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Unlocking Blockchain Potential Through Oracles: Empirical Evidence on Supply Chain Challenges and Performance

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ABSTRACT

This study investigates the positive impacts of blockchain on supply chain challenges as well as its impact on business performance. Moreover, 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 achieve the research goals, the study uses survey data and analyzes them through a partial least squares-path modeling methodology. The results show that, while there is no significant direct impact of blockchain on business performance, an indirect and significant influence exists by exploiting the benefits that blockchain has on supply chain challenges. Finally, the findings suggest that the blockchain's effects can be amplified when it is supported by inbound, hardware, and software oracles; instead, both human and outbound oracles do not render the blockchain technology more effective.

1. Introduction

To succeed in a competitive environment, companies must be able to address the supply chain (SC) challenges they face [31]. However, supply chain challenges (SCC) are constantly changing as existing ones evolve or new challenges emerge due to factors such as technological advancement, disruptions in the competitive environment, macroeconomic events, or pandemics [36, 63]. Therefore, companies must constantly update and improve the tools at their disposal to cope with SCC in competitive environments. Among these tools, blockchain seems to be effective and is increasingly adopted in the SC domain [14].

For instance, Nestlé improves transparency in its SC by creating a public blockchain platform that integrates with a mobile app and enables consumers to track their products from the farm to consumption [74]. Walmart uses blockchain to overcome SCC 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, thereby eliminating the need for manual reconciliations, reducing associated costs, and speeding up payments [37]. Cantina Placido Volpone is one of the first winemakers in the world to adopt blockchain to address existing challenges in the wine industry. Through blockchain, Cantina Placido Volpone tracks the entire process of wine production from the field to the end customer. In this process, it certifies the quality of the final product and establishes a trusting relationship with its customers [22, 36, 50]. Genuino applies blockchain in the collectibles industry. Through a combination of Internet of Things (IoT) sensors applied to match worn jerseys and blockchain technology, Genuino prevents the spread of counterfeit items and creates a new stream of earnings for football clubs [53].

Despite many success stories, it is unclear whether blockchain actually has a positive impact on SCC and business performance (BP) because positive results are enthusiastically claimed, while negative ones go unnoticed [54, 61]. Consequently, we may have a distorted perspective of the real blockchain effects on the SC. This perspective is confirmed by extant academic research on blockchain and SC management. This research has produced discordant results regarding the effectiveness of blockchain in overcoming SCC and improving BP.

Considering Nestlé's application of blockchain for overcoming transparency-related SCC, some studies have found that blockchain has a positive impact on transparency [28, 74, 77], while other studies have argued that blockchain alone is not sufficient to achieve transparency. Moreover, these studies have found it difficult to quantify blockchain's true contribution when applied with other technologies [64, 74]. Walmart's successful application of blockchain has aimed mainly at reducing costs, but again, the literature disagrees on the actual impact of blockchain on costs. On the one hand, blockchain seems to have positive impacts on reducing costs [5, 55]; on the other hand, however, the new costs related to the introduction and maintenance of blockchain nullify those benefits [11, 17]. The "Placito Volpone" winery uses blockchain to build trust with its customers, but some research has found that blockchain either increases trust or makes it irrelevant [13, 76, 36]. Other scholars have found no evidence of blockchain's positive effect [12]. Looking at Genuino's application for overcoming traceability-related SCC, the literature finds that blockchain is an effective tool for traceability, eliminating counterfeit items, increasing quality, and improving data flow [22, 52, 64, 24]. However, if the entire value chain is not involved,

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it is ineffective [53]. We find similar results for delivery-related SCC, where blockchain seems to have an ambiguous impact [1, 51]. Furthermore, while our examples suggest an increase in performance because of blockchain, a similar conflict exists in the literature regarding the impacts of blockchain on BP. Some authors have found a strong and positive influence of blockchain on performance [3], while others identify no direct effect [23, 39, 57]. Therefore, given the unclear relationship between blockchain, SCC, and BP, the first objective of this study is to analyze the relationship between these constructs to understand whether blockchain is useful in overcoming SCC, leading to increased BP.

Going into the details of blockchain applications in the business domain, it emerges that blockchain itself is isolated from the off-chain world, and its capabilities are limited without bridges connecting it with off-chain data [18]. As a result, blockchain applicability depends on side technologies that enable it to interact with data in the ecosystem. Oracles are defined in their essence as the interface for data interaction between blockchain and the real world [45, 69]. As reported in Table 1, we can categorize oracles based on the technology they employ to transfer information from the real world onto the blockchain, and vice versa: inbound oracles transfer information from online or offline sources (e.g., off-chain information such as price details or assets) to the blockchain; outbound oracles allow information to take the reverse path from the blockchain to outside sources; software oracles collect data from digital sources such as databases, and websites; hardware oracles gather data from physical systems such as IoT sensors; human oracles collect information from a variety of sources, including individuals, and check whether they are legitimate [21, 47, 69]. Another example is Walmart, which uses software oracles to collect data from the databases of all parties and transfers it onto the blockchain. 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.

The importance of oracles has led to the literature defining the "Oracle Paradox" as the need to trust oracles before trusting the blockchain [2, 59]. Indeed, malfunctioning oracles, or using oracles unsuitable for the intended purpose, can nullify the effectiveness of the blockchain [18, 46, 47]. Moreover, oracles may suffer from centralization problems [18], malfunction due to technical failure [47], be prone to cyberattacks [27], and have scalability issues [72]. On the other hand, choosing the best oracle improves data accuracy, reliability, trust, and transparency, making blockchain a valuable tool for overcoming SCC and enhancing BP [18, 46, 59]. It follows that oracles are ideal candidates for explaining the discordant results we identified in the literature regarding the relationship between blockchain, SCC, and BP. The second objective of our study is to understand whether oracles influence the effectiveness of blockchain in overcoming SCC and improving BP. Moreover, we investigate the effect of different types of oracles and try to understand which ones should be preferred in any application. Table 1 summarizes the definition of all types of oracles.

Overall, despite the growing interest in blockchain applications for SCs, existing research has yet to provide a clear, unified understanding of whether and how blockchain contributes to overcoming operational challenges and enhancing BP. Much of the literature presents contradictory findings, often overlooking the role of contextual and technical factors that could enhance blockchain's effectiveness [11]. One such overlooked factor is the function and type of oracles. Although oracles are essential for the real-world applicability of blockchain, they are frequently treated as background infrastructure rather than being studied as active components that shape outcomes [25]. This oversight results in a significant research gap that prevents a full understanding of the true enablers of blockchain success in SCs. Our study addresses this critical gap by empirically analyzing the role of oracles in shaping the effectiveness of blockchain in mitigating SCC and improving BP. By distinguishing among different types of oracles, including software, hardware, human, inbound, and outbound oracles, we investigate how they influence blockchain outcomes.

To achieve the research objectives, we devise and analyze various hypotheses by defining a conceptual model that investigates the proposed research questions. We use a survey to collect data from 156 companies and analyze them through a partial least squares-path modeling (PLS-PM) methodology. Our results show that although blockchain has a positive impact on SCC, it does not have a direct impact on BP. However, it can enhance BP factors indirectly by improving SCC. Moreover, our findings indicate that outbound oracles and human oracles have no significant impact on improving SCC and BP. However, when hardware oracles, inbound oracles, and software oracles are employed, blockchain has a higher positive and indirect impact on BP by mitigating SCC compared to the condition without oracles.

This contribution is especially valuable for researchers aiming to reconcile conflicting findings in the literature, offering a foundation for new theory-building on blockchain-enabled SC. Furthermore, our results provide practical insights for business leaders and SC managers, supporting more informed decision-making around strategic technology investments.

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 Sections 4 and 5 present the empirical results and discussion. Finally, Section 6 concludes with theoretical and practical implications as well as future research directions.

2. Literature Review and Hypothesis Development

In recent years, the adoption of blockchain technology has accelerated, enhancing the operational performance of production systems and SCs. However, many aspects of

Table 1
Summary of oracles' definitions.

Oracle type	Definition	Sample sources	Function
Hardware	Devices that capture and translate physical-world conditions into digital data for use in blockchain systems.	Sensors, GPS, RFID	Gathers real-time, environmental data and delivers it on-chain to trigger contract execution.
Software	Digital connectors that extract data from online sources or applications and transmit it to smart contracts.	Web services	Supplies smart contracts with information such as pricing, forecasts, or transactions pulled from the internet.
Inbound	A general type of oracle that feeds off-chain information into the blockchain, including both machine and human inputs.	Web data, sensors, and human reports	Allows smart contracts to be aware of external conditions, enabling logic based on off-chain realities.
Outbound	Oracles that enable blockchain applications to affect external systems by sending them commands or data.	Blockchain events	Notifies or activates off-chain systems in response to smart contract outcomes (e.g., triggering a shipment release, updating a warehouse management system).
Human	Individuals who input verified or expert information directly into blockchain networks when automation is not feasible.	People (experts, validators)	Delivers complex or context-sensitive inputs (such as inspection results or subjective assessments) into smart contracts.

its efficiency remain ambiguous and require further investigation in terms of scenario and model development to better understand its impacts on operational objectives [6]. This section is divided into three sub-sections that focus on specific streams of the previous research to develop our hypotheses. The subsections discuss the literature regarding the relationships between blockchain adoption, SCC, BP, and the effects of oracles. Table 2 presents the most relevant articles in the literature that support our hypothesis development and help clarify the research gap.

2.1. Blockchain and supply chain challenges

The literature discusses blockchain applications in operations and SCs management and categorizes the main challenges this technology can overcome. These challenges are transparency, traceability, cost of managing the SC, delivery risk, trust, and reputation [15, 72, 73].

Looking at transparency-related SCC, some studies have found that blockchain has a positive impact on transparency [28, 77]. A literature review shows blockchain can improve SC transparency through a tracking and tracing process [64]. In addition, it allows transparency to be achieved while preserving privacy, despite the apparent tension between the two [74]. Blockchain provides real-time, immutable information to different parties in an SC, which helps to enhance standards and product quality in the value chain [62]. These trustworthy and transparent records can also help to optimize SC operations from different aspects [66]. However, some limitations need to be considered, such as choosing the right blockchain, selecting the proper IoT technologies to partner with blockchain for information collection, and the choice of communication and security protocols [5]. Moreover, effective government policies to create a proper regulatory system to balance transparency, privacy, and security are required [29]. Consequently, blockchain cannot completely replace existing technologies to achieve transparency, and, where it is implemented, it is difficult to quantify its real contribution to SC transparency [64]. Moreover, establishing effective transparency can hide significant costs and increase operational complexity [41]. Finally, a high level of transparency is not always desirable, as it involves some trade-offs, such as the lack of differentiation with competitors [74].

Turning to traceability-related SCC, blockchain applications for traceability are effective mainly in eliminating counterfeit products, monitoring quality and safety, and process managing [64, 67, 62]. Blockchain-based traceability systems can overcome problems related to data flow management as they enable more transparent and secure end-to-end tracking, increase trust, give visibility to products that comply with international standards, decrease bureaucracy and related costs, reduce fraud and counterfeiting, and facilitate processing [34, 5]. In addition, blockchain traceability systems improve brand perception and security in purchasing. However, to implement effective traceability, it is necessary to bring all the stakeholders onto the blockchain [53]. The weakness or absence of a link in the information transmission chain could lead to ineffectiveness in the traceability system. In addition, blockchain-based traceability systems, increasing the demand for a certain product in the market, could lead to free riding by competitors. Finally, true applications of blockchain for traceability are quite rare, which has led to the scarcity of empirical studies [64].

Looking at delivery-related SCC, blockchain allows for optimal decreases in delivery times [74, 51]. In addition, a blockchain-based solution can improve the delivery and state of original products by helping manage the transportation process, taking care of defects or damages incurred during transportation, and attending to reimbursement procedures [1]. However, although blockchain improves delivery times under stable conditions, in highly disruptive environments,

Table 2
The most relevant articles and the research gap. A: Blockchain and Supply Chain Challenges; B: Blockchain and Business Performance; C: Supply Chain Challenges and Business Performance; D: Impact of Oracles on SCC; E: Impact of Oracles on Business Performance.

Article	A	B	C	D	E
Caldarelli et al. [13]	×				
Kumar et al. [36]	×				
Kopyto et al. [35]	×				
Brookbanks and Parry [12]	×				
Yavaprabhas et al. [76]	×				
Biswas et al. [11]	×				
Ji et al. [34]		×			
De Giovanni [23]		×			
Naclerio and De Giovanni [42]		×			
Markus and Buijs [39]		×			
Sharma et al. [57]		×			
Tseng et al. [65]		×			
Craighead et al. [20]			×		
Wacker et al. [71]			×		
Philsoophian et al. [49]			×		
Vishkaei [67]			×		
Vishkaei and De Giovanni [69]	×	×			
This Study	×	×	×	×	×

it is not always effective. Indeed, if it is impossible to predict upfront what will happen, changing a smart contract reactively is nearly impossible, which results in longer delivery times [51]. Note that a blockchain-based smart contract is a self-executing digital agreement embedded within blockchain platforms that autonomously enforces terms between parties without the need for intermediaries. By relying on predefined conditions and real-time data inputs, these contracts facilitate trust, transparency, and automation in collaborative logistics networks. For instance, in the context of food-sharing SCs, smart contracts enable responsive surplus inventory redistribution by dynamically matching products to receiving partners based on factors like expiry dates, product freshness (using IoT devices such as e-nose, e-eye, etc.), market prices, and donation rates to manage and redistribute surplus inventory, aiming to reduce waste and enhance sustainability [70].

Looking at cost-related SCC, blockchain can contribute to overcoming cost-related SCC through automation, reduced bureaucracy, and the elimination of possible middlemen [5]. Schmidt and Wagner [55] found that blockchain acts on the main causes of transaction costs by limiting opportunistic behavior and reducing environmental and behavioral uncertainty. As a result, blockchain enables the reduction of transaction costs by shifting the ideal governance structure toward market governance [55]. Recent studies have confirmed the benefits of blockchain on transaction costs and its effect on reducing inventory costs, purchasing-related costs, and information-acquisition costs [11, 17]. However, blockchain implies the introduction of new and rarely considered costs. Among these, the literature identifies computational costs due to the computational capacity required to record a transaction on blockchain [33], the costs related to the blockchain used if it is a private platform, the costs related to the amount of information to be recorded, and the cost related to the speed needed to record the information [53]. There are also blockchain energy costs, which have environmental and economic impacts [11]. Analyzing the different costs of introducing blockchain, De Giovanni [21] finds that fixed costs are not particularly relevant for companies, but marginal costs need to be carefully evaluated since if they are too high, the blockchain technology should be abandoned. In summary, blockchain seems to have different effects on different sources of costs, making it unclear whether it contributes to overcoming cost-related SCC or worsens them.

Turning to trust- and reputation-related SCC, we found divergent opinions in the literature on blockchain's effect on trust [76]. Some studies have found that blockchain creates a trustless environment, making trust unnecessary [13, 76, 36]. A reason for this trustless environment is that there are no intermediaries, and thus trust is no longer required of them [72]. Other studies have found no evidence that blockchain eliminates trust [12]. Conversely, they propose that blockchain increases trust between the parties due to, for example, the creation of a single common source of information or the replacement of previous intermediaries with more trustworthy ones [12]. Finally, a stream of literature has found that blockchain-based trust is ineffective in the relationship between partners, and the traditional ways of managing trust are still required [35]. Similarly, Biswas et al. [11] found that blockchain is not always effective in countering SCC related to trust when the level of distrust is very high.

To summarize, although some studies have pointed out the benefits of blockchain in overcoming SCC, other studies have found no impact, or even a negative impact, so clearly consensus has not been reached regarding the effects of blockchain adoption on SCC. Furthermore, the literature lacks quantitative studies aimed at empirically verifying the effect of blockchain on SCC. Therefore, to clarify the effect of blockchain on SCC, we develop our first hypothesis as follows.

H_1**:** Blockchain has a positive impact on SCC.

2.2. Blockchain and business performance

Several studies have examined the implications of the use of blockchain on performance. Taking a SC performance perspective, the introduction of blockchain improves SC performance [30]. However, sometimes this relation is moderated by other factors such as the country effect [28]. Looking at BP, the positive influence of blockchain seems to be confirmed. Blockchain has a positive impact on the performance of oil and gas organizations by improving the flow of information, enhancing security, reducing lead times, and improving logistics operations [3]. Similarly, in the banking sector, blockchain has a positive relationship with BP, as it enables faster cross-border payments, financial trading, and online identity management [69]. Moreover, in urban green transportation systems, such as e-scooters, blockchain can play a key role in mitigating operational issues related to tracking customer behavior and usage patterns [69, 25]. Furthermore, blockchain holds significant promise for improving transparency, traceability, and trust in the food industry by providing real-time, immutable records of products. This helps reduce contamination risks and ensures better food quality [25, 70], which improves BP in this sector [62].

However, other papers have found different effects of blockchain on BP. Among them, a study by Sharma et al. [57] shows that credible blockchain investments enhance market expectations of future earnings, but this 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. Ji et al. [34] found that manufacturers considering introducing blockchain should evaluate not only the impact on their profitability, but also their competitors' response. Indeed, although blockchain creates an advantage for the first mover, it can be quickly eroded by competitors' countermeasures. Similarly, De Giovanni [23] found that blockchain has a weak and marginal impact on BP. This result is also confirmed when incentives, such as collector incentives and consumer incentives, are introduced to foster the potential of closed-loop SCs and reverse omnichannel strategies. Blockchain alone is not enough to improve BP, but must be complemented by a set of strategic actions [42]. Moreover, many improvements in SC performance result from the indirect effects of activities associated with the introduction of blockchain, such as digitization or rationalization of nonessential processes [39]. Therefore, while some articles have found a strong, direct, and positive impact of blockchain on BP, others do not identify a direct effect. Given the contradictory results identified in the literature, we clarify this relation with the second hypothesis.

H_2**:** Blockchain has a positive impact on BP.

2.3. Supply chain challenges and business performance

In this section, we review the literature on SCC and their impact on BP. Overcoming transparency-related SCC can improve BP. Indeed, transparency is achieved through information sharing in the value chain, which reduces uncertainty and increases BP [11]. Increased transparency has a direct effect on performance and an indirect effect through collaboration [26]. However, in some sectors, such as banking, transparency and information disclosure are not related to performance [52].

Successfully overcoming the challenges of traceability in the SC improves BP, minimizing product recalls and related costs [11]. Other studies confirm that traceability has a positive impact on quality and BP. However, improving traceability alone is not sufficient to ensure superior performance, but must be coupled with effective SC coordination. Moreover, the impact of traceability on performance is not immediate but long-term, so plans need to be developed to realize the benefits [60].

Delivery is a strategic advantage, and companies with strong cross-functional delivery capabilities outperform competitors. Digital technologies are essential for managing delivery complexity and dynamic conditions, such as traffic. These decisions impact sustainability by influencing emissions, customer satisfaction, and costs [69]. Similarly, improved SC delivery management through a more agile SC leads to increased BP. For instance, in the healthcare sector, reducing lead times with improved capacity utilization and deliveries increases performance [10]. However, some studies show that improvement is registered only if firms recognize that delivery capability is cross-functional and if they identify which functions create most of the benefits [68].

The literature agrees that overcoming trust-related SCC leads to a benefit in terms of BP. Interestingly, trust toward a supplier has a relevant impact on BP because it improves collaboration, whereas trust toward customers has an insignificant impact on BP [69]. Trust positively affects key performance areas, including market growth, customer satisfaction, and financial returns. Supplier competency alone does not significantly impact performance without the presence of trust [32]. Furthermore, trust within the SC has a greater effect on performance if the relationships are with fewer suppliers than when there are many of them [70].

Overcoming cost-related SCC leads to increased BP. Among the costs studied in the literature are transaction costs [71], innovation costs [20], and costs associated with total quality management practices [24]. However, reducing costs in one functional area may result in an increase in another. An example can be related to adopting reusing practices in subscription businesses to reduce production cost; however, it may negatively impact the inventory costs [67]. Therefore, costs related to non-value-added areas are the ones to be reduced in order to improve BP.

Overcoming most of the SCC identified seems to have a positive effect on BP. However, for some of these, such as transparency-related SCC and traceability-related SCC, we found contradictory results. Moreover, the overall and aggregate effect of all SCC on BP is unclear. Consequently, with the third hypothesis, we test this relationship.

H_3**:** SCC have a positive impact on BP.

2.4. Indirect effect of blockchain on business performance

Despite the advantages of blockchain technology in SC, companies cannot ignore its adoption challenges. However, the numerous benefits of this technology are pushing high-tech companies to invest in new solutions to enhance these issues [7]. Nandi et al. [43] studied the impact of blockchain on performance from a resource-based perspective. The capabilities that result in better performance are: improved process efficiency, product/service quality and flexibility, reduced cost, and reduced process time [24]. Similarly, Markus and Buijs [39] study how blockchain influences SC performance in terms of quality, cost, speed, dependency, and flexibility. Interestingly, many improvements in SC performance do not come from the direct effect of blockchain, but result from the indirect effects of activities associated with the introduction of blockchain, such as digitization or the rationalization of nonessential processes [39]. Integrating technologies like Global Positioning System (GPS), Radio Frequency Identification (RFID), and IoT with blockchain can enhance logistics transparency, shipment tracking, and operational efficiency, which ultimately supports better decision-making and improves overall BP [58].

Therefore, as overcoming SCC enhances BP, there is a possibility that blockchain can indirectly affect performance by mitigating SCC. For instance, blockchain has a mediating role in improving performance indicators such as quality and flexibility by enhancing knowledge sharing in the SC system [49]. Another study shows that US enterprises adopting blockchain perform better in business, whereas in China, companies with deteriorating business efficiency usually implement blockchain to improve their performance [65]. We hypothesize that the unclear relationship between blockchain and BP might be justified by a third variable, which is improving SCC. So, we define the next hypothesis as follows:

H_4**:** Blockchain has a positive and indirect impact on BP through SCC.

2.5. Oracles' effect

The literature reviews so far provide valuable insights into the relationship between blockchain, SCC, and BP. However, it seems to overlook that blockchain is isolated from the world without bridges that allow it to use real-time data from the surrounding environment [18]. Oracles are defined essentially as the interface for data interaction between blockchain and the off-chain world [18, 46]. Oracles can be classified according to the technology used for information retrieval, and include software oracles, hardware oracles, human oracles, inbound oracles, and outbound oracles [21, 47]. Oracles are pivotal tools that nevertheless create a point of failure that can compromise the integrity of the blockchain and the effectiveness of the entire ecosystem [8]. Indeed, the successful adoption of blockchain depends on data-collection technologies for providing real-time, accurate information from multiple sources, including massive data warehouses [58]. This problem is known in the literature as the 'Oracle Paradox" or the 'Oracle Problem," and refers to the need to trust oracles in a system that aspires to be as trustless as blockchain [2, 59].

Oracles affect the authenticity, security, and accuracy of information recorded in blockchain [2]. Consequently, the choice of the right oracle determines the effective application of blockchain and promotes its ability to overcome SCC [45]. Conversely, inadequate oracles or their failure introduces a point of failure to blockchain-based systems. For example, the use of centralized oracles creates the opportunity for the authority managing them to unilaterally shut down the oracle, which puts in question the decentralization of blockchain [47]. Moreover, the information entering the blockchain through these oracles could be manipulated according to the interests of the authority that controls the oracle. This would compromise the effectiveness of blockchain in overcoming transparency, lack of traceability, delivery risk, mistrust, and reputation-related SCC [40]. Similarly, Oracle's failure could result in the slow execution of smart contracts or the inability to proceed with transactions on time, which would be an obstacle in overcoming the costs and addressing delivery risk-related SCC [46]. Indeed, it is not uncommon for complex oracles, such as software oracles or hardware oracles, to malfunction, which slows down operations or provides inaccurate information [47]. In addition, many oracles have scalability issues, and their performance can decrease rapidly when their use becomes intense and widespread, compromising the effectiveness of blockchain [72]. Finally, they may suffer cyberattacks that block their operation or put their control at risk [27].

The literature suggests that blockchain has an impact on BP through its ability to improve information flow, speed up payments, increase security, reduce lead times, and improve logistics operations [3, 69]. However, to achieve these benefits, oracles play an enabling role in all blockchain functions. Thus, the occurrence of the above issues may moderate the direct and indirect effects of blockchain on BP. On the other hand, some studies have identified an insignificant impact of blockchain on BP [23, 57]. These results could be influenced by malfunctioning oracles or their inadequacy for the task for which they were used. The choice of the correct oracles could considerably elevate blockchain performance and foster its impact on BP, contrary to what has been identified in this stream of literature. Some exploratory studies confirm this possibility as the use of oracles reduces performance risk by improving data accuracy, trust, and transparency

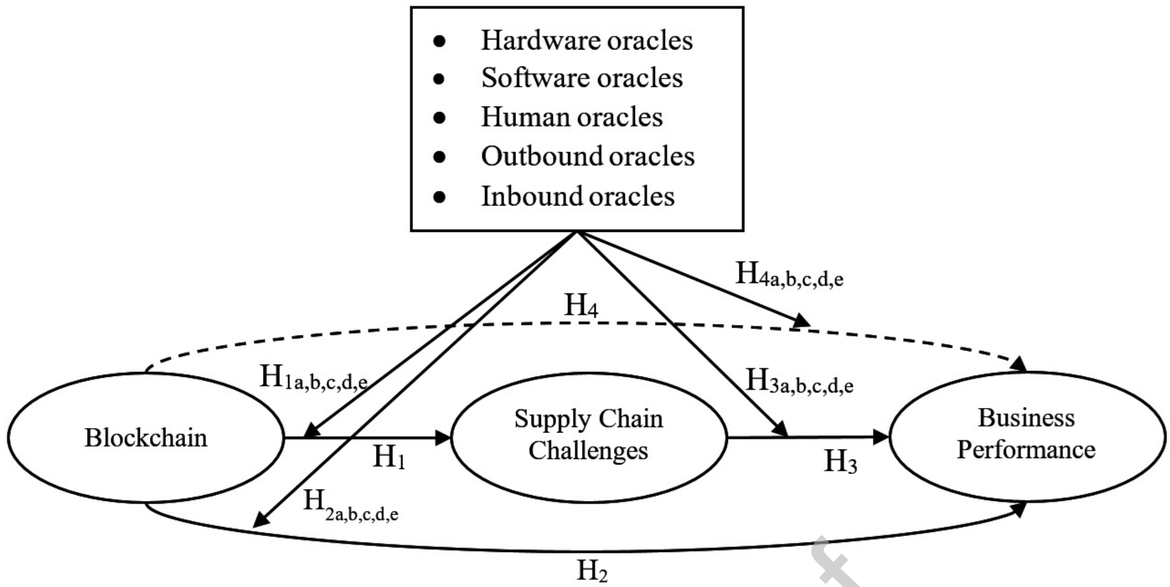

Figure 1: Conceptual model.

[18]. Oracles increase the security and reliability of data used by smart contracts and help to eliminate intermediaries [46]. In addition, if an oracle is used to record the arrival time of goods in a delivery and some related factors, such as the weather conditions, its malfunction could preclude the application of penalties associated with any delay by affecting firms' financial performance [59].

Based on the literature, oracles play a crucial role in implementing blockchain technology and its proper functioning. They can act as moderators that affect the relationships between the main variables identified in the previous hypotheses. Therefore, we define the remaining hypotheses as follows:

$H_{1a,b,c,d,e}$: Oracle solutions facilitate the positive impact of blockchain on SCC,

$H_{2a,b,c,d,e}$: Oracle solutions facilitate the positive impact of blockchain on BP,

$H_{3a,b,c,d,e}$: Oracle solutions facilitate the positive impact of solving SCC on BP,

$H_{4a,b,c,d,e}$: Oracle solutions facilitate the positive and indirect impact of blockchain on BP.

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 blockchain implementation and SCC (H_1), the blockchain adoption to the BP (H_2), and the SCC to BP (H_3) as well as the indirect impact of blockchain on firms' performance (H_4). Furthermore, we verify the effect 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 $H_{4a,b,c,d,e}$).

3. Research Methodology

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

3.1. Survey design and sample description

To test the hypotheses, we created a comprehensive survey that gathered crucial information on various aspects, including the industry and respondents' type of company, the level of investment in blockchain technology, and BP. To ensure the accuracy and effectiveness of the survey, we received feedback from a group of experts on the wording, readability, and comprehensiveness of the questionnaire. Then we selected a sample of 120 firm managers who were active professionals in the SC management domain, as our research focused on this specific area. In total, we received 156 usable observations (12% of the target population of companies, which was 1200), after removing any invalid responses. We distinguished the usable observations according to one of our questions about respondents' familiarity and experience with blockchain technology. Table 3 provides a detailed breakdown of the respondents and the sample characteristics. We conducted various approaches to assess non-response bias. First, 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.

3.2. Methodology

To achieve the objectives of our study, we employed PLS-PM, an estimation algorithm that utilizes components to predict the relationships between constructs and provide their scores at the original scale. PLS-PM is a statistical approach used to explore and quantify relationships among unobserved, or latent, variables by linking them to measurable indicators, known as manifest variables. It is especially useful when traditional assumptions such as normal distribution, large sample size, or observation independence are violated. This method excels in analyzing intricate variable interactions, making it ideal for studies involving complex systems [4, 56, 9]. Given these benefits, PLS-PM has been used widely in various business contexts, including operations management [48], SC management [19], and environmental management [25].

We consider this approach ideal for our study for several reasons. First, this method 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 [16]. Third, the variables in our theoretical model are complex and require a multiplicity of items to be measured reliably. Therefore, we developed a comprehensive list of indicators to measure complex concepts. This list is available in the Appendix. Fourth, PLS allows for the 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. Finally, 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 the entire sample of 156 firms. 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. 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 [25] to assess the internal consistency and the convergent and discriminant validity of the reflective measurement models. The first construct examined is Blockchain (B), which explores the practices managers use to adopt this technology. Specifically, B includes collaboration with developers (B1) to implement blockchain, the analysis of new exchange platforms (B4) resulting from collaboration between the SC partners, and the integration and combination with existing digital technologies (B7) for the full exploitation of blockchain's 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 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 its 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 SCC (SCC) can arise from a range of factors that impact the efficiency, reliability, and transparency of the global SC network. One key challenge is the high transaction costs (SCC1) as well as the costs of 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 SC, 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 pose significant issues for SC 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 trust of customers and stakeholders (SCC7), especially regarding the implementation of transparent and ethical business practices, as well as effective communication and engagement strategies.

The ultimate item list enables us to identify the cross-loadings connected to each construct, which are presented in Table 4. The outcomes show that certain items, such as the cost of managing the SC network, exhibit borderline loadings with values close to 0.6. Nevertheless, the findings from the 5000 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. [19], these items can be retained.

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

Table 3
Sample description.

Sales	#	%	Employees	#	%	Company type	#	%	Professionals	#	%	Industry	#	%
<10	11	7.0	<50	14	8.9	Manufacturer	56	35.7	SC Manager	82	52.2	Food & Beverage	34	21.7
10–50	38	24.2	50–99	40	25.5	Wholesaler	30	19.1	Logistics Manager	12	7.6	Fashion & Apparel	18	11.5
50–100	26	16.6	100–200	20	12.7	Distributor	14	8.9	Operations Manager	13	8.3	Medical & Healthcare	12	7.6
>100	82	52.2	>200	83	52.9	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

Table 4
Summary of the cross-loadings.

	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

index higher than this threshold, as shown in Table 5. 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 [16]. To ensure convergent validity, we evaluated the outer loadings and utilized the average variance extracted (AVE) criterion. As indicated in Table 5, the AVE for each construct is approximately 0.5, which is the recommended value [16]. These results suggest our study has achieved good convergent validity.

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 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 Table 3 and Table 4 show, 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.

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. Table 6

Table 5
Results of correlations, reliability measures, and research hypotheses.

Inter-construct squared correlations and reliability measures				
Construct	Blockchain	Supply chain challenges	Composite reliability	AVE
Blockchain	1.000		0.871	0.658
Supply chain challenges	0.412	1.000	0.853	0.532
Business performance	0.052	0.170	0.772	0.686

Results of the research hypotheses	
Research hypothesis	Direct effects and the results
H_1: Blockchain has a positive impact on SCC.	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

summarizes the results of the multigroup analysis, including additional notes on the advantages and disadvantages of different types of oracles in supporting the findings.

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 SCCs, since H_1 is supported. This result links to several motivations. First, blockchain enhances transparency and traceability in the SC, providing real-time visibility of product movements, reducing the risks of counterfeiting, and improving accountability. Second, blockchain can improve the security of the SC by using encryption and distributed ledger technology, which makes it harder to alter or tamper with data. Third, it offers cost-saving opportunities by reducing the need for intermediaries and streamlining processes, leading to lower transaction costs over the SC. Fourth, blockchain can facilitate trust and collaboration between SC 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 SC partners, reducing the risk of fraud and disputes. Overall, blockchain technology offers significant potential to address some of the key challenges facing SC management and improve its efficiency, security, and reliability.

However, our empirical results suggest blockchain's impact on BP may not always be significant, as H_2 is not supported. There are several reasons for 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 global SCs, which entail networks all over the world. The complexity of implementing blockchain technology in a global context can result in operational inefficiencies, which can negatively impact BP. In general, the benefits of blockchain technology may not be evenly distributed across all stakeholders and partners in the SC, which can limit its overall impact on BP. 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 SC management, its impact on BP may not always be significant, and requires careful consideration and evaluation.

Considering that H_3 is supported, our empirical analysis demonstrates that firms able to solve SCC can significantly improve their BP. These challenges can include issues such as delays in delivery, inefficiencies in production, and a lack of transparency in the SC. By addressing and solving these challenges, companies can improve their BP in several ways. For example, by improving SC efficiency by optimizing inventory management, reducing transportation costs, and improving production processes, companies can reduce costs and increase their profitability. In addition, by improving SC 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 SC practices. Furthermore, by addressing SCC, companies can also reduce the risk of SC 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 BP. Overall, solving SCC 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 SCC has on BP, 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 H_4, according to which blockchain can contribute to BP

Table 6
Summary of the multigroup analysis and additional notes.

Oracle Type	Advantages	Disadvantages
Software Oracles	- Indirectly improve performance and mitigate challenges (H_{3a}, H_{4a}) - Enable complex, accurate smart contracts through real-time external data - Support real-time decision-making in production, inventory, and risk response - Facilitate coordination and communication across the supply chain - Help track product quality, compliance, and reputational risks	- Do not directly improve supply chain challenges or business performance (H_{1a}, H_{2a}) - Centralized sources are vulnerable to tampering and hacking - Introduce delays due to reliance on external websites - Data integrity may be lower than blockchain's own standards
Hardware Oracles	- Directly and indirectly support performance improvements (H_{2b}, H_{3b}, H_{4b}) - Enable real-time data capture from physical world (e.g., temperature, location) via IoT and sensors - Enhance transparency, automation, and traceability - Help identify bottlenecks, reduce manual errors, improve customer satisfaction	- Do not directly solve supply chain challenges (H_{1b}) - Cannot address non-physical SCM issues like fraud or supplier evaluation - Require investment in secure, tamper-proof infrastructure
Inbound Oracles	- Direct and indirect effect on performance via better challenge mitigation (H_{2c}, H_{3c}, H_{4c}) - Provide external datasets (e.g., weather, delivery, consumer behavior, economic indicators) - Enable a more holistic, data-rich view of the supply chain - Improve efficiency, cost control, and risk management	- Do not show direct impact on solving SCM challenges (H_{1c}) - Data security, accuracy, and privacy concerns - Need robust infrastructure for secure, large-scale data integration
Outbound Oracles	- Empirical evidence shows no benefit on SCM challenges. - Conceptually enable blockchain to interact with external systems and provide verified off-chain updates	- Empirical evidence shows no benefit on performance. - Current systems lack protocols for effective interaction with external ecosystems - Cannot yet enable meaningful blockchain contributions to dynamic supply chain environments
Human Oracles	- Empirically shows no impact on SCM challenge-solving. - Add expert knowledge and human judgment unavailable to machines - Support trust-building and collaboration in stakeholder networks - Can verify and validate data manually in complex cases	- Empirically shows no impact on performance. - Subject to bias and inconsistency - Lack of automation and traceability features needed for efficiency gains

indirectly through the effect exerted by the firms' capacity to solve the SCC. Specifically, the use of blockchain technology leads to several benefits for the SCs. These benefits include efficiency, reduced costs, enhanced reputation, customer satisfaction, and reduced risk of disruptions. Similarly, the use of blockchain technology can reduce the risk of SC disruptions, which can have significant negative impacts on BP. By enabling faster and more secure transactions, blockchain technology can also streamline SC management, improve operational efficiency, and reduce costs. Therefore, firms investing in blockchain can expect a significant improvement in BP indirectly, only when the blockchain properly solves SCC.

4.2. Multigroup analysis on software oracles

In this section, we verify how software oracles can be beneficial for unlocking the benefits of blockchain. Software oracles provide a link between the blockchain and external online data sources, such as websites, Application Programming Interface (APIs), and flash news. This enhances the smart contract's accuracy and effectiveness, enabling more complex and sophisticated applications of the blockchain. By leveraging software oracles, blockchain technology can become even more transparent, and efficient, while reducing 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 7, the use of software oracles does not help the blockchain increase BP and solve SCC (H_{1a}; H_{2a}). On the one hand, this can be explained by the centralization of information linked to software oracles, making them vulnerable to hacking, data tampering, and other security risks. Furthermore, 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 SC, reducing the overall effectiveness of the system. However, our empirical findings demonstrate that software oracles can help firms solve SCC 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 SC activities. Also, they can provide valuable insights into industry trends, helping firms to identify emerging opportunities and threats. Software oracles can provide a means of communicating with suppliers, customers, and other stakeholders, facilitating collaboration and coordination across the SC, including tracking product quality and safety, complying with regulatory requirements, and protecting reputations. Finally, software oracles can help firms identify and respond to real and/or possible SC disruptions, reducing the risk of production delays and inventory shortages (H_{4a}). Therefore, while software oracles do not affect the direct effect of the blockchain on SCC and BP, they provide a great source of information to mitigate SCC and increase their impact on BP, 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.

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 SCC. 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, hardware oracles can collect real-time data on various aspects of the SC, such as temperature, location, and other critical parameters. These data can then be fed into the blockchain network, where they can be used to validate transactions, automate SC processes, and ensure greater transparency and traceability throughout the SC. 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 7, demonstrate that the blockchain using hardware oracles cannot provide direct benefits for SCC (H_{1b}). While the use of hardware oracles can provide valuable data and insights into various aspects of the SC, they cannot directly solve all the challenges faced by SC 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 cannot ensure the right products are delivered to the right place at the right time or address issues related to fraud, theft, or counterfeiting. However, they might represent an effective source of information for smart contracts to be adjusted according to the match between these parameters and the real performance of SC partners and stakeholders. Thus, they can provide indirect benefits to firms (H_{4b}). In fact, by enhancing transparency, businesses can better identify inefficiencies and bottlenecks in their SC and take proactive steps to address these issues. By automating SC 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 mitigate risks and protect their reputation by providing greater visibility into suppliers and third-party activities. This can help businesses identify and address issues early, reducing the risk of disruptions, delays, or other SC problems (H_{2b}). Overall, hardware oracles can help businesses improve their SC performance, reduce costs, enhance customer satisfaction, and maintain a competitive advantage in the marketplace.

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 that include 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 SC, 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 in addressing specific challenges in their SC and pursuing 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 SC, 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 SCC. For example, issues related to data privacy, data security, and data accuracy may need to be addressed. Additionally, companies must ensure 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 SCC through inbound oracles (H_{1c}). However, inbound oracles are extremely effective in allowing more effective solutions to SCC, leading to an increase in BP (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 SC 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 SC. By leveraging the use of inbound oracles, blockchain can provide additional layers of validation and verification to SC 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 SC partners make more informed decisions and improve performance (H_{4c}).

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 SC 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 faced by SCs, it is important to note it is not a panacea. One of the key limitations of blockchain technology is its lack of interaction with, and ability to update, the wider ecosystem in which the SC operates. SCs 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 SC management and BP, 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 sharing and updating data across the SC in different ecosystems (e.g., datasets available in different countries). This is a challenge blockchain developers should address in the future.

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 ecosystem, enabling validation and verification processes through real-time, 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 machines cannot replicate. While social interactions and human relationships can play a role in improving SC management and BP, our results demonstrate (see Table 7) that they are unlikely to provide a comprehensive solution to the challenges SCs face when implementing blockchain. Although the use of blockchain technology shows promise for engaging people as human oracles, the current systems have failed to achieve such targets. One of the key challenges SCs face is a lack of transparency and traceability: while social interactions and human relationships can help build trust and improve communication between stakeholders in the SC, 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 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 SC (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 SC. It is important to note that social interactions and human relationships are still important in the context of SCs, particularly in terms of building trust and fostering collaboration between stakeholders. However, they should still be fully integrated within the potential granted by blockchain technology.

5. Discussion

The first objective of this study is to investigate whether blockchain can be a technology capable of supporting companies in overcoming SCCs, and the possible benefits it can have on BP. Our results demonstrate that blockchain has a direct and positive impact on the SC challenge (H_1). This result empirically supports the theory in previous literature that blockchain has a positive effect on transparency [28, 64, 77], traceability [34, 5, 64], delivery [51], costs [17, 5, 55], trust, and reputation [13, 76, 36]. However, our results refute other studies that have found blockchain ineffective in overcoming the same SCC of transparency [52, 64, 41], traceability [53], delivery [51], costs [11, 33, 53], trust, and reputation [11, 35]. For example, Walmart[1] implemented blockchain to enhance food traceability, particularly for products like leafy greens and mangoes. This drastically improved its ability to respond to food contamination issues, strengthened supplier accountability, and helped ensure product freshness for customers.

We find no direct impact of blockchain on BP (H_2). This result aligns with the findings of De Giovanni [23] and Sharma et al. [57], while contrasting with the results of other studies that have identified a positive impact of blockchain on BP [3, 69]. To establish an effective Blockchain system in SC management, firms need internal planning, investment, and a strong data culture. Externally, integrating IoT

[1]https://tech.walmart.com/content/walmart-global-tech/en_us/blog/post/blockchain-in-the-food-supply-chain.html (accessed 18 March, 2026).

Table 7
Results of the multigroup analysis. A: Presence of human oracles (H_{1e}, H_{2e}, H_{3e}, H_{4e}); B: Presence of outbound oracles (H_{1d}, H_{2d}, H_{3d}, H_{4d}); C: Presence of inbound oracles (H_{1c}, H_{2c}, H_{3c}, H_{4c}); D: Presence of hardware oracles (H_{1b}, H_{2b}, H_{3b}, H_{4b}); E: Presence of software oracles (H_{1a}, H_{2a}, H_{3a}, H_{4a}).

Research hypothesis	A	B	C	D	E
$H_{1a,b,c,d,e}$: Blockchain has a higher positive impact on SCC.	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 Performance.	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.

with blockchain enables real-time monitoring and trust, but success depends on widespread coordination and participation, especially with incentives from larger firms. Moreover, managers must possess a mix of business, technical, and relational skills to align internal and external stakeholders for successful implementation [38].

However, we find an indirect impact of blockchain on BP through SCC (H_4). This result aligns with that of Markus and Buijs [39], who found an indirect impact of blockchain on BP. Moreover, we found that the indirect impact is due to the ability of blockchain to overcome SCC rather than because of the complementary activities due to the introduction of blockchain. Therefore, companies that introduce blockchain should expect an indirect impact of blockchain on BP once that blockchain has made it possible to overcome SCC. This statement is supported by our third hypothesis (H_3), which demonstrates that the ability to overcome SCC has a positive impact on BP. We are among the first authors to consider this relation. We complement and elevate the findings of the few previous studies that have demonstrated a positive effect on performance due to overcoming the challenges of "inventory management," "the development of supporting technologies," "the development of effective governance policies," "transparency," "privacy," and "security" [29]. We broaden the concept of the SCC by including and demonstrating the positive effect on "cost reduction," "traceability," "transparency," "reduction of the risk of disruptions," and "reputation and trust." For instance, Maersk[2], in collaboration with IBM, created the TradeLens platform to improve transparency and reduce paperwork in global shipping. By digitizing shipping documents and tracking events through blockchain, TradeLens minimized delays, reduced fraud, and improved coordination among shipping stakeholders. This enabled them to monitor goods in real-time and streamline customs and port operations, thereby improving their BP.

The second objective of the study is to investigate the influence of different types of oracles on blockchain effectiveness and the relationship between blockchain, SCC, and BP. We used the classification of oracles suggested by De Giovanni [21] and Papadouli and Papakonstantinou [47], and found that when hardware oracles (H_{1b}; H_{2b}; H_{3b}; H_{4b}) are used, the impact of SCC on BP, and the indirect and direct impact of blockchain on BP are higher than the condition without oracles. Hardware oracles enable businesses to gain a competitive advantage through improved SC performance, cost reduction, and improved customer relationships. Similarly, when inbound oracles are used (H_{1c}; H_{2c}; H_{3c}; H_{4c}), the impact of SCC on BP, and the indirect and direct impact of blockchain on BP are higher than in 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}; H_{2a}; H_{3a}; H_{4a}), the impact of SCC on BP and the indirect impact of blockchain on BP are higher than in the condition without oracles. Software oracles are an important tool due to their speed and ease of use. However, compared to inbound oracles and hardware oracles, they have no direct influence on BP. This is because the information collected by software oracles is often not as reliable as the blockchain and could compromise the integrity of data in the system. Human oracles (H_{1e}; H_{2e}; H_{3e}; H_{4e}) and outbound oracles (H_{1d}; H_{2d}; H_{3d}; H_{4d}) have no influence on the identified relationships. The outbound Oracle's result can be justified by the lack of protocols and standards that make it possible to render the data extracted from the blockchain usable. Instead, although human oracles 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.

With our results, we empirically demonstrate oracles' function in enabling blockchain for business purposes. We find that none of the identified oracles has a negative effect by worsening SCC and BP through blockchain. This

[2]https://medium.com/geekculture/how-maersk-used-blockchain-to-revolutionize-the-logistics-industry-case-study-5f639bdc154c (accessed 18 March, 2026).

result puts boundaries on the "Oracle paradox" since, in the worst-case scenario, oracles have no effect on the relationships between the analyzed variables [2, 59, 8]. In addition, we find that hardware oracles and inbound oracles are the most resilient to the issues of centralization found in the literature [18, 47], malfunctions [46], scalability [72], and cyberattacks [27]. Overall, they allow better blockchain applications. Software oracles are somewhat effective, while inbound oracles and human oracles are not effective and resistant to these problems, as they have no significant effects. This is the first study that empirically demonstrates the oracle's moderating effect in the relationships between blockchain, SCC, and performance. In particular, it emerges that oracles with greater disintermediation that involve hardware tools to alleviate human error are those that have 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.

6. Conclusions

6.1. Theoretical implications

Despite the increasing attention to blockchain in SC management, prior research lacks consensus on its actual benefits and often neglects the influence of technical factors, most notably, the role of oracles. In other words, oracles act as bridges between blockchain and external data sources, but they are typically overlooked in the literature, being treated as background infrastructure rather than as active components that shape blockchain outcomes.

To address this gap, our study investigates whether blockchain contributes to overcoming SCC and indirectly improving BP, with a focus on the role of oracles. Empirical results confirm that blockchain significantly improves core challenges in the SC, such as transparency, traceability, and visibility. However, there is no direct effect on BP. Instead, blockchain's impact is mediated through its ability to resolve SC issues, validating the importance of indirect pathways. Furthermore, this study examines the impact of different types of oracles, known as hardware, software, inbound, outbound, and human oracles. The results find that hardware and inbound oracles significantly enhance blockchain's effectiveness, improving both SC performance and business outcomes. In contrast, human and outbound oracles show no significant effect, highlighting concerns around data integrity and automation.

This research makes a novel empirical contribution by identifying oracles as crucial enablers in blockchain-enabled SC. It refines existing blockchain literature by revealing how different oracles moderate the relationship between blockchain, SCC, and performance. By doing so, it also informs managerial decision-making on the design and implementation of blockchain systems, emphasizing the importance of choosing the right oracle infrastructure to maximize technological and business value.

6.2. Practical and managerial implications

Based on our findings, we propose the following managerial insights:

- Blockchain should be adopted as a strategic response to overcome specific SCC rather than as a generic technological upgrade. Our findings show that blockchain alone does not directly enhance BP. Instead, its value emerges from its ability to resolve pressing SCC, such as improving transparency, traceability, cost efficiency, and trust, which in turn positively affect performance. Therefore, managers should assess whether blockchain can meaningfully address the particular SCC their firm faces before committing to its adoption.

- Oracles are critical enablers of blockchain effectiveness and should no longer be treated as mere background infrastructure. This study empirically demonstrates that the performance of blockchain in SCs is significantly shaped by the type of oracle used. Firms must consider Oracle design as a strategic choice, not an afterthought, when implementing blockchain-based systems.

- Inbound and hardware oracles are particularly powerful in translating blockchain capabilities into SC and BP gains. Inbound oracles enhance blockchain effectiveness by integrating high-quality, diverse data sources that enrich system reliability. Hardware oracles, by ensuring automation and reducing human error, further amplify blockchain's impact. Managers aiming for performance improvements should prioritize these oracle types when designing blockchain systems.

- Software oracles provide a useful but limited benefit. While they facilitate the indirect effects of blockchain on BP due to their speed and ease of implementation, their lower data integrity limits their ability to drive direct performance outcomes. Thus, software oracles may serve as a tool in early-stage projects but should be upgraded to hardware or inbound systems for more impactful results.

- Human and outbound oracles currently offer limited utility in SC blockchain implementations. Our findings show that these oracle types do not significantly contribute to improving either SCC or BP. Human oracles require trust in manual input, while outbound oracles face challenges related to the usability of extracted blockchain data due to lacking protocols. Their use should be minimized in applications where automation, data accuracy, and real-time processing are critical.

- There is a clear trade-off between oracle effectiveness and investment cost. According to the literature, hardware oracles require the highest capital investment but deliver the strongest impact, while human oracles are inexpensive but largely ineffective. Managers should weigh the expected performance gains against implementation costs and select the oracle infrastructure that offers the best return on investment relative to their SC goals.

- To unlock blockchain's full potential, firms must look beyond the technology itself and focus on its ecosystem components. Implementation success depends not only on integrating blockchain into operations but also on building the right supporting infrastructure. Managers should ensure that their internal capabilities and external partnerships can support a robust oracle strategy tailored to their data needs, automation goals, and performance expectations.

6.3. Limitations and future research

The study we present here to inspire future research is not without limitations. The major part of our sample is related to companies from developed countries. However, recent studies show peculiarities of blockchain applications in developing countries [44] that limit the generalizability of our results. Moreover, our sample mostly includes large firms, and it is important to note that smaller firms have different technological infrastructures and lower investment capabilities. For this reason, it might be interesting to check the performance of oracles in these companies and compare the results with leading companies. Moreover, in this study, blockchain technology is analyzed without considering side technologies such as IoT sensors and artificial intelligence. So, future studies could investigate the effect of combining other technologies with blockchain (e.g., the possible application of artificial intelligence for data entry on the blockchain).

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CRediT authorship contribution statement

Daniel Ruzza: Conceptualization, Investigation, Writing – original draft, Discussion; **Behzad Maleki Vishkaei**: Conceptualization, Formal analysis, Data curation, Writing – original draft; **Pietro De Giovanni**: Conceptualization, Methodology, Formal analysis, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

Appendix

Questionnaire and Descriptive Statistics. Please see Table 8.

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Table 8
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.

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