millions of dollars in profits per year. In our empirical research we investigated what factors led to this condition, and from the coding of the collected data we derived the four most relevant macro issues: Storage capacity, Information asymmetry, Regulatory and normative issue, and financial resources.

Storage capacity

The farmers and the local operators are forced to sell cocoa as soon as it is harvested due to the lack of storage capacity in the country. Their bargaining power is extremely limited by the inability to store the huge amount of cocoa in the country at harvest time. It forces local operators to sell the product immediately at the price of the moment. Expert 2 identifies storage as one of the key problems in the chain. "When the port of Abidjan and San-Pédro are saturated, the country collapses. The number of trucks loaded with cocoa ... is so great that ... the country collapses if this product is not loaded by ship and sent away." Cocoa Barometer reports identify the need to improve warehouse infrastructure as a priority for Ivory Coast. The situation is completely different at the ports of arrival in Europe. Europe has a highly developed storage capacity that allows European operators to meet several months of demand without buying fresh product. In addition, cocoa can be stored for up to 5 years without losing its characteristics. As pointed out by expert 1 "[the big European players] have purchased very large quantities of cocoa in the not-so-distant past and can starve farmers because they can manage the demand for, I don't know how long with reserves ... Having them huge storage facilities they can avoid buying fresh product from the farmers for a long time."

EO1: The storage capacity asymmetry between exporting and importing countries seems to influence the bargaining power of the players in the supply chain creating a disadvantage for the players in the country with an underdeveloped capacity.

Information asymmetry

Farmers do not have access to information such as end-consumer preferences, end-market prices, weather forecasts, and warehouse saturation in Europe that could enable them to bargain for a better price during negotiations. Expert 2 states that "for the average farmer ... to find information with which they could protect themselves and could enhance the value of their work is very difficult ... precisely because they are in a condition of inferiority because they struggle to access information objectively, and even if they did access it, it is not so obvious that they would grasp the content [because they are often illiterate]." On the other side of the supply chain, end consumers do not have access to information regarding the production stage in the field such as, the quality of the product, the use of child labor, the location of plantations to avoid them being in protected territories. Expert 1 says "today you don't have information about what is happening downstairs." Expert 2 states "a gap that there is right now to fully value this kind of supply chain is basically communication to the final customer." Numerous reports analyzed including "Cocoa Barometer Report 2020," "Traceability and transparency of cocoa supply chains in Côte d'Ivoire and Ghana," "Annual report ICI 2020," confirm the importance of these asymmetries. In contrast, exporters in the middle of the chain have easier access to information because of their greater proximity to both ends of the chain. Exporters seem to benefit from the information asymmetries just described because of their privileged position. In particular, the greatest benefit seems to be obtained on the shoulders of the farmers. Expert 1 says "Today [farmers] are completely at the mercy of the traders."

EO2: Information asymmetries seem to harm the players at the two extremes of the chain while appearing to benefit those in central positions.

Regulatory and normative issue

The regulations established by the entity in charge of the sector regulation in Ivory Coast, among their effects, limit competition and artificially create an oligopoly at a strategic point of the chain which is export. The structure of the chain takes the shape of an hourglass with a large number of farmers, a large number of consumers, and a limited number of exporters (Amiel et al., 2019). The oligopoly limits the bargaining power of the players at the farmers who, given limited domestic consumption, are forced to turn to a limited number of players to sell their product and export it. Historical, cultural and social reasons have led to the current situation where the body responsible for creating the standards and making the controls is in public-private co-partnership. Within this body are represented the interests of the government and local people, and the multinational corporation's interest. The three experts agree on this point. Expert 2 "the regulator is privately owned so its purpose is no longer the social purpose ... but they don't also liberalize the chain ... the market has been stuck with exports however the entities that control it are no longer public purpose but have simply become private entities, often multinational corporations, that make their own interests." Expert 1 "the cocoa supply chain in Ivory Coast is strictly regulated there is this institution which is the coffee and cocoa council that imposes clear rules." Expert 3 "the weight of the council is felt more than in other countries i.e. in other countries there is not even [such an institution] the supply chain is managed directly by the ministry of agriculture. Here the coffee and cocoa council has its hand on everything." These considerations are also confirmed by the reports analyzed.

EO3: The rules limiting competition in the middle part of the cocoa chain seem to have a negative effect on the bargaining power of the farmers.

Financial resources

The farmers suffer from severe financial hardship and in most cases, they live below the poverty line. Expert 1: "Farmers are really on the edge if not below the poverty line. I have absolutely seen with my own eyes they live in borderline conditions." This translates into the need to sell the product immediately. In addition, they have the need to be paid immediately and in cash, since they do not have access to credit and the banking system. On the other hand, traders have the option of using numerous financial instruments to meet their financial needs. However, these instruments results in heavy financial costs that burden the whole chain. Expert 2 "those who really keep the whole chain up are mainly the financial institutions, they are the companies that at various levels intervene within the cocoa chain. ... Potentially they don't care at all about making chocolate about eating it or selling cocoa they simply make investments on a very long supply chain that allows them to do various operations to make margins in short profits." Financial asymmetry affects the bargaining power of the parties and ultimately the price producers can ask for their cocoa. Expert 3 argues that despite the minimum price that is imposed by the coffee and cocoa board in the end "it is the trader who makes the price of cocoa and ... he can pull the rope and the neck of the farmers." Expert 2: "these days there is a very heated debate in France just on the issue of cocoa price because now there is again a violent war going on between Ivory Coast and Ghana on the one hand and Cargill mainly and the U.S. traders who do not want to pay the mandatory $400 premium on the product."

EO4: The farmer's low financial availability because of low price and limited access to credit seems to put these players at a disadvantage against the larger players with greater financial availability.

Blockchain effect

The experts involved in the study have participated in cocoa supply chain traceability projects using blockchain. In particular, expert number 3 and number 1 are directly involved in developing blockchain-based solution for agri-food supply chain traceability (Ruzza et al., 2022). Our analysis shows that blockchain, unless supported by appropriate government policies, cannot have a direct impact on warehouse asymmetries, and regulatory and normative aspects. Based on their experience and the literature on the topic, we identified 3 possible impacts of blockchain on agri-food supply chain.

The difficult access to credit of farmers of agricultural supply chains in developing countries due to the lack of information about their ability to repay credit (Bai et al., 2019; Yi et al., 2021). Blockchain-based traceability systems have a crucial impact on the availability of information (Wang et al., 2019; Guo et al., 2021), affecting access to credit for farmers. Expert 3 states that "today a bank loan or any loan has all the criteria of sustainable environment goals, and any investor ... has this whole set of parameters [of sustainability and beyond] to lend the money." While expert 2 tells us "on the one hand for them it's like they have also started to set up a database of all their operations instead of having the papers. So it means that even at the time when for example they have to go for loans, financing of production advances they have concrete data to lean on."

EO5: Blockchain can have an impact on financial asymmetries through information asymmetry by opening access to credit for farmers.

The price on agricultural supply chains is one of the most widely studied issues and it is a major risk factor for farmers. Gaining a fair price depends on farmers' ability to sell their product in the final markets, on the coordination among chain members, and on the tools used to manage price risk (Agrawal et al., 2022; Rodríguez-Espíndola et al., 2020). However, our analysis shows that blockchain can also influence prices as it can help farmers get a fair price for their produce through recording sales information in a transparent and immutable way. Expert 3: "among the information that has to be recorded in the blockchain there is the price information, so the farmer declares that he has given a quantity of cocoa to the cooperative the cooperative declares that he has paid an amount of money and the farmer has to confirm." By recording this information, large multinational corporations acting on the bottle neck of the chain are exposed to public pressure and are forced to comply with pricing laws. In addition, this opens the possibility for farmers to actually see a premium recognized to them whether it is: imposed by the government, due to higher product quality such as organic, due to carbon credits, or recognized by the end consumer. Expert 2: "carbon credits related to agroforestry systems that absorb CO_2 today those who already have the whole supply chain certified in blockchain have them accredited automatically." Expert 1: "the other big result is that the buyer in Italy pays more for their product precisely because it is tracked. The customer in Italy receives the cocoa bag through the exporter obviously receive the bag with the QR code on it. They scan the QR code and therefore they can see how that product was processed and therefore they have added value to that product. The cooperative earns a little more per kilo precisely because the product is tracked. We are at five batches already exported."

EO6: Blockchain can impact financial asymmetries by ensuring that farmers are paid a fair price including any additional premium.

The literature review shows that the most evident impact of blockchain is on information asymmetries. Blockchain has the potential to improve the flow of information from farmers to the final market via the exporter. In addition, it can improve the flow of information from final markets to farmers. Expert 2 says: "the biggest data tampering ... is how much I paid the farmer, how much quantity I harvested from that farmer, what is the plantation of that farmer, where is the plantation located" and again expert 1: "the whole part about deforestation and that's something we are studying because we realize it's important and it's critical and there are the tools to do it." Expert 2 says, "the value that we are giving ... is the ability to give whoever receives the information the certainty that it has been declared by the previous actor on the supply chain and the certainty that once they have received it they can only add more information but they can't eliminate the information at the root."

E07: Blockchain can impact information asymmetries improving the information flow among the actors in the supply chain.

2.3.2 Part II: Development of a system dynamic model

To better understand the interplay between bargaining power, supply chain fairness and blockchain technology we developed a system dynamics model by integrating the evidence identified from our empirical research and insight from the literature review. The model is reality-based and replicates the chocolate supply chain. It considers the natural cycles of cocoa production and export activities. Most parameters are based on real data regarding the chocolate supply chain collected from official documents including those issued periodically by the Ivory Coast Coffee and Cocoa Council, exporters, and the World Bank. The parameters for which data are not available, we used realistic estimates and approximations obtained from the analyzed reports.

We identify three main variables in our model that are useful in answering the research questions. The variable bargaining power asymmetry is built on resource dependence theory. Bargaining power asymmetries in our model are obtained from the combination of the asymmetries between farmers and exporters in the ownership of the four key resources derived from the empirical study: information, financial resource, storage capacity, and relational resource. The imbalance in the control of these resources determines the player with greater bargaining power and the player in a disadvantaged position. To measure supply chain fairness, we borrowed from the Rawlsian principle. According to this principle it is possible to consider the welfare of the most disadvantaged individual to determine the fairness of an economic system (John Rawls, 1999). This method of measurement seems suitable for this context, moreover it is widely used in supply chain literature (Chen and Hooker, 2022; Jiang et al., 2021; Karsu and Morton, 2015). More specifically, we measure supply chain fairness through the survival time without cash inflow farmers, which measures how many days farmers, and their households can survive on the cash at their disposal. The threshold is the minimum money necessary to survive per day to be outside the poverty line. If farmers can survive more than one day the supply chain is fair. If the farmers are not able to be outside the poverty line it is not.

To introduce blockchain, we created a variable called "Blockchain Adoption" that represents the percentage of blockchain adoption in the supply chain. This is an exogenous variable that we can manipulate to see the effects of blockchain introduction. This variable has two intervention points in the model that we take from the empirical observations. First, "Blockchain adoption" positively affects the "minimum price on the field" because through traceability it makes the edge-of-field price paid by the exporter for cocoa visible to all members of the chain. As a result, the exporter is less likely to be led to pay a lower price than the one set by the government including any additional premium. Second, "Blockchain Adoption" affects "farmers information availability" by allowing farmers secure access to useful information during bargaining. Third, "Blockchain adoption" influences "exporters information availability" by allowing exporters and companies involved in processing cocoa into chocolate to have information about the product quality.

Following conventions, we describe our system dynamics model using the causal loops diagram Fig 2. With the causal loops we explain the main variables and the relationships between them. To make the explanation clearer we divide causal loops into four categories based on the four main resources that influence bargaining power: storage capacity, financial resource, relational resource, information. Although we recognize that there are other resources that can potentially influence bargaining power, we focus on these since they are the ones that emerged from the empirical studies as the most critical to the chocolate supply chain in Ivory Coast.

Storage capacity loops

Storage capacity loops capture the effect of the storage capacity resource on bargaining power asymmetries. Ivory Coast has very low cocoa storage capacity. In contrast, exporters have a large capacity in their warehouses in Europe. This results in an asymmetry in the ability to accommodate and maintain cocoa reserves. Experts suggest that government intervention, with targeted investment in the construction of storage sites, may be the most likely solution to the problem. The asymmetry in storage capacity forces farmers to sell harvested cocoa immediately, limiting their bargaining power vis-à-vis exporters. The S-B1 loop captures this idea. When Ivory Coast storage capacity increases, Ivory Coast warehouses saturation decreases, decreasing storage asymmetry, which in turn affects bargaining power asymmetry.

Relational loop

The relational loop captures the relational resources that influence the bargaining power of the parties involved in the supply chain. In the Ivory Coast chocolate supply chain, there are about 5 million farmers. Whereas, the exporters are a few dozen large companies. This disparity is mainly caused by the lack of regulations governing the number of farmers and the presence of two regulations limiting the number of exporters. Loob R-B1 captures the effect of the first of these regulations, which sets very strict requirements for companies to apply for an export license, making it impossible for farmers or small local companies to export cocoa and forcing them to contract with the few strong licensed exporters. Loob R-B2 captures the effect of the second rule, which requires a minimum quantity of 25 tons for export. Again, this is a quantity that is difficult for an individual farmer or small local firms to achieve, and they are forced to sell cocoa to large players capable of aggregating large quantities for export. The result is that exporters can source from millions of farmers while farmers can sell their product to a few licensed exporters causing asymmetry in the number of players with whom the parties can relate which impacts bargaining power.

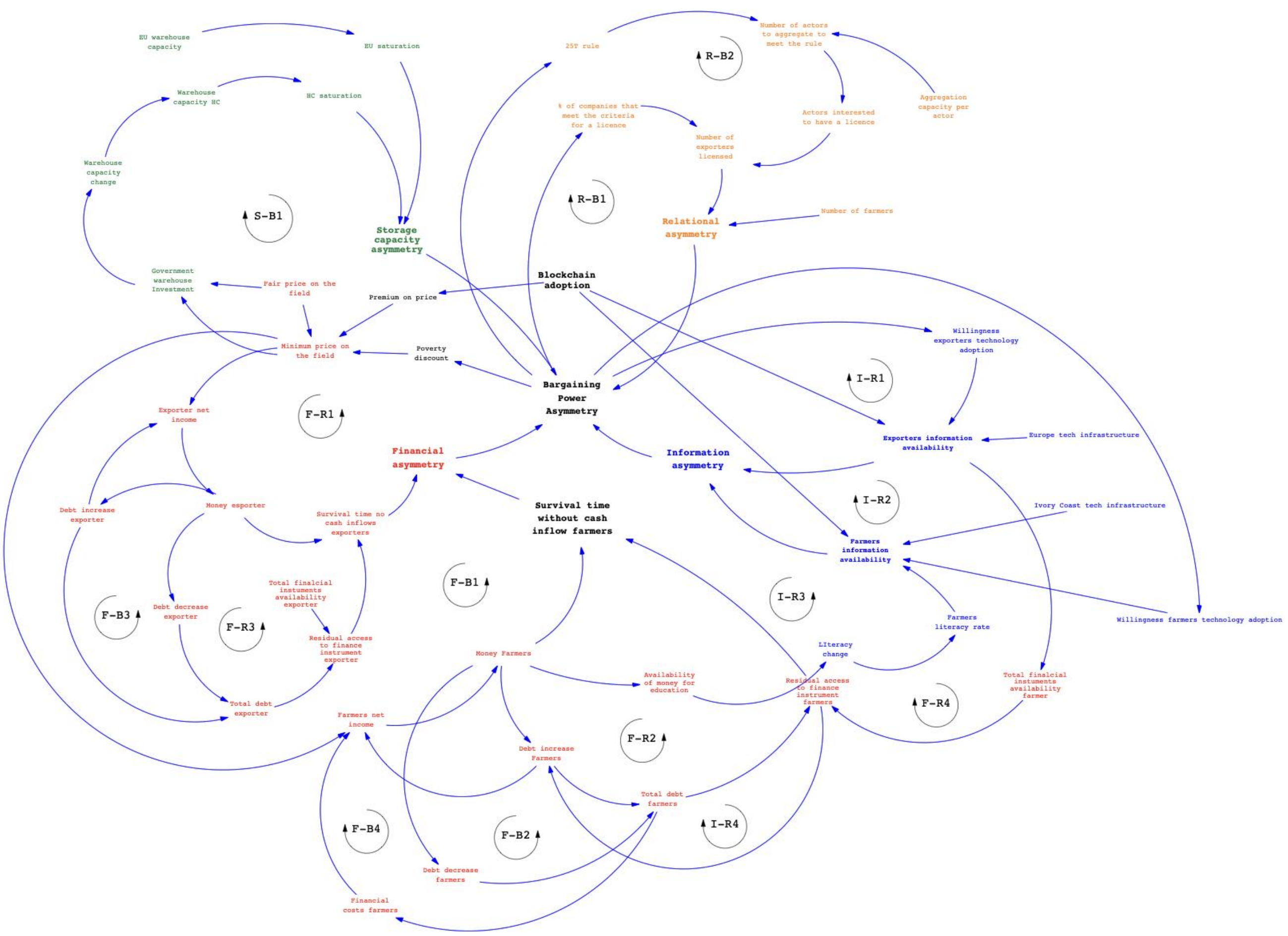
Financial loops

Financial loops capture the influence of financial resources on bargaining power asymmetries. The financial resources available to farmers and exporters are very different for three intimately related reasons: on-the-field price, debt capacity, and information asymmetries that influence farmers' access to debt. We present the three reasons through causal loops starting with the simplest and arriving at the most articulated. With loops F-R1, F-B1, our model considers that the "minimum price on the field" fair to enable farmers and their families to live above the poverty line is not the one applied in the supply chain of chocolate in Ivory Coast. The "minimum price on the field" fair is lowered (or raised) based on asymmetries in bargaining power. The more powerful exporters are, the lower the "minimum price on the field" applied will be. "Minimum price on the field" affects the income of exporters and farmers in opposite ways. With a high "minimum price on the field" farmers benefit with a low minimum price on the filed exporters benefit by determining the asymmetry of financial resources. Starting from the loops just explained the second loop categories identified considers the debt access of farmers loops F-B2, F-R2 and exporters loops F-R3, F-B3. These loops capture the idea that when the money available to cover expenses is not sufficient for survival, exporters or farmers may resort to debt. The total debt available to farmers and exporters has a preset ceiling to avoid unrealistic situations. In the absence of blockchain, it is preset to zero for farmers to represent the current situation. When farmers or exporters use the debt it flows into the money available to them. If exporters or farmers were in a position to have extra money it can be used to decrease the debt. The unavailability of access to debt for farmers compared to the easy access to debt for exporters contributes to financial asymmetries. F-B4, F-R4 loops link financial loops with information loops. The absence of verifiable information on farmers precludes their access to debt because financial institutions have no information to assess farmers' ability to repay. When information about farmers increases the total debt that farmers can access increases.

Information loops

Information loops capture the influence of information resource on bargaining power asymmetries. I-R1, I-R2 loops capture the effect of adoption technologies on information asymmetries. It is necessary for the entire chain to have the desire to adopt blockchain and its enabling technologies. If any actor in the chain decides not to use the technologies necessary for information transmission, or does so by adopting different standards, information transmission would be penalized by diminishing the effect on information asymmetries. The I-R3 loop captures the idea that even if all the technologies needed to transmit information to farmers were implemented, blockchain included, most farmers would not be able to benefit from the increased information available to them because they are illiterate and unable to read and understand the information. To make information capable of improving the situation of farmers by decreasing information asymmetries, it is necessary to reduce illiteracy among farmers. Their level of illiteracy depends on the money they can spend on education and this in turn is related to their earnings. The I-R4 loops link information and financial asymmetries. Information asymmetries affect farmers' ability to collect debt. The flow of information from farmers to consumers gives farmers the ability to demonstrate to lenders their ability to repay a debt. Thus when information asymmetry is reduced the debt that farmers have access to increases because financial institutions will be more likely to grant it to those farmers about whom they are able to collect information. This debt adds to the farmers' financial availability. Farmers can spend the money collected through debt to survive, or invest it in their business in education with the effect of reducing information asymmetry.

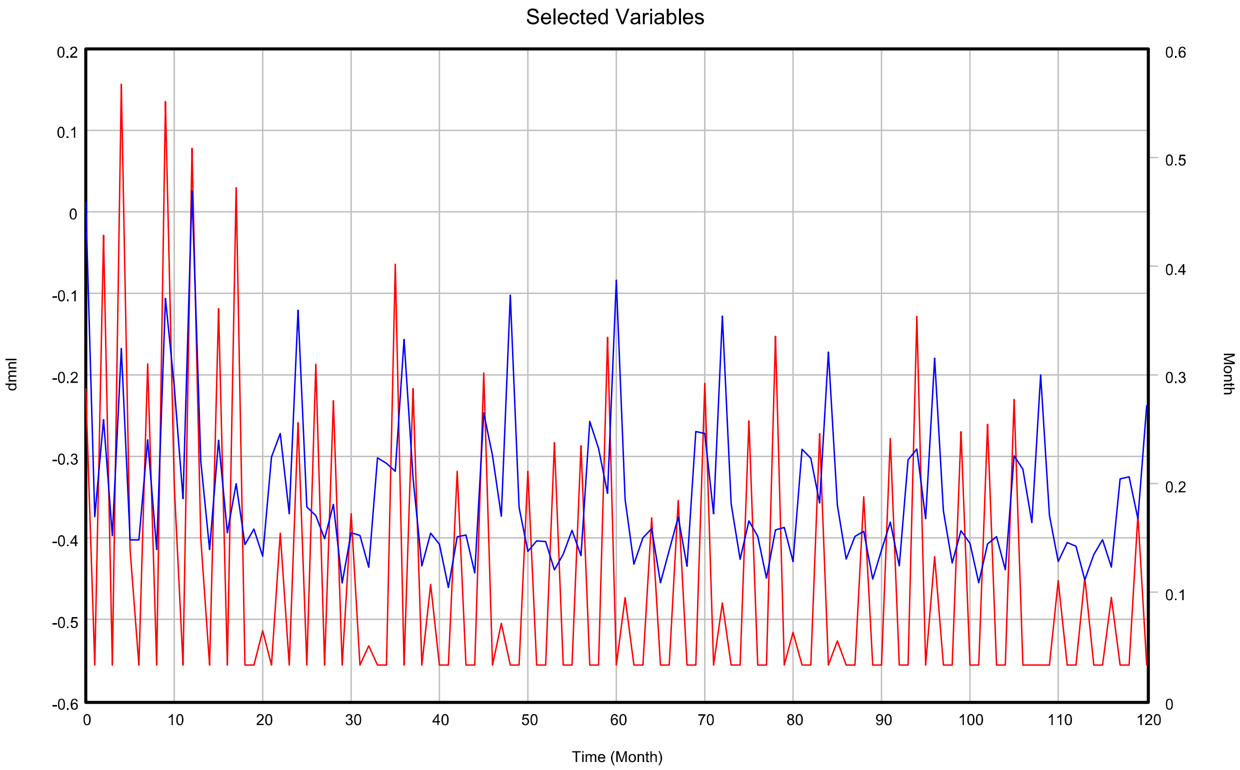
Figure 2: Causal Loop Diagram (CLD) of cocoa supply chain.
Orange: Relational asymmetry related variables
Green: Storage capacity asymmetry related variables
Red: Financial asymmetry related variables
Blue: Information asymmetry related variables
Light blue box: Variables affected by blockchain adoption



2.4. Results

Based on the literature review, we hypothesized that bargaining power affects supply chain fairness. We used the system dynamics model to test our first hypothesis. Figure 3 presents the simulation results in the absence of the blockchain adoption effect. The lines representing bargaining power and supply chain fairness have an up-and-down shape justified by the desire to avoid oversimplifications in the model by keeping it as close to reality as possible. The pattern of the lines is due to the natural cycles of cocoa production and export. We can see that when bargaining power asymmetries, represented by the blue line, increase by improving the condition of farmers supply chain fairness improves (supply chain fairness increases). For further empirical verification, we did a correlation test between the variables and obtained a positive and significant correlation of 0.375. We can therefore conclude that Hypothesis 1 is supported and that when bargaining power asymmetries decrease supply chain fairness increases.

Figure 3: Simulation results illustrating proposition 1
Blue line: Bargaining power asymmetry
Red line: Supply chain fairness



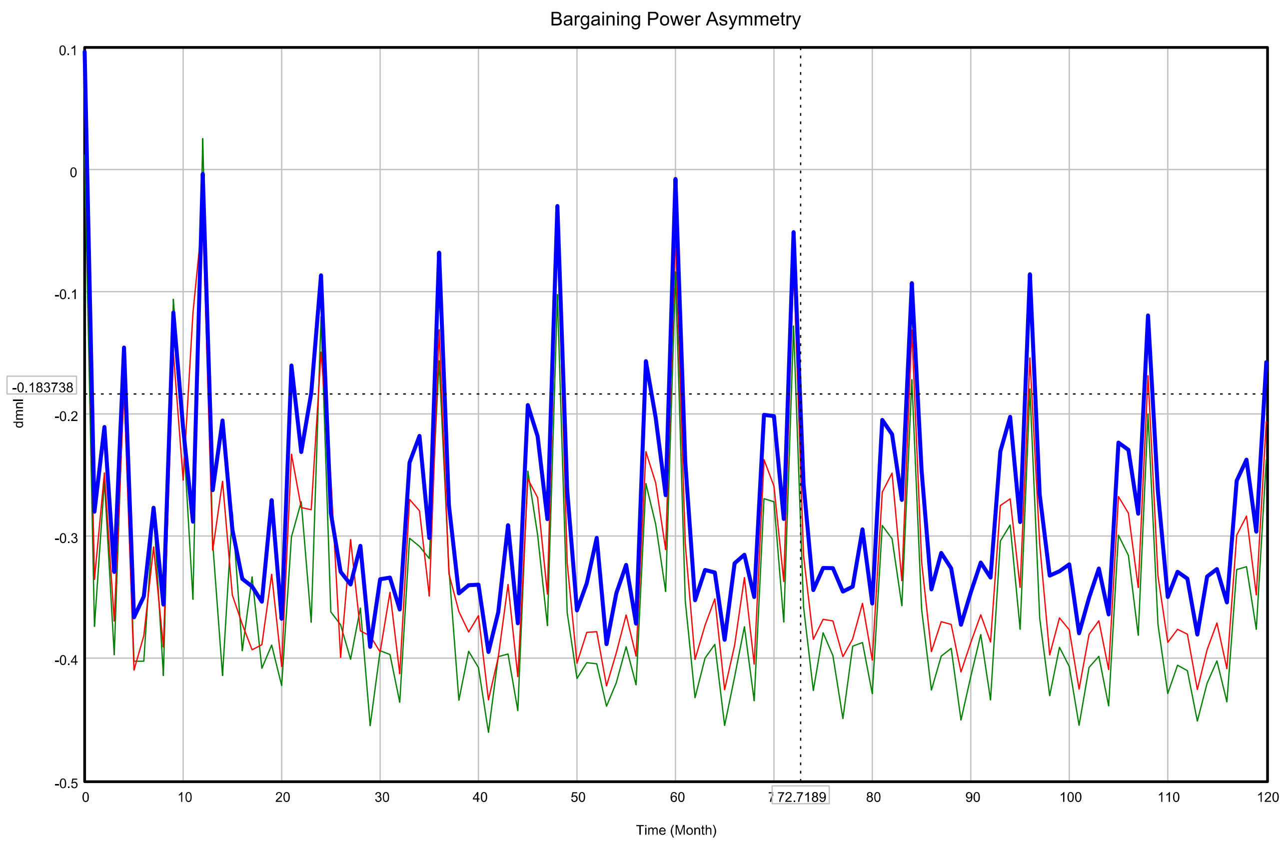
Taking advantage of the potential of the system dynamics model, we introduce blockchain technology by isolating the effect on information asymmetries to test our second hypothesis. Figure 4 shows that as blockchain adoption increase from 0 to 0.8 bargaining power asymmetry decrease as a result of blockchain effect on information asymmetry. In the period analyzed, the increase in blockchain adoption determines bargaining power to get closer to the absence of bargaining power asymmetries represented by bargaining power asymmetries. Furthermore, the graph shows that in the first few months, the difference between the lines representing low blockchain adoption and those representing high blockchain adoption is small. However, the difference increases with the passage of time arriving in the last months of analysis to be significant. We detect path dependencies due to comulative behavior caused by stocks in our model. This shows that although the effect of blockchain adoption is appreciable right away blockchain takes time to realize its full potential. Finally, we can see that sometimes a medium level of blockchain adoption results in a better bargaining power asymmetry than a high level of blockchain adoption. This occurs mainly in the first half of the simulation. We do not consider this result unexpected or surprising since bargaining power is a central variable in our model influenced by numerous causal loops. Among the reasons that could explain this phenomenon we find price volatility, or the different amount of cocoa in circulation and moving at each time point analyzed. However, in the long run these variabilities tend to disappear and higher blockchain adoption results in lower bargaining power asymmetry allowing us to say that hypothesis 2 is supported.

Figure 4: Simulation results illustrating H2

Blue line: Blockchain adoption 0.8

Red line: Blockchain adoption 0.4

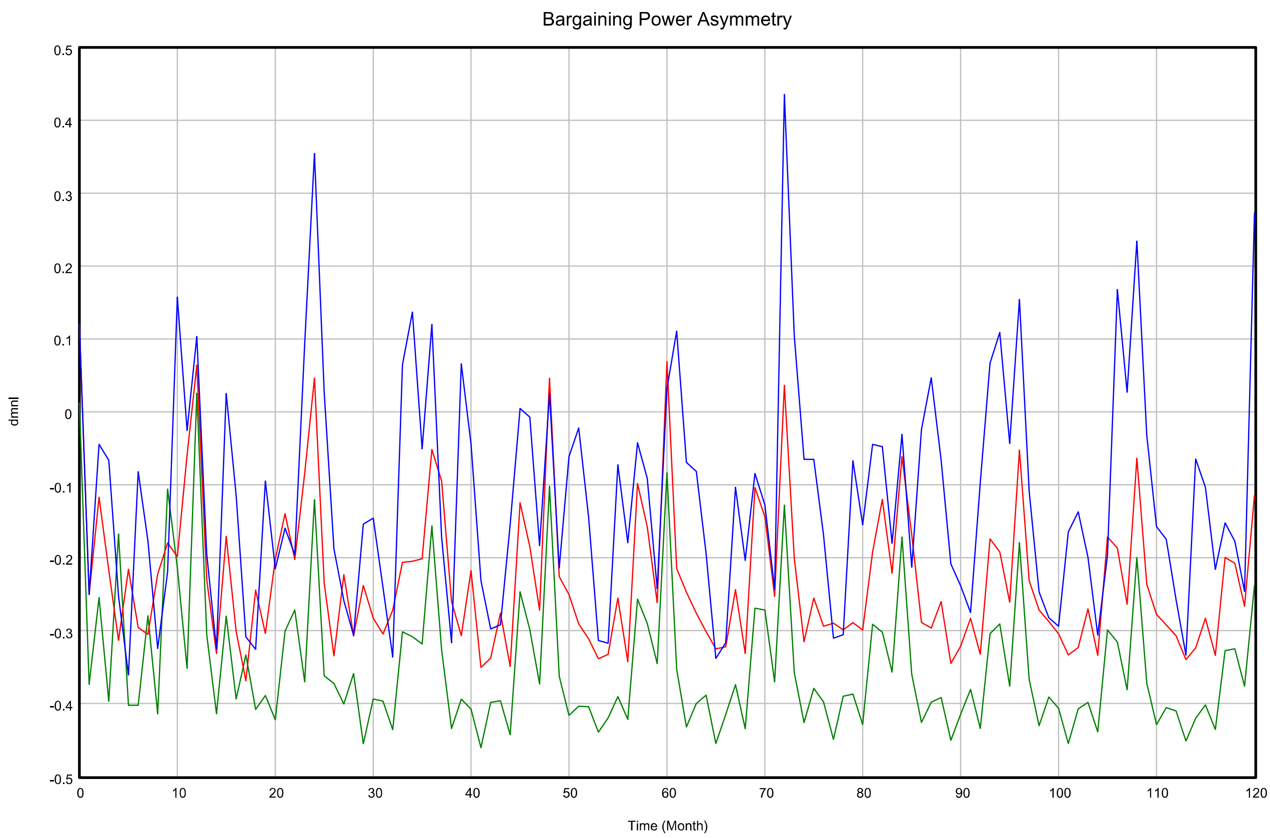
Green line: Blockchain adoption 0



We introduce the effect of blockchain adoption to financial resources to test our third hypothesis. Similar to when seen in the previous section, Figure 5 shows that as blockchain adoption increases from 0 to 0.8 bargaining power asymmetries decrease Improving farmers condition.

Again we see the phenomenon of path dependence and anomalies in the first half of the model. However, we can see that at the same level of blockchain adoption, the effect of blockchain adoption on financial resources results in a greater shift in the curve of bargaining power asymmetries than the effect of blockchain applied to information resources. We can conclude that Hypothesis 3 is supported.

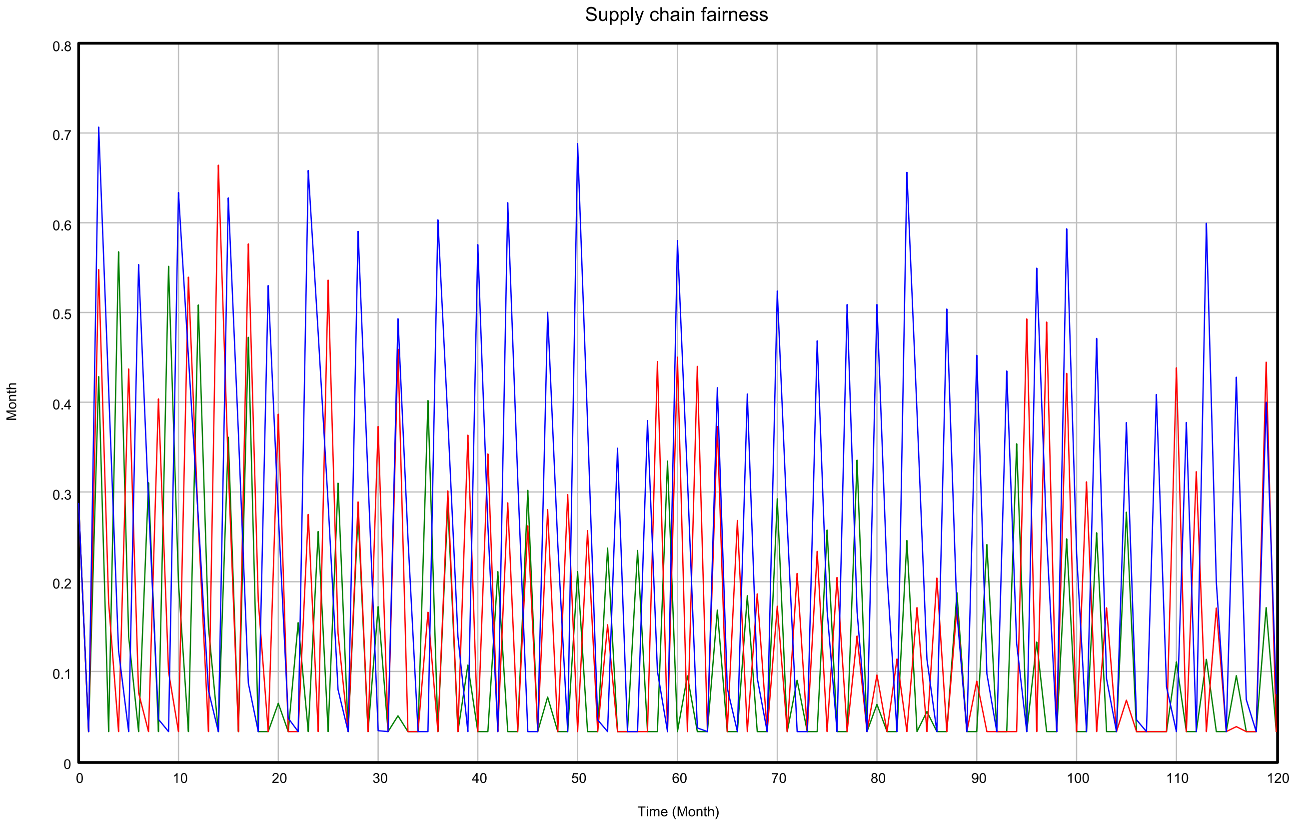
Figure 5: Simulation results illustrating H3
Blue line: Blockchain adoption 0.8
Red line: Blockchain adoption 0.4
Green line: Blockchain adoption 0



We test the last hypothesis by introducing the effect of blockchain simultaneously on both information resource and financial resource. Simulation results show that as blockchain adoption increases from 0 to 0.8 supply chain fairness increases. Blockchain adoption results in a decrease in the frequency of times when farmers live below the poverty line and thus when supply chain fairness is unfair. In addition, curca peaks are higher showing that farmers have better welfare and consequently according to the Rawlsian principle supply chain fairness improves. Again, we see the phenomenon of path dependencies resulting in equal levels of blockchain adoption having a greater effect on supply chain fairness as time passes. We can say that the fourth hypothesis is supported.

Figure 5: Simulation results illustrating H4
Blue line: Blockchain adoption 0.8
Red line: Blockchain adoption 0.4

Green line: Blockchain adoption 0



2.5 Discussion

Global agricultural supply chains such as cotton, coffee, and cocoa, to name a few, suffer from fairness problems. Looking at supply chain literature from a resource dependence theory perspective we ask: How does bargaining power asymmetry affect supply chain fairness? What is the blockchain impact on bargaining power asymmetry and supply chain fairness?

2.5.1 Bargaining power and supply chain fairness

Looking at the literature on supply chain fairness reveals that supply chain fairness is a broad concept that includes within it multiple dimensions. However, especially when we look at distributional fairness, it is related to the ability of all supply chain actors to capture sufficient value to meet their primary needs. This can be achieved through fair price, fair trade, and fair pay (Chen et al., 2022). Some introduce the idea that the presence of supply chain fairness is related to the availability to all actors of certain key resources including information (Choi and Messinger, 2016; Wu and Niederhoff, 2014), or partner relationships (Oyedijo et al., 2021). However, from our best knowledge we have not identified studies that empirically demonstrate this relationship. Looking at bargaining power literature from a resource dependence theory perspective, bargaining power depends on a firm's ownership of resources with high magnitude and criticality (Cheng et al., 2021; Pfeffer and Salancik, 1978). Firms that control these resources within a supply chain have greater bargaining power than others and have the ability to appropriate most of the value created in a supply chain by exploiting their dominance over other members of the chain (Crook and Combs, 2007). We hypothesized that supply chain fairness does not depend directly on resources but is related to the bargaining power of actors in a supply chain. Our results demonstrated this relationship. When bargaining power asymmetries increase, the dominant actor is able to appropriate a greater share of value such that the ability of disadvantaged actors to meet their primary needs is compromised. Conversely, when bargaining power asymmetries decrease, the most disadvantaged actors are more likely to enforce their needs with a benefit in terms of supply chain fairness. We contribute to the supply chain fairness literature by demonstrating the effect of bargaining power on supply chain fairness.

2.5.2 Blockchain adoption effect on bargaining power

Taking inspiration from the chocolate supply chain, where many organizations and companies are beginning to propose blockchain-based solutions for cocoa traceability, we introduced blockchain adoption into our model. Again adopting a resource dependence theory perspective from the literature, it emerges that blockchain results in a different allocation of resources. Specifically, in reference to financial resources (Agrawal et al., 2022; Yi et al., 2021) and information (Casino et al., 2020; Nayal et al., 2021). Some authors touch on the idea that blockchain may influence bargaining power (Gruchmann, 2022; Rejeb et al., 2021) however, the relationship still appears considerably understudied. We investigate the effect of blockchain adoption on bargaining power in a first stage by isolating the effect of blockchain adoption on information and in a second stage on financial resources. We contribute to the literature by showing that in both cases as blockchain adoption increases bargaining power asymmetries decrease. In both cases we find path dependence. Holding the level of blockchain adoption constant we see that the effect on bargaining power asymmetries increases with time demonstrating that blockchain, while effective right out of the box needs time to manifest its full potential. Finally, we see that the effect of blockcahin adoption on bargaining power is greater when it is applied on financial resources than when it is applied on information.

2..5.3 Blockchain adoption effect on supply chain fairness

Finally, we introduce the joint effect of blockchain on information and financial resources into our model to test whether blockchain can improve supply chain fairness through bargaining power. We contribute to the literature by showing for the first time that blockchain has a positive effect on supply chain fairness and can be a solution to fairness problems in global agricultural supply chains.

2.6 Conclusion

We identified the lack of supply chain fairness as one of the main issues in modern agricultural supply chains.

We investigated the chocolate supply chain by combining empirical research and system dynamics to study the relationship between bargaining power asymmetries and supply chain fairness and to understand whether blockchain technology can improve supply chain fairness.
In answering the identified research questions, we have three main contributions.
First, we have shown that when bargaining power asymmetries are reduced supply chian fairness improves. Second, blockchain allows contractual asymmetries to be reduced through its impact on financial resources and information. Third, blockchain allows supply chain fairness to improve through its effect on bargaining power.
This study also provides interesting insights for managers and those working in global agricultural supply chains involving developing countries. Farmers should devote more effort to increasing their bargaining power to improve their welfare and consequently supply chain fairness. To do so, they should act on the resources available to them. For example, referring to the resources in our model farmers could seek to unite through associations or mergers to increase the size of their holdings while simultaneously reducing the number of farmers to whom exporters can turn. They could, with government support expand storage facilities to decrease the urgency to sell cocoa in the harvest months. To decrease information asymmetries they should use blockchain technology to have information about end markets available to them and to make information about their product available to end consumers. In addition, blockchain technology is effective in ensuring that farmers are given a fair price for their product. In fact, blockchain, by recording all transactions in a transparent and immutable manner, precludes the application of prices that are not in line with the established minimum price, including the application of premiums if they are expected. However, blockchain to apply its full potential takes time and must be supported by adequate investment in infrastructure and population literacy. Many NGOs or private companies such as Trusty provide access to this technology at no cost to farmers and invest in training in its use.
Looking at exporters, blockchain introduction could have a dual perspective. It could be an advantage to grant them more information about the product that could allow them to prove quality and adherence to regulations, especially European food safety regulations. In addition, in the case of products contaminated with non-legal or poor quality substances, traceability through blockchain, would allow them to be able to trace back to the farmers who worked incorrectly and take the necessary countermeasures. On the other hand, the introduction of blockchain poses a threat because it grants more bargaining power to farmers. This greater bargaining power translates into a higher on-the-field price demanded by farmers, which consequently reduces the exporter's margin. Exporters need to be able to sterilize this price increase by passing the increase on to the end customer, perhaps justifying it with the increased information they are able to collect. Alternatively, they need to make their activities more efficient by reducing or limiting as much as possible the costs associated with lower value-added activities. One example is financial institutions that by lending money to exporters are able to appropriate some of the value created in the supply chain. Better financial management by exporters could offset the higher costs related to raw material acquisition.
Our work is not without limitations that are also insights for future research. The system dynamics model we developed is general but specific at the same time. General because it frames typical dynamics of agricultural supply chains of this type such as production, seasonality, and product flow. Specific because it was developed specifically on the Ivory Coast cocoa supply chain such as storage issues, rules present in Ivory Coast for export,

price dynamics. Future research could build on the model we identified and adapt it to the dynamics of other agricultural supply chains with similar issues such as, for example, the cotton supply chain. The specificity of the context analyzed also influences the measurement of bargainign power where we considered the most important resources in the Ivory Coast cocoa supply chain. In other supply chains the key resources to be considered might be different. In addition, for these reasons the effect of blackchain adoption could also be different. Finally, our model considers a reasonably long time horizon of 10 years. Future studies could investigate what happens over the long term and introduce the effect of market shocks such as production outside the norm or cocoa price hikes.

7. Appendix

2.1 Appendix
Literature review table

	SC fairness	BG Power	Resource 1: information	Resource 2: financial	Resource 3: concentration	Blockchain and smart contract
(Parviziomran and Elliot, 2023)		X		X		
(Sheu and Gao, 2014)		X			X	
(Matsui, 2022)		X				
(Chen et al., 2017)		X	X			
(Huang et al., 2019)		X		X		
(Chang et al., 2022)		X				
(Towner, 2020)		X		X		
(Guo, 2023)		X	X			
(Chen et al., 2022)	X			X	X	
(Wu and Niederhoff, 2014)	X			X		
(Choi and Messinger, 2016)	X		X			
(Agnetis et al., 2019)	X					
(Oyedijo et al., 2021)	X		X			
(Liu et al., 2012)	X					
(Ho et al., 2014)	X	X		X		
(Du et al., 2014)	X	X	X			
(Guo et al., 2021)					X	X
(Lohmer et al., 2020)			X			X
(Wang et al., 2019)			X			X
(Manupati et al., 2020)			X			X
(Casino et al., 2020)						X
(Nayal et al., 2021)			X			X
(Gruchmann, 2022)		X	X			X

(Kamble et al., 2020)			X			X
(Rejeb et al., 2021)		X	X		X	X
(Agrawal et al., 2022)			X	X	X	X
(Rodríguez-Espíndola et al., 2020)			X	X		X
(Bai et al., 2019)				X		X
Yi et al., (2021)				X		X

Causal loop in the SD model

INFORMATIONS LOOPS

Bargaining power affect top down adoption change

Loop I-R1

Information asymmetry

Bargaining Power Asymmetry

Exporters Adoption Change

Willingness of Exporters for technology adoption

Exporters information

Loop I-R2

Information asymmetry

Bargaining Power Asymmetry

Bargaining power change

Bargaining power balance

Exporters Adoption Change

Willingness of exporters chain for technology adoption

Farmers information

Analfabetismo

Loop I-R3

Information asymmetry

Bargaining Power Asymmetry

Poverty discount

Minimum price on the field

Farmers net income

Money farmers

Availability of money for education

Literacy change

Farmer Literacy rate

Farmers information

Debt ed information asymmetry

Loop I-R4

Information asymmetry

Bargaining Power Asymmetry

Exporters Adoption Change

Willingness of Exporters chain for technology adoption

Farmers information asymmetry

Total financial instruments availability farmer

Residual access to finance instrument farmers

Debt increases farmers

Farmers net income

Money farmers

Availability of money for education

Literacy change

Farmer Literacy rate

Farmers information

FINANIAL LOOPS

Price loops

Loop F-R1

Financial asymmetry

Bargaining Power Asymmetry

Poverty discount

Minimum price on the field

Exporter net income

Money Exporter

Survival time no cash inflows exporters

Loop F-B1

Financial asymmetry

Bargaining Power Asymmetry

Poverty discount

Minimum price on the field

Farmers net income

Money farmers

Survival time without cash inflow farmers

Farmers Debt

Loop F-B2
Financial asymmetry
Bargaining Power Asymmetry
Poverty discount
Minimum price on the field
Farmers net income
Money farmers
Debt decreases farmers
Total debt farmers
Residual access to finance instrument farmers
Survival time without cash inflow farmers

Loop F-R2
Financial asymmetry
Bargaining Power Asymmetry
Poverty discount
Minimum price on the field
Farmers net income
Money farmers
Debt increases farmers
Total debt farmers
Residual access to finance instrument farmers
Survival time without cash inflow farmers

Exporters debt
Loop F-R3
Financial asymmetry
Bargaining Power Asymmetry
Poverty discount
Minimum price on the field
Exporter net income
Money Exporter
Debt decreases exporters
Total debt exporter
Residual access to finance instrument exporter
Survival time no cash inflows exporters

Loop F-B3
Financial asymmetry
Bargaining Power Asymmetry

Poverty discount
Minimum price on the field
Exporter net income
Money Exporter
Debt increases exporter
Total debt exporter
Residual access to finance instrument exporter
Survival time no cash inflows exporters

Bottom-up information asymmetry and farmers debt

Loop F-R4
Financial asymmetry
Bargaining Power Asymmetry
Exporters Adoption Change
Willingness of Exporters chain for technology adoption
Farmers information
Total financial instruments availability farmer
Residual access to finance instrument farmers
Survival time without cash inflow farmers

Loop F-B4
Financial asymmetry
Bargaining Power Asymmetry
Exporters Adoption Change
Willingness of Exporters chain for technology adoption
Farmers information
Total financial instruments availability farmer
Residual access to finance instrument farmers
Debt increase farmers
Total debt farmers
Financial costs farmers
Farmers net income
Money farmers
Survival time without cash inflow farmers

RELATIONAL RESOURCES

Loop R-B1
Number of players asymmetry

Bargaining Power Asymmetry
% of companies that meet the criteria for a licence
Number of exporters licensed

Loop R-B2
Number of players asymmetry
Bargaining Power Asymmetry
25T rule
Number of actors to aggregate to meet the rule
Actors interested to have a license
Number of exporters licensed

STORAGE CAPACITY

Loop S-B1
Warehouse saturation asymmetry
Bargaining power asymmetry
Poverty discount
Minimum price on the field
Government warehouse Investment
Warehouse capacity change
Warehouse capacity HC
HC saturation

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Chapter 3

Unlocking the Blockchain Potentials through Oracles: Empirical Evidence on Supply Chain Challenges and Performance

Abstract

This study investigates the positive impacts of blockchain on supply chain challenges as well as its direct and indirect impacts on business performance. Then, it studies the influence of different types of blockchain oracles including software, hardware, inbound, outbound, and human oracles on the relationships between the blockchain, supply chain challenges, and business performance. To reach the research goals, it uses a survey to collect the data from 156 companies and analyze them through a Partial Least Squares Path Modeling (PLS-PM) methodology which is an estimation algorithm that utilizes components to predict the relationships between constructs and provides their scores at the original scale. The results show that there is no meaningful direct impact of blockchain on business performance, but the impact of blockchain on supply chain challenges and the indirect influence of blockchain on business performance through supply chain challenges is significant. Moreover, inbound, hardware, and software oracles can increase the positive impact of adopting blockchain technology on improving supply chain challenges and business performance and they are more efficient compared to human and outbound oracles. Compared to previous research, this study considers blockchain implementation, supply chain challenges, and business performance simultaneously to provide useful insights to managers who are seeking to enhance firms' performance through blockchain adoption. Moreover, it is the first paper to empirically verify the oracle's moderation effect on the considered relations.

3.1 Introduction

Blockchain is a distributed ledger with a chain of blocks for recording the information of valid transactions. Because of the versatility and extensive impact of blockchain on multiple aspects of business, it has been defined as a general-purpose technology (De Giovanni, 2020). Within the supply chain context, it enhances secure transactions, as a product moves across the chain interacting with several actors like suppliers, manufacturers, distributors, and retailers to reach the end consumer (Jardim et al., 2021). Recently some companies are implementing blockchain to overcome the challenges in their supply chains. Most companies claim a performance improvement after blockchain adoption. For example, Nestle improves transparency in its supply chain by creating a public blockchain platform that integrates with a mobile app and enables consumers to track their products from the farm to consumption (Yang et al., 2021). Walmart uses blockchain to overcome supply chain challenges related to data management and reconciliation procedures with suppliers. It implements a blockchain-based solution to reduce data discrepancies in the invoice and payment process for freight carriers. Eliminating the need for manual reconciliations has reduced associated costs and speeded up payments (Vitasek et al., 2022). Cantina Placido Volpone is among the first winemakers in the world to adopt blockchain to address existing challenges in the wine industry. Through blockchain, they track the entire process of wine production from the field to the end customer certifying the quality of the final product and establishing a trusting relationship with their customers (Prencipe et al., 2022). Genuino applies blockchain to overcome challenges in the collectibles industry. Through the combination of Iot sensors applied to match worn jerseys and blockchain technology, they certify the originality of match-worn jerseys by professional soccer players as collectibles. On the one hand, they prevent the spread of counterfeit items on the other hand they create a new stream of earnings for football clubs (Ruzza et al., 2022). Despite interesting studies about the effectiveness of blockchain for overcoming supply chain challenges and for business performance improvement we have identified conflicting opinions in the literature. Some papers show that blockchain is effective in overcoming trust-related supply chain challenges (Chang et al., 2020), while for others when the level of distrust is too high blockchain is not effective (Biswas et al., 2023). Similarly, on the one hand, we identify blockchain as effective in reducing supply chain challenges related to costs through automation and disintermediation (Azzi et al., 2019), on the other hand, these studies do not consider the costs due to blockchain implementation, which declines in both fixed and variable costs (De Giovanni, 2020). A similar situation is found in the effect of blockchain on business performance. Some authors find a strong and positive influence of blockchain on performance (Ji et al., 2022; Nandi et al., 2020; Wambaa et al, 2018), while others identify no direct effect of blockchain on performance (De Giovanni, 2022; Markus and Buijs, 2022; Sharma et al., 2023). Given the contradictory results in the literature, our first research question is:

RQ1: Is there a significant relationship between implementing blockchain technology, supply chain challenges, and business performance? How do they affect each other?

From the examples analyzed oracles emerge as pivotal tools to ensure the effective application of blockchain. Oracles can be defined as the bridges through which information is transferred from the real world to the blockchain and vice versa. De Giovanni, (2021, 2022) classified oracles based on several criteria. Inbound oracles are defined as oracles that allow information to be transferred from online or offline sources within the blockchain. Outbound oracles allow information to take the reverse path by leaving the blockchain to other databases. A further distinction is between software oracles that take data from online sources, hardware oracles that take data from physical systems such as IoT sensors, and human oracles that take information from a network of individuals. In the examples considered, Walmart uses software oracles to take information from both the company's information system and partners' information systems and insert it into the blockchain. Placido Volpone Winery uses human oracles to place on the blockchain information about wine production processes. Genuino uses hardware oracles by inserting chips into game jerseys to record relevant information on the blockchain and ensure the originality of match-worn jerseys. Even though every business application of blockchain involves the use of oracles, we have not been able to find quantitative studies on the topic that test their effect. However, recently interesting exploratory studies have found that oracles could influence the effect of blockchain on performance (Chung et al., 2023; Omar et al., 2021) and overcome cost-related supply chain challenges (Taghavi et al., 2023). Thus, we frame our second research question:

RQ2: Which types of blockchain oracles are more efficient in solving SC challenges and improving business performance?

To study these research questions, we devise and analyze various hypotheses by defining a conceptual model that investigates the proposed research questions. We use a survey to collect the data from 156 companies and analyze them through a Partial Least Squares Path Modeling (PLS-PM) methodology. Our results show that blockchain has a positive impact on supply chain challenges, but it does not have a direct impact on business performance. However, it can enhance business performance factors indirectly by improving supply chain challenges. Moreover, our findings indicate that outbound oracles and human oracles have no significant impact on improving supply chain challenges and business performance. However, when hardware oracles, inbound oracles, and software oracles are employed, blockchain has a higher positive and indirect impact on business performance through mitigating supply chain challenges compared to the condition without oracles. The remainder of this study is organized as follows. Section 2 reviews the literature, clarifies the research gap, and develops the research hypothesis. Section 3 describes the data collection and methodology, and section 4 presents the empirical results and discussion. Finally, we provide the managerial implication in section 5 and section 6 concludes with future research directions.

3.2 Literature review

In the literature review, we analyzed the operations and supply chain literature regarding blockchain, supply chain challenges, business performance, and oracles to develop our hypotheses. Table 1 summarizes the main papers considered.

	Blockchain in SC	SC Challenge	Performance	Oracle
(Chang et al., 2020)	X	X		
(Hastig and Sodhi, 2020)	X			
(Pournader et al. 2020)	X			
(Wang et al. 2019)	X			
(Azzi et al. 2019)	X	X		
(Wang, Singgih, et al. 2019)	X			
(Calatayud et al., 2019)	X	X		
(Johnson, 2006)	X	X		
(Graves et al., 2022)		X		
(Wambaa et al., 2018)	X		X	
(Yousefi and Mohamadpour Tosarkani, 2022)	X		X	
(Ji et al., 2022)	X		X	
(Sharma et al., 2023)	X		X	
(De Giovanni, 2022)	X		X	
(Markus and Buijs, 2022)	X		X	
(Nandi et al., 2020)	X		X	
(Nayal et al., 2021)	X		X	
(Kumar et al., 2022)		X	X	
(Ghode et al., 2023)	X	X	X	
(Han et al., 2013)		X	X	
H1a, 2a, 3a				
(Chung et al., 2023)				X

(Omar et al., 2021)				X
(Taghavi et al., 2023)				X
(Nelaturu et al., 2020)				X
(De Giovanni, 2021)				X

Table 1 - Literature review summary

3.2.1 Blockchain and supply chain challenges

Supply chains face numerous challenges that are made even more challenging due to unpredictable phenomena such as covid19, or new technologies. Many studies are looking at the technology's effect on supply chain challenges. Graves et al., (2022) study supply chain challenges consequent to covid19 disruption from a supply and demand perspective. The results show that supply chain challenges are influenced by supply chain length, the cost of lead time, the difficulty of forecasting due to high uncertainty, and the use of lean practices that have made supply chains less resilient. Johnson, (2006) in a call for special issue identify new supply chain risks and challenges caused by globalization and new technologies and call for new studies on the subject. Among the technologies identified, some studies have analyzed the possible impacts of blockchain on supply chain challenges. Chang et al., (2020), develop a state of the art of blockchain literature in the field of operations and demonstrate the ability of blockchain to solve supply chain challenges. The authors identify six supply chain challenges. Based on the literature and real application cases, the authors show that blockchain has an impact on all identified supply chain challenges. Azzi et al., (2019) identify traceability and effective data flow management as the main supply chain challenge. The results show that blockchain can bring numerous benefits that enable the supply chain challenge overcome. It enables more transparent and secure end-to-end tracking, increases trust, gives visibility to products that comply with international standards, reduces bureaucracy and related costs, reduces fraud and counterfeiting, and facilitates processing. However, it introduces other challenges that need to be limited through certain expedients including choosing the right blockchain, choosing the right IoT technologies to partner with blockchain for information collection, and using communication protocols and security. Calatayud et al., (2019) develop the concept of self-thinking supply chains where technologies such as blockchain, IoT, and artificial intelligence are primary. The results show that self-thinking supply chains are particularly effective in overcoming supply chain challenges in developing countries. Challenges identified include those related to traceability and logistics services.

From the papers analyzed so far, emerges that because of new technologies new supply chain challenges emerge (Johnson, 2006; Azzi et al., 2019). On the other hand, new technologies enable to overcome some existing supply chain challenges (Chang et al., 2020; Calatayud et al., 2019). If we consider blockchain technology, among the supply chain challenges that blockchain seems able to improve we identify traceability, dispute resolution, cargo integrity and security, supply chain digitalization, compliance, and trust and stakeholder management (Chang et al., 2020). However, other authors have shown that blockchain is not a panacea. For example, regarding trust and stakeholder relationships Biswas et al., (2023) show that companies avoid using blockchain when the level of distrust is very high. As a result, blockchain is not always effective in countering supply chain challenges related to trust. Similarly, some works show that blockchain is capable of overcoming cost-related supply chain challenges through automation, reduction of bureaucracy, and elimination of possible middlemen (Azzi et al., 2019). However, these studies ignore the fact that blockchain requires an upfront investment to equip the company with the technological infrastructure and expertise to effectively manage blockchain, as well as variable management costs (De Giovanni, 2020). As a result, the effect of blockchain on supply chain challenges affecting costs is unclear. Moreover, the studies identified are mainly literature reviews and theoretical papers. Quantitative studies aimed at empirically verifying the effect of blockchain on supply chain challenges are missing. Therefore, to clarify the blockchain effect on supply chain challenges we developed the first hypothesis.

H_1: Blockchain has a positive impact on SC challenges.

3.2.2 Blockchain and business performance

In the literature, the blockchain effect on many performance indicators has raised some interest. Supply chain performance, firm performance, financial performance, and business performance have been considered. Among the studies that have looked at performance from the supply chain performance perspective, Wambaa et al, (2018) study the effect of blockchain on supply chain performance together with the country effect. The results show that the use of blockchain has a high and positive impact on supply chain performance. Supply chain performance is affected by supply chain transparency and blockchain transparency. In addition, there are no significant differences between the countries analyzed. Similarly, Markus and Buijs, (2022) study how blockchain influences supply chain performance in terms of quality, cost, speed, dependency, and flexibility. Interestingly, the results show that many improvements in supply chain performance do not come from the direct effect of blockchain but result from the indirect effects of activities associated with blockchain introduction such as digitization or rationalization of nonessential processes. Other papers have studied blockchain with sustainability performance. Nayal et al., (2021) study the effect of blockchain adoption on sustainable supply chain performance. The results show that blockchain has a positive effect on sustainable supply chain performance. In addition, the need for green lean practices can induce the adoption of blockchain, as blockchain in turn can influence the success of green lean practices. Yousefi and Mohamadpour Tosarkani, (2022), use an analytical approach to investigate the effects of blockchain technology adoption on sustainability performance in the mining sector. The results demonstrate a significant impact of blockchain on performance mainly with smart contracts, traceability, and transparency. In addition, blockchain makes it possible to limit commodity counterfeiting and limits the risks associated with possible conflicts within the supply chain.

Sharma et al., (2023) develop large-scale empirical research to investigate whether blockchain adoption impacts firm performance and the moderating effect of a firm's intangible capital and environmental dynamism. The results show that credible blockchain investments have a positive effect on market expectations of future earnings, but it is not correlated with current performance. The effect on future earnings expectations is greater for companies that have higher intangible capital and operate in a more dynamic business environment. This is because they are more likely to have the know-how to take advantage of the blockchain benefits. Blockchain is a key element of a firm's dynamic capabilities that can result in a competitive advantage. Nandi et al., (2020) study the impact of blockchain and supply chain systems on performance from a resource-based view perspective. The results show that the capabilities that result in better performance are: improved process efficiency, product/service quality and flexibility, reduced cost, and reduced process time. Finally, the industry type has a determining influence on the effect on performance. Ji et al., (2022) develop a game with two manufacturers and one retailer to study the impact of blockchain on pricing decisions and supply chain member's financial performance. The results show that manufacturers when choosing to introduce blockchain, should consider the impact not only on their profitability but also the impact of their competitors' response. In addition, the introduction of blockchain has a different impact on profits and prices depending on the market environment. The impact on profits is greater for first movers. De Giovanni, (2022) analyzes the implications of blockchain on circular economy systems, with closed-loop supply chains and reverse omnichannel strategies, considering incentives. The results show that blockchain is an effective technology for improving closed-loop supply chains and reverse omnichannel capabilities. However, blockchain has a weak and marginal magnitude impact on business performance. Regarding incentives, collector incentives activate the potential of blockchain while consumer incentives activate the potential of closed-loop supply chains and reverse omnichannel strategies. However, the impact of blockchain on business performance remains negligible.

From the analyzed papers we get contradictory results regarding the impact of blockchain on performance. Some papers find a strong and positive influence of blockchain on supply chain performance (Wambaa et al, 2018) while others do not identify any direct result of blockchain on supply chain performance (Markus and Buijs, 2022). According to Markus and Buijs, (2022) the blockchain effect on performance would not be due to the blockchain itself but to all the activities required to introduce blockchain such as digitization and rationalization of resources (Markus and Buijs, 2022). Similarly, turning to firm performance some studies find a positive effect of blockchain introduction on firm performance. This effect would be even stronger for first movers (Ji et al., 2022) and more intense in certain industries than others (Nandi et al., 2020). Other work identifies no effect on performance especially on current performance, while identifying a positive effect on future performance expectations (Sharma et al., 2023). Similarly, De Giovanni, (2022) finds a weak and negligible effect on business performance. Given these contradictory results, the effect of blockchain on performance is unclear. So, our next hypothesis is.

H2: Blockchain has a positive impact on Business Performance

3.2.3 Supply chain challenges and business performance

We have identified a limited number of studies that consider the supply chain challenge effect on business

performance. Kumar et al, (2022), through a case study, identify key supply chain challenges and opportunities. They also try to understand how to manage them to increase supply chain performance. The results of their analysis show that the salary of employees, tiny warehouse space, and inventory cost management are the three main challenges. While the three main opportunities identified are the client's order frequency, transportation, and client quantity. To increase supply chain performance the company should develop new products, do vigorous marketing, and increase the availability of products on the shelves. Ghode et al., (2023) study the supply chain challenges associated with the introduction of blockchain and the effects on supply chain performance. One of the most significant challenges is related to the ability to bring all stakeholders onto the blockchain. Next comes the development of supporting technologies and the development of effective government policies that balance transparency, privacy, and security. Overcoming these challenges has positive effects on supply chain performance. Han et al., (2013) study supply chain challenges related to emerging market penetration and their effects on financial performance. The authors focus on inventory supply as the main challenge. The results show that emerging market penetration is related to better financial performance and does not necessarily result in higher inventory levels.
Given the literature, it seems that overcoming supply chain challenges results in improved business performance. Consequently, our third hypothesis is:

H3: Supply chain challenges have a positive impact on Business Performance.

3.2.4 Blockchain and business performance through supply chain challenges

The literature analyzed above identifies an unclear relationship between blockchain and business performance. Among the papers analyzed Markus and Buijs, (2022) identify no direct impact of blockchain on business performance but find an indirect impact through all activities related to the introduction of blockchain. The introduction of blockchain requires several activities to make the enterprise ready to implement the technology. Among these activities, we can find the creation of tools for the input of data on the blockchain, the training of staff to use the new technology, and the adaptation of the enterprise technology infrastructure. Taking inspiration from this insight, we hypothesize that the unclear relationship between blockchain and business performance might be justified by a third variable. For this reason, we develop a fourth hypothesis in which we hypothesize an indirect effect of blockchain on business performance through supply chain challenges.

H4: Blockchain has a positive and indirect impact on Business Performance through Supply Chain Challenges

3.2.5 Oracles effect

One of the key factors that make blockchain effective for business purposes is the creation of bridges to enable blockchain to exchange information with the real world. Without these connections, blockchain applicability is limited. Oracles are the gates that enable the transfer of information from the real world to blockchain and vice versa. Oracles are extremely important because they establish how information can be placed on blockchain by determining the reliability and credibility of the system. While most studies ignore the oracles issue some studies have recently begun to consider these tools. Chung et al., (2023) position their paper at the intersection of sustainability, infrastructure financing, and blockchain-enabled investments to study what are the emerging areas of research, the enabling function, and the implications of blockchain for sustainable infrastructure and smart city financing. Interestingly, the authors explore the use of decentralized oracle networks for information gathering on the blockchain. The results show that the use of oracles reduces the performance risk of sustainable infrastructure as they improve the verifiability of performance-based financing through data accuracy, trust, and transparency. As a result, the financial attractiveness of investments increases. Omar et al., (2021) propose a blockchain-based solution to solve problems associated with online auctions. They explore the use of oracles to ensure the reliability of data used by smart contracts, transparency, and elimination of intermediaries. The proposed smart contract-based solution on Ethereum demonstrates better performance in terms of transparency, traceability, and security than centralized solutions. Taghavi et al., (2023) investigate which oracle is the best from the perspective of reliability and cost-effectiveness. In the initial phase of the simulation, oracles with a shorter history were more likely to be used. However, when the system settled down, the oracles that proved to be most successful were those with a balance between price and performance, or those that were very cheap. Nelaturu et al., (2020) propose a new decentralized oracle protocol that takes inspiration from crowdsourcing voting mechanisms. The authors show that there is a winning Nash equilibrium and that this solution can work and provide a high level of security for the blockchain information. The system includes a simplified and an ordinary version and rewards and penalties for participants.

Given the importance of oracles to the proper functioning of blockchain these could moderate the relationships between the variables identified in the previous hypotheses. Oracles could influence the effect of blockchain on performance (Chung et al., 2023; Omar et al., 2021), because without effective oracles blockchain may be ineffective in achieving expected performance improvements. In addition, oracles can affect supply chain challenges. For example, if we consider cost-related supply chain challenges, oracles determine the cost of acquiring information and the investment required to implement blockchain (Taghavi et al., 2023). Therefore, we define the remaining hypotheses as:

$H_{1a,b,c,d,e}$: Oracle solutions facilitate the positive impact of blockchain on SC challenges,
$H_{2a,b,c,d,e}$: Oracle solutions facilitate the positive impact of blockchain on Business Performance, $H_{3a,b,c,d,e}$: Oracle solutions facilitate the positive impact of solving SC challenges on business performance”,
$H_{4a,b,c,d,e}$: Oracle solutions facilitate the positive and indirect impact of blockchain on business performance”.

We use the labels “a” for software oracles, “b” for hardware oracles, “c” for inbound oracles, “d” for outbound oracles, and “e” for human oracles, to evaluate whether certain oracles improve some of the established relationships. Figure (1) summarizes the conceptual model, including both the direct relationships between the blockchain implementation to the supply chain challenges (H_1), the blockchain adoption to the business performance (H_2), and the SC challenges to the business performance (H_3) as well as the indirect impact of blockchain on firms' performance (H_4). Furthermore, we verify the effect that oracles have on the aforementioned relationships by analyzing whether a certain relationship can be improved by implementing specific oracles ($H_{1a,b,c,d,e}$, $H_{2a,b,c,d,e}$, $H_{3a,b,c,d,e}$, and $H_{4a,b,c,d,e}$).

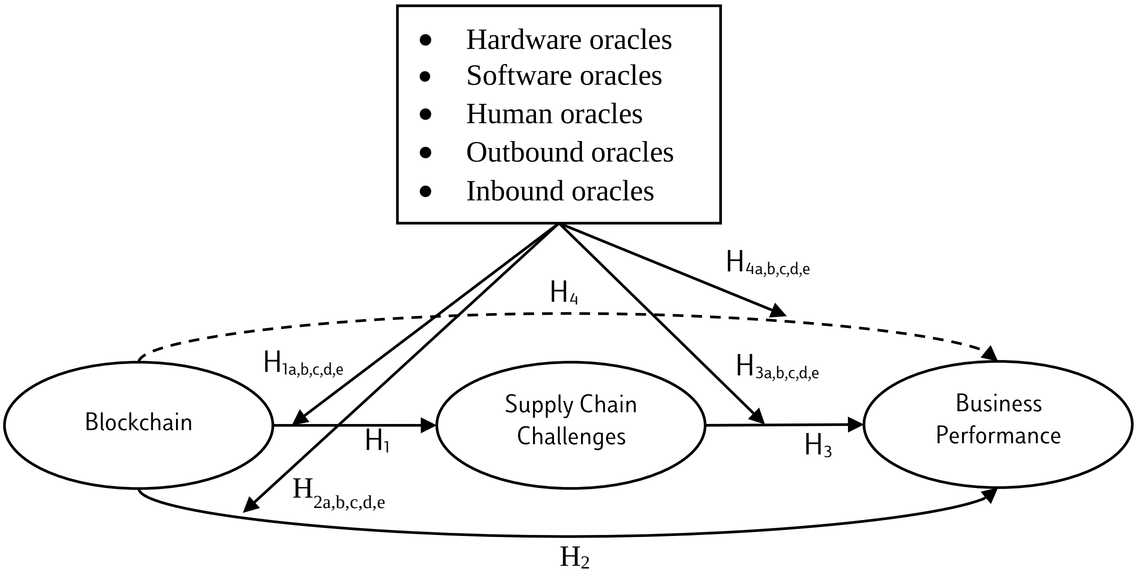

Figure 1 - Conceptual model

3.3 Methodology

This section explains the survey design and sample description, the methodology that we used to analyze the collected data, and the model assessment to clarify the research steps.

3.3.1 Survey design and sample description

To test our research hypotheses, we created a comprehensive survey that gathered crucial information on various aspects, including the industry and company type of the respondents, the level of investment in blockchain technology, the implementation of reverse omnichannel strategies, the effectiveness of the CLSC network, and business performance. To ensure the accuracy and effectiveness of our survey, we pre-tested it on a group of experts from diverse backgrounds such as professors, Ph.D. students, professionals, and managers. The experts provided feedback on the wording, readability, and comprehensiveness of the questionnaire. Based on the valuable feedback received, we made necessary modifications and improvements to the survey to ensure its optimal quality. To initiate the data collection process, we selected a sample of 120 firm managers who were active professionals in the supply chain management domain, as our research focused on this specific area. We reached out to them through email and within two weeks, we received a majority of the responses. To increase the scope of our investigation, we also followed up with the respondents via phone. In total, we received 156 usable observations, after removing any invalid responses. This sample size represents approximately 12% of the target population of companies we aimed to survey, which was 1200. Notably, over half of the organizations surveyed had a sale turnover of more than 100 million (52%) and a workforce of more than 200 employees (53%). Our data collection primarily focused on European (73%) and American (16%) companies, with a majority of the respondents being supply chain managers (52%) working in the manufacturing (36%) and retail (23%) sectors. The findings revealed a diverse industrial landscape, with the food and beverage sector (22%) and fashion and apparel sector (12%) being the most prevalent. Table 2 provides a detailed breakdown of the respondents and the sample characteristics. We conducted various approaches to assess non-response bias. Firstly, we compared early and late respondents (i.e., the first and second to third surveys) using a one-way analysis of variance (ANOVA). The results indicated no significant differences between the early and late responses for all items, supporting our conclusion that non-response bias is not a significant concern. Additionally, we checked for non-response bias using demographic variables such as company size, number of employees, and average turnover. Again, we found no significant differences between the groups. All items in the questionnaire were measured on a 7-point Likert scale, with 1 indicating not agreeing and 7 indicating full agreement. As the difference between the items was essential and could be directly compared, we analyzed the data at the original items' scale. The Appendix describes the items along with their means and standard deviations.

3.3.2 Methodology

To achieve the objectives of our study, we employed Partial Least Squares Path Modeling (PLS-PM). PLS-PM is an estimation algorithm that utilizes components to predict the relationships between constructs and provide their scores at the original scale. Given these benefits, PLS-PM has been widely utilized in various business contexts, including operations management (Peng & Lai, 2012), supply chain management (Colicev et al., 2016), and digital transformation (De Giovanni and Cariola, 2021).

Following the guidelines of operations management literature (Peng & Lai, 2012) and marketing literature (Hair et al., 2012) we have considered this approach to be ideal for our study given several reasons and measures that we have implemented. First, this method is advantageous because it does not require any distributional assumption on the data, unlike maximum likelihood covariance-based approaches. Second, PLS-PM provides less biased estimates than other structural equation modeling approaches for sample sizes lower than 200 observations while achieving the same power above 200 observations (Chin, 2010). Third, the variables that are included in our theoretical model are complex variables that require a multiplicity of items to be reliably measured. Looking for example at the supply challenges, these contain within them a series of different challenges that cannot be enclosed in a single item. We have therefore developed a comprehensive list of indicators to measure complex concepts which is available in the appendix and is explained in the next paragraph. Fourth, PLS allows for simultaneous estimation of both the measurement model and the structural model, reducing the risk of biased parameter estimates. This can be especially useful in exploratory research where the structure of the underlying relationships is not well understood. Fifth, PLS can handle both linear and nonlinear relationships, which makes it well-suited for modeling complex systems with nonlinear relationships between variables. Accordingly, we have implemented PLS-PM in XL-Stat 12 to estimate the research hypotheses on both the entire sample of 156 firms as well as comparing groups of firms. In the latter, the groups are formed using the dummy variables that distinguish firms according to the adoption of specific oracles, specifically: software oracles adopted by 97 firms, hardware oracles adopted by 95 firms, inbound oracles adopted by 89 firms, outbound oracles adopted by 109 firms, and human oracles adopted by 72 firms.

3.3.3 Model assessment

The present investigation aims to model firms' traits related to their business using reflective scales. To achieve this goal, we followed the procedure outlined in De Giovanni and Cariola (2020) to assess the internal consistency, convergent, and discriminant validity of the reflective measurement models. The first construct examined is Blockchain (B), which explores the practices that managers use to adopt this technology. Specifically, B includes the collaboration with developers (B1) to implement blockchain, the analysis of new exchanging platforms (B4) resulting from the collaboration between the supply chain partners, and the integration and combination with existing digital technologies (B7) for the full exploitation of its potential. In addition, the use of smart contracts (B2) allows for new and innovative ways to manage agreements and transactions, while ensuring compliance with existing regulations (B6), such as data protection and privacy rules. However, two variables, namely the development of tokens (B3) and the establishment of ad hoc training programs (B5), were excluded from the construct based on our analysis. The second construct examined is Business Performance (BP), which includes items related to market share (BP1), profits (BP2), and return on investment (BP3). These measures provide insights into the firm's performance compared to competitors, the firm's capacity to generate economic value, and the firm's capacity to recover investments through economic outcomes, respectively. Notably, cost savings, cost of energy, and cost of environmental impact were excluded from the analysis based on exploratory factor analysis.

Finally, the construct Supply chain challenges (SCC) can arise from a range of factors that impact the efficiency, reliability, and transparency of the global supply chain network. One key challenge is the high transaction costs (SCC1) as well as the costs for managing (SCC4) the complex and geographically dispersed network of suppliers and customers: this can lead to delays, errors, and other inefficiencies that can impact product quality and customer satisfaction. Another challenge is ensuring product traceability (SCC2) and transparency (SCC3) throughout the supply chain, particularly in industries such as food and pharmaceuticals where safety and quality are critical. Furthermore, delivery risks (SCC5), such as theft, damage, or delays, can also pose significant issues for supply chain management. The SCC construct also includes the verification of suppliers and third parties (SCC6), which is particularly difficult in industries where there is a high risk of fraud or counterfeiting. The latter also reflects in the reputation and the trust of customers and stakeholders (SCC7), especially regarding the implementation of transparent and ethical business practices, as well as effective communication and engagement strategies.

Sales %			Employees # %			Country %			Company type # %			Professionals # %			Industry # %		
< 10	11	7.0%	< 50	14	8.9%	Europe	115	73.2%	Manufacturer	56	35.7%	SC Manager	82	52.2%	Food & Beverage	34	21.7%
10-50	38	24.2%	50-99	40	25.5%	USA	25	15.9%	Wholesaler	30	19.1%	Logistics Manager	12	7.6%	Fashion & Apparel	18	11.5%
50-100	26	16.6%	100-200	20	12.7%	Asia	4	2.5%	Distributor	14	8.9%	Operations Manager	13	8.3%	Medical & Healthcare	12	7.6%
> 100	82	52.2%	>200	83	52.9%	Other	13	8.3%	Supplier	21	13.4%	Sales Manager	3	1.9%	Automobile	11	7.0%
									Retailer	36	22.9%	Production Manager	9	5.7%	Mechanic	7	4.5%
												Purchasing Manager	2	1.3%	Energy	7	4.5%
												Procurement Manager	8	5.1%	Furniture	6	3.8%
												Distribution manager	2	1.3%	E-commerce	5	3.2%
												Other	26	16.6%	Aerospace	4	2.5%
															Sport	4	2.5%
															Entertainment	4	2.5%
															Glass	3	1.9%
															Cement	3	1.9%
															Telecommunications	2	1.3%
															Luxury	2	1.3%
															Beauty & Cosmetics	2	1.3%
															Electrical and electronics	2	1.3%
															Chemical	1	0.6%
															Other	30	19.1%
Total	156	1		156	1		156	1		156	1		156	1		156	1

Table 2 – Sample description

The ultimate item list enables us to identify the cross-loadings connected to each construct, which are presented in Table 3. The outcomes show that certain items, such as the cost of managing the supply chain network, exhibit borderline loadings with values close to 0.6. Nevertheless, the findings from the 5,000 resample reveal that these loadings (and weights) are significant at 0.05 and, therefore, represent crucial items in terms of content validity. As stated by Colicev et al. (2016), these items can be retained.

	Supply Chain Challenges	Business Performance	Blockchain
Transaction costs over the global supply chain network (SCC1)	0.674		
Product traceability (SCC2)	0.755		
Product transparency (SCC3)	0.806		
Costs to manage the Supply Chain Network (SCC4)	0.653		
Delivery risks (SCC5)	0.787		
Verification cost of suppliers and third parties (SCC6)	0.739		
Protecting the reputation and enhancing the trust (SCC7)	0.677		
Market share (BP1)		0.830	
Profits (BP2)		0.836	
ROI (BP3)		0.820	
Consulting developers (B1)			0.838
Modifying the management of contracts and transactions (B2)			0.792
New platforms (B4)			0.805
Aligning the technology requirement with the regulations (B6)			0.802
Integrating blockchain technologies with other digital technologies (B7)			0.819

Table 3 – Summary of the cross-loadings

The assessment of the construct reliability index is a crucial step to ensure good internal consistency, which is achieved when the index exceeds 0.7. Our study has demonstrated that all constructs in our model have a reliability index higher than this threshold, as shown in Table 4. Furthermore, each item's reliability is assessed by checking whether its squared loading is higher than 0.7, which means that at least half of the item's variance is extracted by its corresponding construct (Chin, 2010).

To ensure convergent validity, we evaluated the outer loadings and utilized the Average Variance Extracted (AVE) criterion. As indicated in Table 4, the AVE for each construct is approximately 0.5, which is the recommended value according to Chin (2010). These results suggest that our study has achieved good convergent validity.

Index of composite reliability	Average Variance Extracted (AVE)	Construct	Blockchain	Supply Chain Challenges
0.871	0.658	Blockchain	1.000	
0.853	0.532	Supply Chain Challenges	0.412	1.000
0.772	0.686	Business Performance	0.052	0.170

Table 4 – Inter-construct squared correlations and reliability measures

Finally, an important aspect of our analysis is assessing the discriminant validity, which determines the extent to which each construct is distinct from the others. To achieve good discriminant validity, the Average Variance Extracted (AVE) should be greater than the squared correlation among the constructs, and item loadings within their constructs should be higher than those on other constructs. As can be seen in Tables 3 and 4, both of these criteria are met in our model. Our construct reliability indexes are all above the recommended threshold of 0.7, and each item's reliability is also above 0.7. Furthermore, our AVE values are around the recommended value of 0.5, indicating good convergent validity. Overall, our results show good internal consistency, convergent validity, and discriminant validity, providing a sound basis for evaluating the structural model.

3.4 Results

In this section, we test the research hypothesis using a PLS-PM approach for Structural Equation Modeling. We start with hypotheses 1, 2, 3, and 4 and then move on to multigroup analysis considering the effect of oracles.

3.4.1 Hypothesis testing on the entire sample

According to the results in Table 5, blockchain technology offers several benefits that can positively impact the management of supply chain challenges since *H1* is supported. This result links to several motivations. Firstly, blockchain enhances transparency and traceability in the supply chain, providing real-time visibility of product movements, reducing the risks of counterfeiting, and improving accountability. Secondly, blockchain can improve the security of the supply chain by using encryption and distributed ledger technology, which makes it harder to alter or tamper with data. Thirdly, it offers cost-saving opportunities by reducing the need for intermediaries and streamlining processes, leading to lower transaction costs over the supply chain. Fourthly, blockchain can facilitate trust and collaboration between supply chain partners, promoting better communication and coordination. Finally, blockchain can enable the development of smart contracts that can automate and enforce the terms of agreements between supply chain partners, reducing the risk of fraud and disputes. Overall, blockchain technology offers significant potential to address some of the key challenges facing supply chain management and improve its efficiency, security, and reliability.

Even though, our empirical results suggest that blockchain's impact on business performance may not always be significant *H2* is not supported. There are several reasons for explaining this result. The adoption of blockchain requires significant investments in technology and infrastructure, which can offset the potential benefits. Furthermore, the benefits of blockchain may not be fully realized if there is a lack of standardization or interoperability among different blockchain systems. This might be especially through for global supply chains, which entail networks all over the world: the complexity of implementing blockchain technology in the worldwide context can result in operational inefficiencies, which can negatively impact business performance. In general, the benefits of blockchain technology may not be evenly distributed across all stakeholders and partners in the supply chain, which can limit its overall impact on business performance. Finally, one should not forget the limitations linked to the poor regulatory frameworks around blockchain, which can create uncertainty and pose legal and compliance risks. Therefore, while blockchain technology has the potential to improve supply chain management, its impact on business performance may not always be significant and requires careful consideration and evaluation.

Research Hypothesis	Direct effects and the results
H_1: Blockchain has a positive impact on SC challenges.	0.642*** (Supported)
H_2: Blockchain has a positive impact on Business Performance.	*-0.062* (Non supported)
H_3: Supply chain challenges have a positive impact on Business Performance.	0.452***(Supported)
H_4: Blockchain has a positive and indirect impact on Business Performance through Supply Chain Challenges	0.290** (Supported)

***p=value<0.01; **p=value<0.05; *p=value<0.1

Table 5 – Results of the research hypothesis

Considering that *H3* is supported, our empirical analysis demonstrates that firms able to solve supply chain challenges can have a significant increase in their business performance. These challenges can include issues such as delays in delivery, inefficiencies in production, and lack of transparency in the supply chain. By addressing and solving these challenges, companies can increase their business performance in several ways. For example, by improving supply chain efficiency through the optimization of inventory management, the reduction of transportation costs, and the improvement of production processes, companies can reduce costs and improve their profitability. In addition, by improving supply chain visibility and transparency, companies can enhance their reputation and increase customer satisfaction. This can lead to increased customer loyalty and repeat business, as customers are more likely to trust and purchase from companies that are transparent and accountable in their supply chain practices. Furthermore, by addressing supply chain challenges, companies can also reduce the risk of supply chain disruptions. This is particularly important in industries that rely heavily on just-in-time inventory management, where even minor disruptions can have significant impacts on business performance. Overall, solving supply chain challenges can have a positive impact on a company's bottom line, as it can increase profitability, enhance reputation, and reduce the risk of disruptions. According to the significant impact that solving the supply chain challenges has on business performance, companies should invest in solutions and technologies that can help to address and solve them.
This finding is highly evident thanks to the support of *H4*, according to which blockchain can contribute to business performance indirectly through the effect exerted by the firms' capacity to solve the SC challenges. Specifically, the use of blockchain technology leads to several benefits for the supply chains, like efficiency, cost reduction, enhanced reputation, customer satisfaction, and reduced risk of disruptions. For example, by improving supply chain transparency and accountability, firms can improve their reputation and increase customer satisfaction. This, in turn, can lead to increased customer loyalty and repeat business. Similarly, the use of blockchain technology can reduce the risk of supply chain disruptions, which can have significant negative impacts on business performance. By enabling faster and more secure transactions, blockchain technology can also streamline supply chain management, improving operational efficiency and reducing costs. Therefore, firms investing in blockchain can expect a significant improvement in business performance indirectly, only when the blockchain properly solves SC challenges.

3.4.2 Multigroup Analysis on Software Oracles

In this section, we verify how software oracles can be beneficial for unlocking the benefits of blockchain. The integration of software oracles with blockchain technology can have a significant impact on its effectiveness. Software oracles provide a link between the blockchain and external online data sources, like websites, APIs, and flash news. This enhances the accuracy and reliability of smart contracts, enabling more complex and sophisticated applications of the blockchain. By leveraging software oracles, blockchain technology can become even more secure, transparent, and efficient, while reducing the risk of fraud and errors as well as costs and inefficiency. With the ability to verify and validate sources of information, businesses can unlock new opportunities for innovation and growth. Overall, the integration of software oracles with blockchain technology has the potential to revolutionize the way we think about data verification and smart contracts, opening up new possibilities for businesses and organizations. According to our empirical results displayed in Table 6, the use of software oracles does not help the blockchain to increase business performance and solve supply chain challenges (H_{1a}; H_{2a}). On the one hand, this can be explained by the centralization of information linked to the software oracles, making them vulnerable to hacking, data tampering, and other security risks. Furthermore, the software oracles might not be as immutable as the blockchain is, compromising the integrity of the data being transmitted. Finally, relying on websites and news sources can introduce unnecessary delays and inefficiencies in the supply chain, reducing the overall effectiveness of the system. However, our empirical findings demonstrate that can help firms solve supply chain challenges and increase performance (H_{3a}). Software oracles provide real-time updates on market conditions, allowing firms to make informed decisions about production, inventory management, and other key supply chain activities. Also, they can provide valuable insights into industry trends, helping firms to identify emerging opportunities and threats. The software oracles can provide a means of communicating with suppliers, customers, and other stakeholders, facilitating collaboration and coordination across the supply chain, including tracking product quality and safety, complying with regulatory requirements, and protecting the reputation. Finally, software oracles can help firms to identify and respond to real and/or possible supply chain disruptions, reducing the risk of production delays and inventory shortages (H_{4a}). Therefore, while software oracles do not help when it turns to register information on the blockchain, they provide a great source of information to mitigate the supply chain challenge and increase their impact on business performance, allowing the blockchain to exert an indirect and positive impact on the firms. Therefore, blockchain should rely on software oracles as a secondary source of information complementing the batches of information derived from other sources.

3.4.3 Multigroup Analysis on Hardware Oracles

In this section, we analyze the role of hardware oracles to enhance the effectiveness of blockchain for performance and supply chain challenges. Among the other oracle types, hardware oracles provide a secure and reliable way to interface between the digital and physical worlds. By integrating with sensors, IoT devices, and other hardware, the hardware oracles can collect real-time data on various aspects of the supply chain, such as temperature, location, and other critical parameters. This data can then be fed into the blockchain network, where it can be used to validate transactions, automate supply chain processes, and ensure greater transparency and traceability throughout the supply chain. Hardware oracles can also enhance the security of the blockchain network by providing a secure and tamper-proof mechanism for storing and transmitting data, thus reducing the risk of fraud, counterfeiting, and other malicious activities. Our empirical findings, which are displayed in Table 6, demonstrate that the blockchain using hardware oracles cannot provide direct benefit for supply chain challenges (H_{1b}). While the use of hardware oracles can provide valuable data and insights into various aspects of the supply chain, they cannot directly solve all of the challenges faced by supply chain management. For example, hardware oracles cannot address issues related to transaction costs, supplier selection, or regulatory compliance. Hardware oracles can provide data on factors such as temperature, location, and other physical parameters, but they cannot ensure that the right products are delivered to the right place at the right time or address issues related to fraud, theft, or counterfeiting. Even though, they might represent an effective source of information for the smart contracts to be adjusted according to the match among these parameters and the real performance of supply chain partners and stakeholders. Thus, it can provide indirect benefits to firms (H_{4b}). In fact, by enhancing transparency, businesses can better identify inefficiencies and bottlenecks in their supply chain and take proactive steps to address these issues. By automating supply chain processes and reducing manual intervention, hardware oracles can also improve efficiency, reduce costs, and enhance customer satisfaction (H_{3b}). Hardware oracles can also help businesses to mitigate risks and protect their reputation by providing greater visibility into suppliers and third-party activities. This can help businesses to identify and address issues early, reducing the risk of disruptions, delays, or other supply chain problems (H_{2b}). Overall, the use of hardware oracles can help businesses to improve their supply chain performance, reduce costs, enhance customer satisfaction, and maintain a competitive advantage in the marketplace.

3.4.4 Multigroup Analysis on Inbound Oracles

This section examines the effectiveness of blockchain when it is complemented by inbound oracles. The latter refers to external datasets including a wide range of information, such as shipping and delivery data, weather patterns, consumer behavior data, and economic indicators. By integrating this data with the blockchain, companies can create a more comprehensive view of their supply chain, which can help them identify patterns and trends that may not be immediately visible through internal data alone. The inbound oracles have all the right ingredients to enable the blockchain by supporting companies to address specific challenges in their supply chain and pursue performance optimization, such as improving delivery times, optimizing inventory management, or mitigating risks associated with supplier relationships. According to our empirical results, by linking the blockchain to external datasets, companies can create a more robust and accurate picture of their supply chain, which can help them improve efficiency, reduce costs, and enhance overall performance (H_{2c}). However, it is important to note that the integration of inbound oracles with blockchain systems also presents certain challenges, which limit the chance to effectively solve SC challenges. For example, there may be issues related to data privacy, data security, and data accuracy that need to be addressed. Additionally, companies must ensure that they have the necessary technological infrastructure to manage and store large amounts of data securely. These motivations can support the idea of a missing connection between blockchain and supply chain challenges through the inbound oracles (*H_{1c}*). However, the inbound oracles are extremely effective in allowing more effective solutions to supply chain challenges, leading to an increase in business performance (*H_{3c}*). For example, inbound oracles using external datasets such as weather data, traffic data, and shipment data can be used to track the movement of goods and provide real-time visibility into their location, condition, and quality. Similarly, the information obtainable from inbound oracles can be used to monitor and mitigate supply chain risks such as disruptions due to natural disasters, political instability, or economic factors. By leveraging this data, companies can proactively identify potential issues and take corrective action before they impact the supply chain. By leveraging the use of inbound oracles, blockchain can provide additional layers of validation and verification to supply chain transactions, which can further reduce risks and increase trust. These external datasets can include weather data, market data, and other relevant information that can help supply chain partners make more informed decisions and improve performance (*H_{4c}*).

3.4.5 Multigroup Analysis on Outbound Oracles

In principle, the integration of outbound oracles with blockchain technology can enhance the effectiveness of the blockchain by enabling the transfer of off-chain data to the blockchain. Outbound oracles facilitate the transmission of data from the blockchain to external data sources, allowing for real-time updates and interactions with off-chain systems. This enables the blockchain to be used in a wide range of applications, from financial transactions to supply chain management. By providing a link between the blockchain and external data sources, outbound oracles enable the validation and verification of off-chain data, enhancing the blockchain's capacity to give input to the ecosystem. While blockchain technology has been hailed as a potential solution to the challenges and issues faced by supply chains, it is important to note that it is not a panacea. One of the key limitations of blockchain technology is its lack of interaction with and updating the wider ecosystem in which the supply chain operates. Supply chains are complex and dynamic systems that involve a wide range of stakeholders, including suppliers, manufacturers, distributors, retailers, and customers. These stakeholders interact with each other in a variety of ways, and their behavior is influenced by a range of factors, including market conditions, regulatory requirements, and technological innovations. For blockchain technology to be effective in improving supply chain management and business performance, it needs to be able to interact with and update this wider ecosystem. According to our findings, this set of outcomes cannot be achieved by the current blockchain systems (*H_{1d}*; *H_{2d}*; *H_{3d}*; *H_{4d}*). Blockchain requires the development of standards and protocols that can facilitate the sharing and updating of data across the supply chain in different ecosystems (e.g., datasets available in different countries). This is a challenge that blockchain developers should address in the future.

3.4.6 Multigroup Analysis on Human Oracles

The use of human oracles can enhance the effectiveness of blockchain technology by enabling verification and validation through the engagement of people. Human oracles can provide a link between the blockchain and the eco-system, enabling the validation and verification processes through real-time and fresh information.

This can enhance the accuracy and reliability of the blockchain verification processes while ensuring tokens and other benefits to people playing the role of human oracles. One interesting insight resulting from the use of human oracles is that they can also enable more complex and sophisticated applications of the blockchain, by providing expert knowledge and judgment that cannot be replicated by machines. While social interactions and human relationships can play a role in improving supply chain management and business performance, our results demonstrate (see Table 6) that they are unlikely to provide a comprehensive solution to the challenges faced by supply chains when implementing blockchain. Although the use of blockchain technology shows good premises to engage people as human oracles, the current systems fail to achieve such targets. One of the key challenges faced by supply chains is the lack of transparency and traceability: while social interactions and human relationships can help build trust and improve communication between stakeholders in the supply chain, they do not provide the level of information to make blockchain effective. Although social interactions and human relationships can help improve collaboration and cooperation between stakeholders, they do not provide the level of automation and optimization that is necessary for achieving significant efficiency gains. Again, in principle, blockchain technology can help address this challenge, by providing a decentralized and automated platform that can streamline many of the processes involved in the supply chain (H_{1e}; H_{2e}; H_{3e}; H_{4e}). However, social interactions and human relationships can be subject to bias and inconsistency, which can lead to errors and inefficiencies in the supply chain. It is important to note that social interactions and human relationships are still important in the context of supply chains, particularly in terms of building trust and fostering collaboration between stakeholders. However, they should be still fully integrated within the potentials granted by blockchain technology.

Research Hypothesis: Does the group with oracles perform better than the group	In presence of Human oracles $H_{1e; 2e,3e, 4e}$	In presence of Outbound Oracles $H_{1d; 2db,3d, 4d}$	In presence of Inbound Oracles $H_{1c; 2c,3c, 4c}$	In presence of Hardware Oracles $H_{1b; 2b,3b, 4b}$	In presence of Software Oracles $H_{1a; 2a,3a,4a}$
$H_{1a,b,c,d,e}$: Blockchain has a higher positive impact on SC challenges.	*0.019* (Non supported)	*0.009* (Non supported)	*0.055* (Non supported)	*0.060* (Non supported)	*0.015*(Non supported)
$H_{2a,b,c,d,e}$: Blockchain has a higher positive impact on Business Performance.	*0.022* (Non supported)	*0.273* (Non supported)	0.523*** (Supported)	0.587*** (Supported)	*-0.014* (Non supported)
$H_{3a,b,c,d,e}$: Supply chain challenges have a higher positive impact on Business	*0.047* (Non supported)	*0.123* (Non supported)	0.510**(Supported)	0.468**(Supported)	0.394*(Supported)
$H_{4a,b,c,d,e}$: Blockchain has a higher positive and indirect impact on Business Performance through Supply Chain Challenges	*0.008* (Non supported)	*0.112* (Non supported)	0.311** (Supported)	0.287* (Supported)	0.261* (Supported)

***p=value<0.01; **p=value<0.05; *p=value<0.1

Table 6 – Results of the Multigroup analysis

3.5 Discussion and theoretical contribution

The first objective of the study is to investigate whether blockchain can be a technology capable of supporting companies in overcoming supply chain challenges and the possible benefits that it can have on business performance. The second objective of the study is to investigate the influence that oracles have on the relationship between blockchain, supply chain challenges, and business performance. Looking at the first objective, our results demonstrate that blockchain has a direct and positive impact on supply chain challenge H_1. This result empirically demonstrates the relationship previously theorized in exploratory studies based on multiple case studies and literature reviews (Chang et al., 2020; Azzi et al., 2019). Therefore, we can state that blockchain offers the ability to overcome some of the most important supply chains challenges thanks to the increase in transparency, efficiency, reliability of the supply chain, and the reduction of risks. We find no direct impact of blockchain on business performance (H_2). This result is aligned with De Giovanni, (2022) and Sharma et al., (2023), while denying the results of other studies that identified a positive impact of blockchain on business performance (Ji et al., 2022; Nandi et al., 2020). However, we find an indirect impact of Blockchain on business performance through supply chain challenges (H_4). The result is in accord with what has been shown by Markus and Buijs, (2022) who find an indirect impact of blockchain on business performance. However, we found that the indirect impact is due to the ability of blockchain to overcome supply chain challenges rather than because of the complementary activities due to the blockchain introduction. Therefore, companies that introduce blockchain should expect an indirect impact of blockchain on business performance once that blockchain has made it possible to overcome supply chain challenges. This statement is confirmed by the (H_3) result which demonstrates that the ability to overcome supply chain challenges has a positive impact on business performance. We are among the first authors to consider this relation. We complement and elevate the findings of the few previous studies that had demonstrated a positive effect on performance due to overcoming the challenges of "inventory management" (Han et al., 2013), "development of supporting technologies", "development of effective governance policies", "transparency", "privacy", and "security" (Ghode et al., 2023). We broaden the concept of the supply chain challenges by including and demonstrating the positive effect on cost reduction, traceability, transparency, reduction of the risk of disruptions, reputation, and trust.

Looking at the second objective of the paper, oracles play a pivotal role in blockchain effectiveness for business purposes as they allow the exchange of information between the blockchain and the external world. For this reason, we have verified the effect of the oracles on the previously identified relationships. When hardware oracles are used ($H_{1b, 2b, 3b, 4b}$) the impact of supply chain challenges on business performance, and the indirect and the direct impact of blockchain on business performance are higher than the condition without oracles. Hardware oracles enable businesses to gain a competitive advantage through improved supply chain performance, cost reduction, and improved customer relationships. Similarly, when inbound oracles are used

($H_{1c, 2c, 3c, 4c}$) the impact of supply chain challenges on business performance, and the indirect and direct impact of blockchain on business performance are higher than the condition without oracles. These results are justified by the information coming from multiple sources that can be on the blockchain thanks to inbound oracles. When software oracles are used ($H_{1a, 2a, 3a, 4a}$) the impact of supply chain challenges on business performance and the indirect impact of blockchain on business performance are higher than the condition without oracles. Software oracle is an important tool due to its speed and ease of use. However, compared to inbound oracles and hardware oracles they have no direct influence on business performance. This is because the information that is collected by software oracles is often not as reliable as the blockchain and could compromise the integrity of the data in the system. Human oracles ($H_{1e, 2e,3e, 4e}$) and outbound oracles ($H_{1d,2d,3d,4d}$) have no influence on the identified relationships. The outbound oracles result can be justified by the lack of protocols and standards that make it possible to make the data extracted from the blockchain usable. Instead, human oracles, although they allow information that cannot be captured by machines to be recorded, they do not provide the required level of automation and optimization. Furthermore, a human oracle may be more prone to errors and needs trust in the human factor. Studies that not only consider the effect of oracles when applying blockchain but at least consider their existence is extremely limited. However, oracles are indispensable for blockchain applications in business. The existing theory has mainly two perspectives on oracles: the taxonomies that classify oracles (De Giovanni, 2021, 2022) and theoretical studies that explain the effectiveness of oracles by nevertheless considering them undifferentiated and ignoring previous classifications (Omar et al., 2021; Taghavi et al., 2023; Nelaturu et al., 2020). This study advances the previous literature being the first to empirically demonstrate the importance of oracles and their moderating effect in the relationships between blockchain, supply chain challenges, and performance. We extend the previous literature by showing that oracles are not all the same, but it is necessary to carefully consider the type of oracle we are dealing with since the effects can be very different. In particular, it emerges that oracles that result in greater disintermediation and the use of hardware tools that make a human error or the possibility of counterfeiting more difficult are those that result in the greatest positive effect. In contrast, oracles that leave room for doubt regarding data integrity have no positive effect on the relationships identified in the previous hypotheses.

3.6 Managerial insights

Given our findings, we make several suggestions for managers who want to apply blockchain to overcome supply chain challenges and improve business performance. First, blockchain should be adopted with the primary goal of overcoming specific supply chain challenges that affect the company's business. In fact, blockchain guarantees performance improvement only through overcoming supply chain challenges. Managers should evaluate the supply chain challenges of their business and the effectiveness of blockchain in overcoming them before investing in blockchain-based solutions. Second, oracles should be carefully considered as they are a major element in the effective implementation of blockchain. All oracles are not the same but have peculiarities that make them suitable for specific applications. Third, we find that none of the oracles useful to unlock the blockchain can help to directly solve the supply chain challenges. Therefore, the current state of blockchain technology is not helpful to find optimal resolutions to supply chain issues. In the future, blockchain developers should work on the previous limitations to develop new blockchain platforms that can suit supply chains in a global context. Fourth, inbound oracles are more effective than outbound oracles for improving the effect of supply chain challenges on business performance and for both the direct and indirect effects of blockchain on business performance. Therefore, we suggest that managers consider using inbound oracles rather than taking information from blockchain if the goal is to increase business performance. Fifth, among the hardware, software, and human oracles the hardware oracles are the ones that improve the effect of supply chain challenges on business performance and both the direct and indirect effect of blockchain on business performance. While software oracles enable the direct and indirect positive effect of blockchain on business performance although of lower significance and intensity than hardware oracles. We do not find any effect of human oracles. Interestingly, previous exploratory studies show that the costs associated with these three types of oracles are different. Hardware oracles require the greatest investment while human oracles are the cheapest with software oracles in between (Ruzza et al., 2022). Thus, we can identify a tradeoff between investment and the oracle's effectiveness. Managers should consider whether investing more resources to have more effective oracles is justified by the expected benefits and supply chain challenges. If yes, they should lean toward hardware oracles since they have proven to be the most effective. If not, they should consider adopting software oracles or human oracles. In conclusion, we suggest a set of practices to be adopted to implement blockchain in supply chains to exploit the full potential of blockchain and unlock its power through the oracles:

- Identify key supply chain challenges that affect corporate business profitability;
- Determine whether blockchain can have an impact on the identified supply chain challenges;
- Establish goals to be achieved with blockchain implementation;
- Do all the side activities necessary for blockchain introduction such as staff training, skill acquisition, and technological adaptation of the company;
- Carefully weigh the pros and cons of the different types of oracles to be used and choose the most suitable ones to achieve the goals;
- Implement blockchain;
- Periodically monitor the impact of blockchain and adjust the system if necessary.

3.7 Conclusions

This paper studied the relationships between blockchain, supply chain challenges, business performance, and the moderating effect of oracles. The results show that blockchain has no direct impact on business performance. However, it has an indirect impact on business performance through supply chain challenges. This relationship is confirmed by the positive and significant effect of supply chain challenges on business performance. This search is not without limitations that we present here to inspire future research. From a methodological perspective, the first limitation is associated with our sample. Our sample consists of 156 observations, future work could replicate the study with more observations and analysis techniques. The sample contains mostly companies in developed countries such as Europe (73%) and America (16%). However, recent studies have shown peculiarities of blockchain applications in developing countries (Nayal et al., 2021) that limit the generalizability of our results. Future studies could test the effectiveness of oracles in developing country supply chains or global supply chains that include developing countries within them. Finally, if we look at the size of the firms considered we see that most of our sample consists of large firms. Smaller firms have different technological infrastructures and money availability. For this reason, it might be interesting to check the performance of oracles in these companies. In these contexts, cheaper oracles such as human oracles might result in better performance than more expensive hardware oracles. Looking at the rest of the paper, blockchain technology is analyzed without considering the side technologies such as IoT sensors or artificial intelligence. Future studies could investigate the effect of combining other technologies with blockchain. Moreover, as technologies progress continuously the list of oracles considered here may not be exhaustive and could be expanded in the future. Consider, for example, the possible application of artificial intelligence for data entry on the blockchain. The supply chain challenges considered refer to the main supply chain challenges identified in the literature. Future studies could consider challenges that are emerging due to disruptive events such as the Covid-19 pandemic, sustainability, and the current geopolitical condition. Examples of these include challenges associated with reshoring or commodity shortages. Finally, future studies could investigate the cost-effectiveness of oracles, an aspect that was not considered in this study but could influence the practical usability of oracles.

3.8 Appendix 1: Questionnaire and descriptive statistics

Questions	Mean	Standard deviation
In the last two years, our company invested in blockchain technology by:		
- Consulting developers (B1)	4.924	1.573
- Modifying the management of contracts and transactions (B2)	4.393	1.523
- Tokens# (B3)	4.305	1.519
- New platforms (B4)	4.796	1.623
- New training programs# (B5)	4.682	1.732
- Aligning the technology requirement with the regulations (B6)	4.870	1.558
- Integrating blockchain technologies with other digital technologies (B7)	4.807	1.718
In the last two years, our company has successfully managed the following Supply Chain challenges:		
- Transaction costs over the global supply chain network (SCC1)	5.097	1.332
- Product traceability (SCC2)	5.240	1.671
- Product transparency (SCC3)	5.154	1.644
- Costs to manage the Supply Chain Network (SCC4)	5.140	1.432
- Delivery risks (SCC5)	5.190	1.322
- Verification costs of suppliers and third parties (SCC6)	5.086	1.498
- Protecting the reputation and enhancing the trust (SCC7)	5.719	1.347
- Management of reverse logistics flows# (SCC8)	4.423	1.507
- Identification of green suppliers# (SCC9)	4.671	1.501
- Solution of security and privacy issues# (SCC10)	4.764	1.591
In the last two years, our company has performed in terms of:		
- Market share (BP1)	4.853	1.964
- Profits (BP2)	4.737	1.991

	- ROI (BP3)	4.814	1.797
	- Cost saving# (BP4)	4.664	1.791
	- Cost for energy# (BP5)	4.297	1.692
	- Environmental impact# (BP6)	4.695	1.619

#excluded from the analysis

3.9 References

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