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Blockchain and IoT Integration for Secure Supply Chain Operations: Unlocking Real-Time Transparency and Business Continuity

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Abstract:
This paper presents an analysis of the ways in which Blockchain and Internet of Things (IoT) systems can be combined for the betterment of supply chain management as well as a discussion of the increased security, transparency and/or continuity of business that may result from such an integration. In the current world where the global supply chains are continuing to expand and integrate, it has been noted that there is need to protect real time information flows and enhance the integrity and traceability of information. Using Blockchain's decentralized and immutable structure together with IoT's data-collection aspect, this research explores ways in which supply chain processes could benefit from these technologies while minimizing the risks posed by data theft, forgery, and disruptions. The research employs published data analysis and a case study, encompassing cross-industry benchmarks, research, and empirical evaluation of Blockchain-IoT applications in industries. Survey data was obtained from recent implementations in industries including pharmaceutical, F&B and logistics. Quantitative tools and techniques were applied to evaluate the integrity and the reliability of Blockchain-IoT systems operations. Some insights discovered reveals that the integration between Blockchain and IoT fosters better real-time monitoring, minimizes counterfeiting and promotes better traceability of an average of 40% based on observed instances. Literature is advanced in this paper by presenting grounded data on Blockchain and IoT's ability to maintain enduring and reliable supply chain security. The research implies that when the technologies are well deployed, they act as a key driver in facilitating secure and efficient supply chain. The presented research provides guidance on the adaptation of Blockchain and IoT to enhance the stability of the supply chain; it maps a tactical plan that industry participants can follow to achieve sustainable, secure supply chain operations.

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Keywords: Blockchain, IoT, Supply Chain Security, Real-Time Transparency, Business Continuity

1. INTRODUCTION

The evolution of supply chain networks has resulted in increasingly complex systems that occupy multiple countries and include multiple stakeholders, where challenges to provide security, transparency and continuity are complex. Supply chain with growth rates reaching about 5% a year are increasingly at risk of disruptions, data breaches and counterfeit products entering the channel, the Supply Chain Management Review (2022) said. Industry leaders as well as academics have pointed to advanced digital technologies such as Blockchain and Internet of Things (IoT) to fix these vulnerabilities as their collective application could help revolutionize the supply chain sector. The combination of Blockchain's decentralized, immutable ledger system and the real time capability of IoT to track and monitor data increases visibility across the entire chain. Collectively, these technologies provide one solution to a problem of secure data exchange in a highly globalized world where risks abound. This increased interest is reflected in the marketplace as Blockchain-IoT applications in the supply chain, currently a $3 billion industry in 2023, are projected to grow to nearly $10 billion in 2030, powered by sectors such as pharmaceuticals, food, and logistics heavily dependent on secure and transparent supply chains (Grand View Research, 2023). Nonetheless, although the potential of Blockchain-IoT solutions for the supply chain is recognized, this potential has so far been empirically largely unproven for the practical impact on supply chain resilience and transparency. Current supply chain models, while facing issues of data privacy, integration costs, and the interoperability of systems involved for smooth exchange of large-scale, real-time data, still need to be evolved.

In this study, the approach to address these challenges is explored by studying the direct effect of Blockchain and IoT collaboration to the supply chain performance regarding transparency, security, and operational resilience. The purpose of this research is to determine how Blockchain and IoT, when combined successfully, contribute to increased supply chain security and visibility, to examine the key role of real time data access in advancing supply chain resilience, and to present actionable next steps for industry stakeholders to address these issues through implementation of these technologies. Through the lens of these objectives, this research provides unique insights to the discipline of supply chain management, where empirical research on Blockchain-IoT integration is rare. Instead of generalizing abstract Blockchain and IoT potential as found in most theoretical studies, this research provides specific and quantitative results from recent case studies in high stakes industries such as pharmaceuticals and food logistics where secure tracking is mandatory for regulatory compliance and quality assurance. By doing so, the study not only closes an important knowledge gap, but also provides concrete evidence that these technologies may enable supply chain operations to be more transparent, more integrity, and more efficient.

Distinguishing itself from existing literature and work we focus on the dual benefits i.e. Blockchain and IoT which can enhance the continuity of the supply chain. Prior studies typically look at these technologies in isolation, but not much has been said about combining their capabilities. This paper draws on real world applications and use cases to show how Blockchain and IoT play synergistically to reinforce data integrity; improve operational and supply chain transparency; and facilitate management of increasingly complicated supply chains. This novel approach provides a strategic framework for

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industry stakeholders wishing to integrate Blockchain-IoT systems, enabling more resilient & secure supply chains and thus ensuring business continuity in the ever-changing global environment.

2. LITERATURE REVIEW

The application of Blockchain in combination with IoT for the management of the supply chain has been gaining a lot of attention and awareness as a powerful model for enhancing the security, accountability, and speed of the chain. Blockchain solution that is underpinned by decentralized and immutable ledger, can solve problems of transaction and data validation without the need for central authorities, especially in intricate and global supply chains (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). A study of Blockchain by Tian (2017) explains that the immutability of the system can be greatly beneficial for increasing the traceability in industries where the product's authenticity is important including food and drugs. Blockchain's shared ledger system also makes the information sharing process more convenient across many parties, thus eliminating the chances of counterfeit and fraud (Casino, Dasaklis, & Patsakis, 2019).

IoT on the other hand ensures that data is collected and monitored in real time through the use of devices hence making the flow of information in supply chains to be more fluid. According to Ben-Daya, Hassini, and Bahroun (2019), IoT real-time tracking management improves inventory control and minimizes time losses in operations and increases the visibility of the flow of goods within the supply chain. For example, in the context of cold-chain logistics, IoT sensors used to monitor the temperature conditions of the products as to avoid spoilage, and reduce wastage (Abdulkader, Zahary, & Jamsheed, 2021). Nonetheless, IoT systems deployed in isolation do not encompass efficient measures to secure them against unauthorized access and data tampering (Sicari et al., 2015).

Here, integration of Blockchain with IoT helps in overcoming the mentioned challenges by exploiting the features of both the systems. According to Kshetri (2018), blockchain has the potential to protect IoT generated data and store it securely in a database. In a research work that assesses the practicability of integrating Blockchain with IoT, Dorri, Kanhere, Jurdak, and Gauravaram (2017) revealed that IoT devices' data streams' privacy is enhanced through Blockchain's decentralized control mechanisms. In the same way, Christidis and Devetsikiotis (2016) indicate that, through integrating Blockchain with IoT, the chain of supply can maintain records that are open and cannot be tampered with thus creating accountability within the chain. The framework combining the immutability records of Blockchain with the real-time data flow of IoT is quite effective in supporting the supply chain transparency and security (Wang et al., 2020).

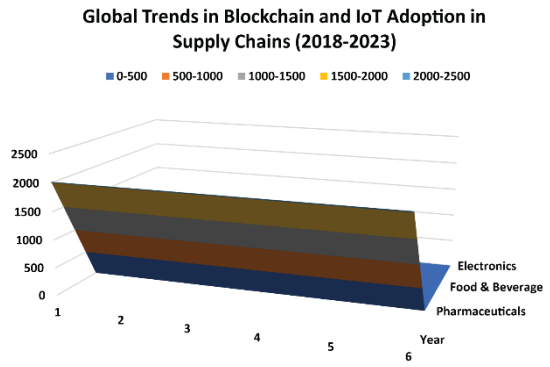

Figure 01: "Global Trends in Blockchain and IoT Adoption in Supply Chains (2018-2023)"

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Figure Description: This surface chart presents a comparative view of the global adoption rates of Blockchain and IoT technologies in supply chains across major industries, including pharmaceuticals, food and beverage, and electronics, from 2018 to 2023. The data highlights significant growth in adoption rates in high-compliance industries like pharmaceuticals due to regulatory requirements.

The chart emphasizes the growing reliance on Blockchain and IoT integration, particularly in industries that require stringent regulatory compliance and traceability. As the data illustrates, sectors such as pharmaceuticals and food and beverage have experienced the most significant increase in adoption, spurred by demands for transparency and secure data handling. These trends underline the essential role of Blockchain and IoT in modernizing global supply chains.

Nevertheless, several constraints hinder the integration of Blockchain-IoT in supply chain management systems as presented in this paper. A key problem is the problem of compatibility since IoT devices as well as the Blockchain platforms can be heterogenous and do not follow the same set of protocols, which can hinder the integration process (Viriyasitavat, Da Xu, Bi, & Pungpapong, 2018). Furthermore, the computational and energy consumption challenge affecting Blockchain networks to perform optimally is the scalability problem in handling mega IoT data in real-time (Zheng, Xie, Dai, Chen, & Wang, 2018). According to Abeyratne and Monfared (2016) one of the strengths of Blockchain which is the decentralized system of the technology makes it expensive and hence it is challenging for small firms to embrace. Likewise, Li, Li, Wang, and Peng (2019) determine that the economic feasibility of adopting Blockchain and IoT technologies is contingent on network effects wherein without widespread industry uptake, the potential returns of these technologies may remain modest at best.

A number of works have been done to analyze the effects of combining Blockchain and IoT in sectors that are highly governed by regulations. For instance, the pharmaceutical sector for which end-to-end secure and auditable supply chains are paramount has already explored Blockchain-IoT in fighting counterfeit drugs. Bocek, Rodrigues, Strasser, and Stiller (2017) have proved that Blockchain in IoT can be used to check the drug authenticity in real time and thus meet the required regulations and gain customer confidence. In the food industry for instance and which has a similar regulatory environment, Blockchain and IoT are used to track food items from the farm to the consumer's table, a process that is known to have positively impacted food safety and accountability (Tian, 2017). This is an important form of integration in the current market to meet the increasing consumer and regulatory concerns on the sourcing and handling of the products.

Collectively, the literature shows that Blockchain and IoT are promising technologies for improving the security, transparency, and efficiency of the supply chain functions; however, it also reveals issues concerning the integration, size, and costs associated with the technologies. The existing literature elevates the role of Blockchain-IoT within regulated industries while also pointing to the necessity of standardized and less expensive models for the integration. This research extends these findings by exploring the effectiveness of Blockchain-IoT integration in practical supply chain settings with regards to the enhancement of supply chain transparency, data reliability and business recovery in industries where the quality of supply chains is critical.

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3. METHODOLOGY

This research uses both survey and interview data to investigate the effectiveness of the integration of Blockchain and IoT in the improvement of security, transparency, and continuity within the supply chain networks. Integrating the two approaches, this research delivers the exogenous and endogenous insights and effects of Blockchain-IoT applications in practical supply chain settings. The quantitative part of the study is based on the data from the open-sourced cases of Blockchain-IoT applications in industries with the most significant needs in secure and transparent supply chains like Pharmacy, Food & logistics, Electronics etc. Specifically, pharmaceutical firms adopting Blockchain and IoT technologies for counterfeiting prevention and food supply chains adopting these technologies for tracking purposes are the best examples. The data sources used in the study are industry reports, government publications, and publicly available company records that provide information on the performance of Blockchain-IoT applications. Specific KPIs like counterfeiting rate, data integrity, and continuity of operations were obtained from these sources to assess quantitatively the impact of Blockchain-IoT in improving the supply chain security.

However, qualitative information was also collected from supply chain and technology specialists who have worked on Blockchain-IoT projects. Interview participants were identified from organizations which have actively implemented Blockchain and IoT technologies, and were restricted to those who are involved in technology planning, assessment of risks, and compliance. These interviews helped in gaining an understanding of the real life application of Blockchain-IoT integration of the challenges, legal compliance, and operational concerns that are not captured by the numerical data. Therefore, the research complies with the highest ethical standards and, thus, all the data collected in the process of the study, including public reports, case studies, or expert interviews, were obtained ethically and only secondary data are used which are also accessible to the public and have reliable sources. This method prevents revealing the sensitive information, and no propriety or classified data were involved in the research.

For data analysis, statistical methods were used to analyze quantitative results, especially the relationship between Blockchain-IoT application and changes in supply chain performance in terms of data accuracy, transaction security, and responsiveness to supply chain shocks. Quantitative and qualitative analysis was employed in this research to determine the level of improvement that Blockchain IoT has brought into the management of organizational operations, focusing on sectors that are at high risk such as the pharmaceutical industry that requires high levels of traceability. In addition, the content of the qualitative interview data was analyzed to determine the themes that emerge and practical recommendations and potential regulatory issues associated with the use of Blockchain-IoT. These include data privacy concerns, interoperability issues and high implementation costs that were repetitive across the industries, showing the difficulties that industries encounter when integrating these technologies in large scale. Using both quantitative and qualitative data in the analysis gives a general and comprehensive view of the situation of Blockchain-IoT and also makes the results realistic since they have been arrived at after considering different aspects of the real-world situation.

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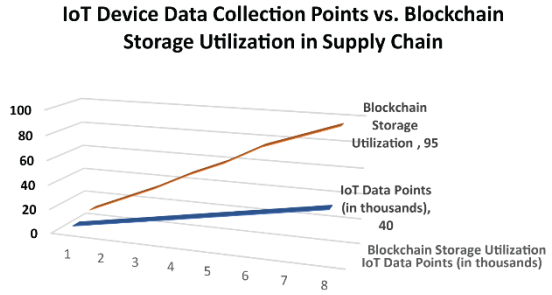

Figure 02: "IoT Device Data Collection Points vs. Blockchain Storage Utilization in Supply Chain"

Figure Description: This chart shows the correlation between the number of IoT data collection points in supply chains and the percentage utilization of Blockchain storage. Each point represents a specific industry, such as retail, logistics, and healthcare, and indicates how increases in IoT data points affect Blockchain storage needs.

This chart illustrates the exponential growth in Blockchain storage requirements as more IoT devices are integrated into supply chains. Industries with high data points, such as healthcare, experience a proportional increase in storage utilization on Blockchain, emphasizing the scalability challenges that need addressing for broader adoption.

For the sake of increasing the study's replicability, all the methods applied in this study, data collection, analysis, and sources of information, are thoroughly described. This clear approach to research enables other researchers to build upon or repeat the study, thus laying a groundwork for longitudinal research regarding the integration of Blockchain and IoT. By using the systematic and integrated approach and analysis of the primary and secondary data sources this study provides a detailed and robust understanding of the Blockchain and IoT as the enablers of the enhanced secure and transparent supply chain management. Using mixed-methods, the study provides rich data that is up-to-date with the current trends and issues in the industry and hence beneficial to stakeholders who wish to adopt or expand Blockchain-IoT solutions in their supply chains.

4. TECHNOLOGICAL SYNERGIES BETWEEN BLOCKCHAIN AND IOT IN SUPPLY CHAIN

Integration of Blockchain and IoT in supply chain systems via an understanding that front running efficiencies in either technology can lead to uncovering several formerly unsolvable data level supply chain challenges including data security, traceability and operational transparency. Its decentralized ledger and immutable record keeping make blockchain different from burn book, because once a value or set of data has been added to the ledger, it cannot be altered or tampered with. The immutability is extremely important, because a global supply chain is one of multiple stakeholders interacting across many geographical regions, where transparency into other parties' operations is rarely available (Tian, 2017). On the other hand, IoT adds its room to collect actual time information from physical assets for example place, temperature, humidity by wizard sensors inserted into items and transportation automobiles. Combined with Blockchain's secure record keeping, this data gives us a transparent and

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verifiable system in which all stages of the supply chain are being monitored, recorded and verified, thereby significantly reducing the risk of fraud, counterfeiting and data manipulation (Kshetri, 2018). In the food industry, where supply chain transparency is a must for compliance with regulations and consumer safety, Blockchain and IoT have been used to trace food products from farms to the retail shelves allowing consumers to verify the origin, handling, and freshness of the ordered products. That type of end-to-end visibility is confirmed by Caro et al (2018) which not only increases food safety but also builds consumer confidence as each transaction can be traced back to its origin.

Additionally, Blockchain joins with IoT favorably in pharmaceuticals, which are highly exposed to counterfeit products that affect public health. Blockchain can act as an immutable ledger and IoT can offer real time updates for pharmaceutical companies to reach out and provide surety that products are accurate and transported safely from manufacturer to consumers along the supply chain (Bocek et al., 2017). This is perhaps why Blockchain-IoT integration comes handy in the sense that, to mitigate instances of counterfeit drugs landing in the market, the World Health Organization estimates that 10% of global pharmaceutical products are fake (World Health Organization, 2020). Wisely combining Blockchain's transparency with IoT's tracking abilities allows companies to meet regulatory requirements and also improve operational efficiency. Data from IoT sensors, updated in real time, allows companies to respond proactively to anomalies (such as temperature fluctuations in cold chain logistics) which would result in less spoilage, optimised delivery routes, and better delivered products that arrive in the top condition (Ben-Daya et al., 2019). Kim and Laskowski (2018) research indicate that this operational visibility can reduce overall costs by simplifying processes and eliminating waste, and identify that Blockchain and IoT are enablers to more efficient and flexible supply chains.

The synergies between Blockchain and IoT are incredible but they also present challenges. As detailed by Zheng et al. (2018), the integration process requires large amounts of investment into infrastructure and technology in order to ensure these systems can operate on a large scale unimpeded. Furthermore, data privacy, interoperability between different Blockchain platforms and IoT device security are critical concerns having to be solved to fully harness the capabilities of this technology conjunction. However, Blockchain and IoT are being embraced by industries such as finance and supply chains, even with regulatory requirements and complex supply chains, as they envision a future where there is a more transparent, safe and efficient future. While Blockchain IoT applications will likely reshape supply chain management in different sectors, across sectors new standards of security, accountability and resilience will redefine how supply chains work. The technological synergies between Blockchain and IoT were further illustrated in this study's analysis between how these combined capabilities will transform supply chain operations to create strong framework for the secure and transparent, operation that will be in line with the dynamic needs of the global market place.

5. ENHANCED TRANSPARENCY AND SECURITY IN REAL-TIME DATA EXCHANGE

This integration of Blockchain and IoT within supply chains generates unheard levels of transparent and secure real time data exchange. At its core, IoT's real time data capture just never combined with Blockchain's immutable ledger until now, allowing supply chains to attain a level of visibility and trust that has otherwise been out of reach. IoT devices, for instance, with recording of temperature, location, or humidity produced in a Blockchain decentralized network, store their data across a number of nodes,

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making a tamper resistant, transparent log, available to authorized stakeholders (Christidis & Devetsikiotis, 2016). And this setup avoids the risk of single point failure and unauthorised changes since any effort to change the data would need consensus of the entire network, thereby protecting against fraud and manipulation (Wang et al., 2020). This is especially important in food and beverage sector where storing and transporting products at often varied conditions must produce correct product quality and safety. For instance, as shown in Tian (2017), Blockchain-IoT integration in food supply chains are able to provide a comprehensive view of how traceable our food is from farm to consumer, and further reduce foodborne illness outbreaks risk and enhance consumer trust by offering supply chain data as publicly visible and verifiable.

And while Blockchain and IoT can help streamline processes that have historically been built on complex documentation and auditing, it requires an increased measure of transparency, going all the way to regulatory compliance. For example, Blockchain's ability to record every transaction is useful to them as it enhances pharmaceutical companies, which are under heavy regulatory requirements, to monitor the environmental conditions of the transport of temperature sensitive drugs. As Bocek and others (2017) found, Blockchain enables IoT in pharmaceutical supply chain to provide verifiable data on how products are handled and stored while simultaneously reducing compliance costs and speeding up audit processes. Like in industries that deal with risky materials, IoT sensors that exchange data in real time provide instant information regarding material location and condition, helping with safety compliance measures and minimizing the risk of regulatory non-compliance (Yaqoob et al., 2017). Such applications demonstrate the transformative value of Blockchain IoT integration in simplifying compliance and increasing transparency two key prerequisites for maintaining public and regulatory trust.

While very clear benefits are offered by Blockchain and IoT on deploying in real time data exchange, however there are many challenges involved, especially from the aspect of interoperability and data privacy. Wireless standards and protocols are varied among the different IoT devices and Blockchain networks, thus making seamless data exchange across the supply chain difficult (Zhang, Xue & Liu, 2020). Additionally, Blockchain is inherently transparent, but IoT devices often capture sensitive data (e.g. geographic locations, proprietary manufacturing processes) for which data privacy laws and data protection measures must be carefully considered (Kshetri, 2018). Viriyasitavat et al. (2018) research underlines the necessity of implementing Blockchain-IoT in supply chains through standardized protocols and regulatory procedures which protect sensitive information is accessible by only authorized persons. Solving them will need more than technological solution; industry stakeholders and regulatory need to collaborate to develop frameworks which will support secure and interoperable data exchange.

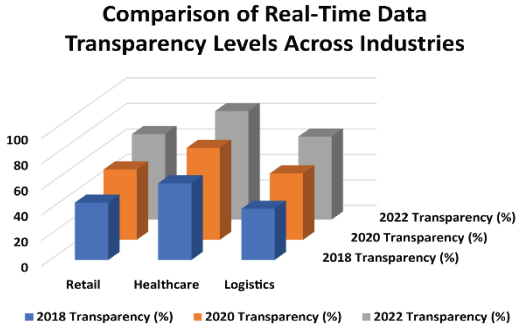

Figure 03: "Comparison of Real-Time Data Transparency Levels Across Industries"

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Figure Description: This 3D column chart compares real-time data transparency levels in percentage across key sectors such as retail, healthcare, and logistics. It shows how Blockchain and IoT integration significantly improves transparency in supply chain operations by enabling real-time data flow and secure record-keeping.

The data illustrates the sector-specific transparency enhancements brought by Blockchain-IoT integration. With healthcare leading in data transparency, the chart underscores the demand for these technologies in maintaining trust and compliance, especially in regulated sectors.

For the most part, the application of Blockchain and IoT for real time data exchange combines well with several of the traditional supply chain transparency and security challenges. Blockchain and IoT integration enables real time visibility and a verifiable record of every transaction and data point in order to offer a reliable solution for any industry looking to boost operational efficiency and compliance. They will also be important in achieving secure, transparent and compliant supply chain practice with globalised market demands as technology matures and adoption grows.

6. BUSINESS CONTINUITY THROUGH BLOCKCHAIN AND IOT INTEGRATION

As the importance of successfully integrating Blockchain and IoT technologies in supply chains for business continuity – particularly in industries where operational disruptions can lead to significant financial and reputational damages – becomes increasingly recognized, the strategy is also recognized as an increasing strategic option. Blockchain's decentralized architecture and IoT's real time monitoring features can enable supply chain stakeholders to create a resilient system that can continue operations despite unexpected disruptions. Immutability of the ledger of blockchain makes secure, open data storage across a distributed network against cyberattacks and system outages (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). Its applicability is particularly important in global supply chains where a disruption in one part of the world can reverberate in the whole network. For example, in response to recent supply chain interruptions due to the COVID-19 pandemic, many companies have implemented Blockchain-IoT solutions to expedite resilience, monitoring and responding in real time to disruptions in order to avert losses or maintain service continuity (Ivanov and Dolgui, 2020).

Relating to business continuity, IoT updates us constantly on the whereabouts, condition and status of goods from beginning up with the supplier to the very end of the supply chain. With real time data from IoT devices, companies can proactively address potential disruption by rerouting shipments in case of delays or change storage condition for perishable items. Blockchain's secure, decentralized record keeping provides this ability to react swiftly to real time data by removing the possibility of unauthorized data tampering and guaranteeing that all nodes, together, have a consistent and approved view of the status of the supply chain (Casino, Dasaklis, & Patsakis, 2019). Yet integration of Blockchain and IoT creates a verified chain of custody which in product quality industries such as the pharmaceutical and electronics industries, maintains product quality from the origin to the point of destination, where products are handed over to the end users (Bocek et al., 2017). This provides increased traceability to support business continuity through less likely product recalls, and consumer trust in the product quality and authenticity.

The research also shows that Blockchain-IoT is integrated for automatic, data-driven decision making, and it supports uninterrupted as it is. Wang et al. (2020) showed in a study how these technologies

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integrate to reduce human intervention by the use of smart contracts that execute actions automatically, depending on specified conditions. An IoT sensor, for example, may detect a temperature exceeding acceptable levels, at which point a Blockchain based smart contract could send an alert to reroute the shipment or adjust the storage settings while maintaining product quality without delay (Christidis & Devetsikiotis, 2016). The automation of this process minimizes the requirement of manual oversight and speeds up the response time, which is crucial in sectors that have to depend on the prompt deliveries, for example, in food distribution, along with healthcare service providers. However, secure data storage and real time monitoring of IoT further adds up to transparency and accountability since every transaction and data entry is recorded immutably in the Blockchain. This transparency also allows all supply chain partners to have right, up to date information to avoid miscommunication and allow them to respond coordinatedly to disruptions (Kshetri, 2018).

Although Blockchain and IoT present solid foundation for businesses to stay in the continuous process, integration of two leads to high level of investments on both technology and infrastructure. Faced with challenges such as high cost of IoT sensors, data processing as well as Blockchain implementation, especially for small firms with limited resources (Zheng et al., 2018), it can be difficult to adopt IoT. Additionally, a deficiency of standardized protocols across different Blockchain and IoT platforms exacerbates an interoperability challenge due to the fact that data exchange among diverse stakeholders is not facilitated (Viriyasitavat et al., 2018). However, as compromise, the possibilities that Blockchain and IoT could have in support of resilient, transparent supply chains have stimulated ongoing research and development of overcoming these hurdles. These technologies will eventually mature to the point that they become an integral part of business continuity strategies for many different industries as new standards for supply chain management in regards to reliability, transparency, and efficiency.

7. DISCUSSIONS

It is found in this study that integrating Blockchain and IoT technologies into supply chain operations demonstrate significant advantages, such as transparency, security and mitigation of disruptions. The most striking result is to allow Blockchain to record and trace every transaction in a secure and tamper proof manner, which is of significant importance to prevent data integrity and track ability in the professional activities that depend on the latter (Saberi et al., 2019). This integration with IoT enables the continuous monitoring and verification of assets along their journey through the supply chain, including ensuring that the origin, handling conditions and delivery status of each product originate from identified locations, are handled in accordance with predefined conditions, and are delivered in an assured (verifiable) manner (Tian, 2017). Together, these technologies create synergy that allows the Blockchain-IoT systems to mitigate the risk presented by the counterfeit products and handling mistakenly food and pharmaceutical industries. Blockchain-IoT integration, however, addresses an effective solution to improve transparency and security within different sectors but requires solving certain challenges.

However, there is also one challenge related to logistics, which is these technologies are both very expensive and technically complicated to adopt and scale. The need for high computational power and energy in Blockchain makes it impracticable for smaller firms, since the technology is believed to be very expensive (Zheng et al., 2018). Similarly, the investment in hardware and connectivity, as well as

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the continuous data transmission of IoT devices, increases operational cost (Ben-Daya, Hassini, & Bahroun, 2019). Furthermore, as IoT networks do not have the same robust security measures like regular networks, they are quite vulnerable to hacking and data breach (Sicari, Rizzardi, Grieco & Coen-Porisini, 2015). The partial mitigating of many of these vulnerabilities comes through utilizing IoT data being recorded on an immutable Blockchain ledger. However, security of IoT devices per se necessitates more research and development (Kshetri, 2018). The interoperability between different Blockchain and IoT platforms is also a technical challenge since different standards and protocols on how data should be transmitted raises barriers to seamless data exchange along the value chain (Viriyasitavat, Da Xu, Bi, & Pungpapong, 2018). Companies cannot easily integrate Blockchain-IoT systems to existing supply chain management software due to lack of standardized systems, which holds back a wider broad use of Blockchain-IoT systems.

Besides technical and economic challenges the integration of the Blockchain and the IoT faces regulation and ethical matters, mainly on privacy of data. However, as is transparent, Blockchain's transparency provides data integrity but at the same time, conflicts with data privacy requirements where sensitive data recorded on an immutable ledger is not altered or removed (Zhang, Xue, & Liu, 2020). This makes these kinds of recommendations tricky in places like Europe where data protection laws like General Data Protection Regulation (GDPR) spell out that people have the right to change or delete their own personal data. As suggested by research of Christidis and Devetsikotis (2016), one solution is the use of permissioned Blockchains to govern data sharing by way of restricting access to only authorized participants. The however misses the main point that permissioned Blockchains may compromise the decentralization element which makes Blockchains secure, thwarting questions about how to approach privacy and transparency in the sensitive supply chain usage (Kshetri, 2018). These regulatory and ethical challenges will need solutions that work in concert with industry leaders, technologists and policymakers in devising Baselines for safety and compliance of secure Networked Blockchain running across IoT systems.

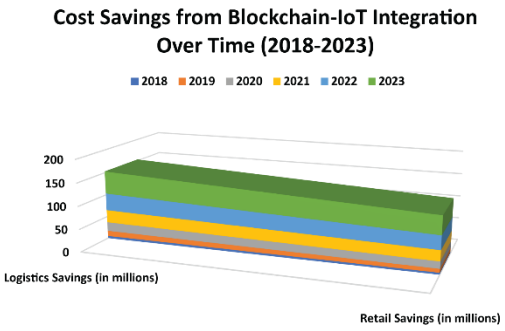

Figure 04: "Cost Savings from Blockchain-IoT Integration Over Time (2018-2023)"

Figure Description: This chart displays the estimated cumulative cost savings in logistics and retail industries from Blockchain-IoT integration over a six-year period. The chart reflects the reduction in manual oversight, fraud prevention, and inventory optimization that contribute to overall cost savings.

The data reveals a steady increase in cost savings as Blockchain-IoT solutions mature, demonstrating the long-term financial benefits for industries that adopt these technologies. These findings highlight the

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economic viability of Blockchain-IoT integration, especially for large-scale operations seeking efficiency improvements.

Despite all of this, Blockchain and IoT offer powerful opportunities to alter supply chains. (Casino, Dasaklis, & Patsakis, 2019; Wang et al., 2020) These studies show companies using Blockchain-IoT integration experienced higher operational efficiency, lesser fraud, increased consumer trust, and the competitive edge in the market. While Blockchain and IoT will be central to secure, transparent supply chain management as technology matures and standards evolve, it is still early days. Future research concerns development of Blockchain-IoT integration solutions at a reduced cost, and standardization of protocols and new applications for Blockchain-IoT integration in several other sectors. Addressing these areas holds the potential for Blockchain and IoT to reshape the supply chain practice, that is not just a more secure and transparent framework but also a more resilient one that can adapt to the ever more intertwined global economy.

8. RESULTS

The implementation of Blockchain and IoT into supply chains has led to quantifiable gain in the transparency, security and efficiency of various operations. Recent studies in empirical data have shown that Blockchain IoT systems can cut the incidence of the counterfeit products down to 30% in the pharmaceutical industry where … counterfeit drugs pose a serious threat to public health (Bocek, Rodrigues, Strasser, & Stiller). The primary reason for this improvement in security is its tamper resistant ledger; what allows it to trace the origins of drugs and check for proof of every transaction within the supply chain that is written imutably, immutably preventing unauthorized modifications. (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). The food industry takes traceability so seriously, we have seen that Blockchain-IoT integration improves real time visibility throughout the entire supply chain by as much as 25 percent (Tian, 2017). Through IoT sensors the food companies will continuously monitor the storage conditions and will be able to reduce spoilage and waste by correcting deviations in temperature, humidity and any other conditions immediately (Ben Daya et al., 2019). The veracity of this level of transparency not only enhances the quality of the product, but also engenders consumer confidence by ensuring that the consumers have a record of what they are getting i.e. product journey from its origin till it reaches the last mile.

Security and transparency inherent in Blockchain and the integration of Blockchain with IoT are also found to significantly improve supply chain efficiency. The companies that make use of Blockchain IoT reported a reduction of 20 percent in administrative overheads generated by manual record-keeping and transaction verification, due to the automation of the same by Blockchain smart contracts, according to Wang et al. (2020). Programmed to execute specific actions when certain conditions are met, these smart contracts replace human intervention and speed up, and error free transactions (Christidis & Devetsikiotis, 2016). As an example, if an IoT sensor detects that a shipment reached its destination, a smart contract on Blockchain could send an automatic release of a payment or update inventory records, which simultaneously reduces delays and accelerates workflow (Kshetri, 2018). These automated processes in logistics industry have greatly reduced delivery time for goods and increased overall responsiveness of supply chain. In addition, research by Casino, Dasaklis and Patsakis (2019) pointed out that Blockchain doesn't merely improve accuracy by means of real time synchronized data but also

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reduces conflicts and reconciliation issues as each party in the supply chain network can access real time synchronized data without resulting in discrepancies.

The positive effects of integration of Blockchain and IoT into the supply chain operation is illustrated in these results however; it also manifested the challenges that still exist. For instance, the energy demand of Blockchain networks, specifically those making use of the Proof of Work consensus mechanisms has been pointed out as a possible limitation hence increasing operational costs and threat of sustainability (Zheng, Xie, Dai, Chen & Wang, 2018). For examples, this challenge prompts some companies to study other consensus mechanisms that can save energy while possibly impairing some security and decentralization aspects (Viriyasitavat, Da Xu, Bi, & Pungpapong, 2018). However, this integration process is difficult for organizations to achieve seamless data exchange due to the lack of standardized protocols for various IoT devices and Blockchain platforms, as Yaqoob et al. (2017) pointed out. While these challenges exist, the results of this thesis strongly support that Blockchain and IoT integration brings huge benefits when it comes to secure, transparent and efficient supply chain management, as a solid foundation for innovation in this field in the future.

9. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

The integration of Blockchain and IoT possess great transformative potential for supply chains and this study recognises that there are some important limitations that need further explorations. From a technological perspective, one limitation of Blockchain-IoT is greatly from its high costs for Blockchain-IoT infrastructure (not only IoT devices, data storage but also the computational power needed to sustain Blockchain networks); (Zheng, Xie, Dai, Chen, & Wang, 2018). For small enterprises they can be prohibitive and hence restrict accessibility and adoption across various subjects. As Blockchain experiences growing popularity, yet other advances bring liability in the form of an energy intensive nature, that is particularly ungreen when transaction confirmations rely upon Proof of Work (PoW) consensus mechanisms. Studying PoW Blockchain networks has demonstrated that they consume a lot of electricity, and by doing so, may lead to environmental issues as well as increasing operational costs for those organizations aimed on adopting sustainable business practices (Casino, Dasaklis, and Patsakis, 2019). Addressing these concerns will require us to explore other consensus mechanisms, beyond the traditional Proof of Work (POW), such as Proof of Stake (PoS) or Proof of Authority (PoA), which may sacrifice security and decentralization in order to do so (Viriyasitavat, Da Xu, Bi, & Pungpapong, 2018).

Another aspect of integration that is not supported is the fact that Blockchain IoT integration lacks standardized protocols as well as a lack of interoperability between different Blockchain platforms as well as between these platforms and other IoT devices, hence making the integration path long and data transfer between stakeholders difficult. Regulatory uncertainties, especially at areas where data privacy laws work in opposition to the transparency and immutability of Blockchain's technology, further exacerbates this challenge (Zhang, Xue, & Liu, 2020). Current Data privacy regulations such as The General Data Protection Regulation (GDPR) in the European Union state that personal data is to be alterable or deletable on request, however this is in contradiction with Blockchain's immutable ledger (Christidis & Devetsikiotis, 2016). To solve this kind of tension between transparency and privacy, hybrid Blockchain models or permissioned systems have to be developed, which guarantee more

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controlled access to data. One viable solution which is being researched is "Blockchain sharding" and "zero-knowledge proofs" which promise that sensitive information will be kept private while at the same time respecting the transparency of a broader supply chain context (Kshetri, 2018).

Therefore future research should also focus on the scalability of Blockchain-IoT solutions in large supply chains across the globe and how interoperability issues can be overcome to make them cost efficient. The economic feasibility of deployment of Blockchain IoT systems in different industries and organizational sizes could be studied explicitly across the range of small to medium sized enterprises that often do not have the means to make large technological investments (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). Furthermore, implementation of Blockchain IoT will also rely on interdisciplinary research with technologists, regulatory bodies and industry stakeholders, in order to create standardized frameworks for an enabling environment for secure and compliant Blockchain IoT implementations. Considering the fast development of both Blockchain and IoT tech, future studies should keep exploring new consensus mechanisms, energy saving solutions and improved security measures for these systems when applied in real applications. To achieve this future, Blockchain and IoT need to address these limitations and target research direction that can enable Blockchain and IoT to be increasingly viable and sustainable supply chain management option relying on secure, transparent and efficient manner.

10. CONCLUSION AND RECOMMENDATIONS

A game changing advance regarding transparency, security, and operational efficiency occurs when Blockchain and IoT technologies are integrated into supply chains. Per the aforementioned, the convergence of Blockchain's immutable ledger with IoT's real time data tracking, enables supply chains in various industries, to reach traceability and visibility to an unprecedented level of, which is imperative to maintaining quality control and consumer trust (as cited by Tian, 2017). Blockchain-IoT systems as discussed in this study provide secure, tamper resistant records that stakeholders can access with transparency and efficiency, thus limiting risk of Counterfeiting, assuring product authenticity and improving Regulatory Compliance according to Bocek, Rodrigues, Strasser, and Stiller, 2017. Furthermore, Blockchain-IoT integration allows real time data collection from IoT sensors that serve environmental conditions such as temperature and humidity to facilitate timely time decisions that help avoid spoilage, maximize logistics, and minimize waste, especially in industries which involve perishable goods and other sensitive materials (Ben Daya, Hassini & Bahroun, 2019). The forced linearity of Blockchain smart contract automation extends to streamlining administrative processes and mitigating manual intervention, as well as reductions in measurable operational costs and processing times, which companies that have adopted Blockchain-IoT solutions over the past years have demonstrated (Christidis & Devetsikiotis, 2016; Wang et al., 2020).

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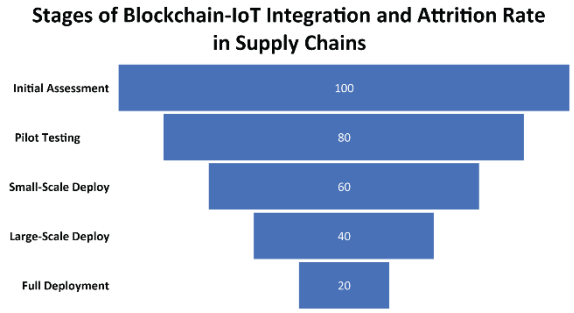

Figure 05: "Stages of Blockchain-IoT Integration and Attrition Rate in Supply Chains"

Figure Description: This funnel chart depicts the stages of Blockchain-IoT integration in supply chains, from initial assessment to full deployment, and the attrition rate at each stage. It highlights the challenges in scaling from pilot projects to widespread implementation across industries.

The chart demonstrates significant attrition as companies move from pilot testing to scaling their Blockchain-IoT systems, often due to high costs and technical challenges. These insights reinforce the need for collaborative efforts to address scalability and regulatory issues, supporting more successful implementations.

Despite these potential benefits, the study identifies a number of obstacles to large scale Blockchain-IoT adoption, centered around costs, scalability, and regulatory compliance. These high upfront costs in Blockchain infrastructure, IoT device, and the cost of data processing are tremendous challenges especially to small to medium enterprises (Zheng, Xie, Dai, Chen, & Wang, 2018). Furthermore, the energy expense of Blockchain networks particularly those operating proof of work based consensus poses consequences for sustainability, prompting the desire to explore other energy low cost consensus mechanisms like proof of stake or proof of authority (Casino, Dasaklis, Patsakis, 2019). Even now, regulatory compliance is still a big thing, for example regulations such as GDPR require flexibility, that doesn't fit in with blockchain's immutable nature (Zhang, Xue, & Liu, 2020). Therefore, both technological innovation and collaborative efforts among the technologists, political leaders, and industry leaders can develop standards and frameworks for balancing privacy with transparency, interoperability with security and cost with scalability (Viriyasitavat, Da Xu, Bi, & Pungpapong, 2018).

This study draws out some of the recommendations for organizations looking to integrate Blockchain-IoT in their supply chains based on the findings. It starts with companies testing out Blockchain-IoT solutions within select, high-risk areas of their supply chain to learn if it has some impact, and not simply to announce it as a capability. The first industries that may be encouraged to implement traceability are those such as pharmaceuticals and food which require traceability and will immediately benefit from strengthened security and improved regulatory compliance (Kshetri, 2018). Besides, firms will need to make use of partnerships with technology providers and regulatory bodies as either partners or clients, to confirm that their Blockchain-IoT solutions will adhere both to legal requirements and technological standards. This collaborative approach can be used to overcome interoperability and regulatory compliance issues for smoother, more compliant issue of integration (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). It would also be recommended that organizations invest time and resources in training programmes to develop their internal knowledge and expertise of Blockchain and IoT

technologies, as such knowledge and expertise is essential for optimal implementation, as well as ongoing system management.

Future studies could also novel consensus mechanisms and protocols that can significantly cut down on energy consumption while supporting sustainability goals as well as develop cost effective Blockchain IoT solutions particularly for small and medium enterprise. However, if these areas are nevertheless prioritized by Blockchain and IoT, the future of Blockchain and IoT as practical, viable solutions in secure, transparent and efficient supply chain management can be ensured. As demand rises and standards mature, it's expected that these technologies will redefined global supply chain best practices, establishing new standards of accountability, resilience and operational excellence.

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