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# Enhancing Security and Traceability in Aerospace Supply Chains through Block Chain Technology

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

This study explores the impact of blockchain technology on aerospace supply chains, focusing on mitigating risks such as supply chain disruptions, counterfeit parts, and regulatory compliance challenges. A mixed-methods approach was employed, combining quantitative and qualitative analysis using data sourced from publicly available databases, including the Federal Aviation Administration (FAA), the Aerospace Industries Association (AIA), the International Air Transport Association (IATA), and reports from blockchain technology providers. Descriptive analysis identified supply chain disruptions (M = 3.74, SD = 1.17) as the most significant risk, followed by counterfeit parts (M = 3.34, SD = 1.20). Structural Equation Modeling (SEM) demonstrated that part authentication and provenance tracking had the strongest impact on improving traceability ($\beta$ = 0.40, $p < 0.001$) and transparency ($\beta$ = 0.38, $p < 0.001$). A Cost-Benefit Analysis (CBA) revealed a positive return on investment, with cost-benefit ratios up to 2.31. Blockchain adoption was also found to reduce $CO_2$ emissions by up to 25%, while improving operational efficiency through shorter procurement lead times and lower administrative costs. However, regulatory misalignment and interoperability challenges remain barriers to full adoption. The study concludes that blockchain is a transformative tool for enhancing traceability, security, and sustainability in aerospace supply chains.

*Keywords: Blockchain; aerospace supply chain; part authentication; counterfeit parts; regulatory compliance.*

## 1. INTRODUCTION

The aerospace industry operates within a highly regulated and intricate environment, where effective supply chain management is essential to ensuring the safety, reliability, and performance of aircraft and related components [1]. Ramirez-Peña et al. [2] posits that aerospace supply chains involve multiple stakeholders, including manufacturers, suppliers, regulatory bodies, and operators, requiring precise coordination and stringent oversight to function smoothly which in turn causes these networks to face several significant challenges. As the aerospace industry becomes more globalized, ensuring the authenticity, traceability, and security of components is crucial for maintaining both aircraft quality and public safety [3,4].

Blockchain technology has emerged as a promising solution to these challenges by offering a decentralized and immutable ledger that enhances the security, traceability, and efficiency of aerospace supply chains. Leng et al. [5] contends that blockchain's decentralized nature provides transparency across the entire lifecycle of aerospace components, thereby improving collaboration among stakeholders and addressing critical issues such as counterfeit parts, regulatory compliance, and operational efficiency. One of the most pressing concerns in aerospace supply chains is the presence of counterfeit parts, which pose serious risks to the safety and reliability of aircraft as these parts, often originating from unauthorized suppliers or involving substandard materials, can result in component failures, thus compromising the overall safety of aircraft [6]. Given the global nature of aerospace supply chains, ensuring the authenticity of parts is increasingly difficult, as components are sourced from multiple suppliers and locations. Goebel and Rajamani [7] avers that regulatory bodies, such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA), impose strict standards for aerospace manufacturing and maintenance, making compliance essential to avoid legal consequences, financial penalties, and reputational damage.

Santhi and Muthuswamy [8] further argues that aerospace supply chains are frequently disrupted by external factors such as geopolitical instability, natural disasters, and global pandemics of which these disruptions can lead to significant delays in the delivery of components and disrupt production schedules, causing financial losses and operational inefficiencies. Thus, developing strategies for predicting, monitoring, and mitigating such disruptions is vital to maintaining the efficiency and continuity of aerospace operations [9,10].

Blockchain technology offers a viable solution to both the counterfeit parts issue and supply chain disruptions by enabling greater traceability and transparency. Di Vaio and Varriale [11] posits that through the use of a decentralized ledger, blockchain enables the tracking of aerospace components from their point of origin to their final destination, ensuring that each part used in an aircraft can be authenticated and verified, as this level of traceability reduces the risk of counterfeit components entering the supply chain. To Sum Ho et al. [12] notes that platforms such as IBM's blockchain-based system have been developed to track the entire lifecycle of aerospace components, from raw materials to final assembly, offering real-time data on suppliers, manufacturing processes, and quality control checks. which ensures compliance with industry regulations and enhances transparency throughout the supply chain.

In addition to improving traceability and security, blockchain technology can significantly enhance the efficiency of aerospace supply chain operations. Dutta et al [13] contends that real-time information sharing facilitated by blockchain enables stakeholders to streamline critical processes such as procurement, inventory management, and logistics. For instance, Kitsantas and Chytis [14] notes that Honeywell has developed a blockchain platform that reduces paperwork and automates key processes, allowing suppliers, manufacturers, and customers to access real-time information on inventory levels, procurement procedures, and shipment statuses. This increased visibility contributes to improved collaboration among supply chain partners while also reducing operational inefficiencies and costs.

Despite the potential benefits of blockchain technology, its implementation in aerospace supply chains faces several challenges. Wasim et al. [15] points out that one of the primary hurdles is the integration of blockchain technology with existing aerospace systems, many of which still rely on legacy infrastructure. Transitioning to blockchain-based solutions requires significant investment in both technology and personnel training, which can act as a deterrent for many companies. Furthermore, Dutta et al. [13] notes that the scalability of blockchain platforms remains a concern, particularly given the high volume of transactions generated by aerospace supply chains which ensure that blockchain systems can efficiently handle these transaction volumes which is crucial for their widespread adoption.

Another significant challenge lies in the regulatory environment surrounding blockchain technology in aerospace. Efthymiou et al. [16] states that while regulatory bodies such as the FAA and EASA have shown interest in exploring blockchain's potential to senhance supply chain security, standardized regulations governing its use have not yet been fully developed. Without a clear regulatory framework, companies may hesitate to adopt blockchain technology due to concerns over compliance with existing industry regulations. Additionally, Jovanovic et al. [17] suggests that issues related to data privacy, interoperability between different blockchain platforms, and the need for industry-wide standards must be addressed to facilitate broader blockchain adoption in aerospace supply chains.

Joannou et al. [18] provide evidence of IBM's blockchain platform, which tracks the lifecycle of aerospace components and has shown improvements in quality control by providing real-time data on manufacturing processes and helping identify potential issues early. Moreover, Kumar et al. [19] contend that the immutability of blockchain data reduces the likelihood of counterfeit parts entering the supply chain, as the technology makes it difficult to tamper with or falsify information. Similarly, Honeywell's blockchain platform has been used to streamline procurement, inventory management, and logistics processes. By reducing paperwork and enabling real-time information sharing, Honeywell has demonstrated how blockchain can improve the efficiency of aerospace supply chains while fostering better collaboration among stakeholders [20,21,22]. Thus, this study achieves the following objectives:

1. Analyzes the key challenges and risks in managing aerospace industry supply chains, including counterfeit parts, disruptions, and regulatory compliance, focusing on mitigation strategies.
2. Investigate the potential of blockchain technology to enhance security, traceability, and transparency in aerospace supply chains with specific applications such as part authentication, provenance tracking, and supply chain visibility.
3. Evaluate the economic, operational, and environmental implications of implementing blockchain technology in aerospace supply chains, highlighting both benefits and limitations.
4. Identifies the technical, organizational, and regulatory factors influencing the adoption of blockchain technology in aerospace, assessing critical issues like data privacy,

interoperability, and standards development.

## 2. LITERATURE REVIEW

The aerospace industry, characterized by its high-tech innovations and stringent safety protocols, encounters substantial challenges in supply chain management. A primary concern is the proliferation of counterfeit parts, which pose severe risks to aircraft safety and reliability [6]. Hobbs et al. [23] document the infiltration of counterfeit components into the aerospace sector, where even minor discrepancies in material composition or manufacturing tolerances can result in malfunctions or catastrophic failures in critical systems. As such, counterfeit parts compromise the integrity of the entire supply chain, often evading detection through standard quality control measures. They present safety risks and potential reputational and financial damage for aerospace companies. Regulatory bodies, such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA), have introduced stringent inspection protocols aimed at ensuring traceability [16]. Despite the advances in technologies like blockchain and AI-based tracking systems, counterfeit parts persist in the industry, necessitating stronger oversight and collaborative industry efforts [24,25].

The complexity of aerospace supply chains is further exacerbated by their reliance on global suppliers, making them susceptible to frequent disruptions caused by external factors such as geopolitical instability, natural disasters, and pandemics, including the COVID-19 pandemic, which significantly disrupted production schedules, with manufacturers facing shortages of critical parts that led to cascading delays in production timelines as Roscoe et al. [26] observes. In addition, Lund et al. [27] note that geopolitical tensions in regions critical to aerospace production have contributed to temporary factory shutdowns and logistical challenges, as Natural disasters, including earthquakes and floods, have further damaged infrastructure and delayed transport routes. Some companies have responded by diversifying their suppliers and developing contingency plans, yet many of these strategies remain reactive, leaving firms vulnerable to future crises. The industry's dependence on just-in-time delivery systems and a limited number of key suppliers amplifies its vulnerability to such disruptions, necessitating a shift towards more flexible risk management strategies to enhance resilience [26,28].

Aerospace firms also face challenges in regulatory compliance, as adherence to evolving safety and quality standards is crucial. Belhadi [9] highlights that the increasing complexity of national and international regulations, such as those set by the FAA and EASA, poses significant challenges for manufacturers and suppliers, as non-compliance can result in financial penalties, loss of certification, and reputational harm. Frameworks like the Aerospace Quality Management System (AQMS), the International Traffic in Arms Regulations (ITAR), and standards such as AS9100 and Nadcap aim to streamline compliance processes. However, ongoing technological advancements and shifting geopolitical dynamics demand constant vigilance from aerospace firms to maintain compliance, as failure to meet these evolving standards undermines customer trust and market competitiveness [29,30]. Hence, there is a need to strengthen counterfeit detection systems, enhance supply chain risk management strategies, and continuously improve regulatory compliance measures to ensure operational safety, reliability, and efficiency in a complex global environment [31].

### 2.1 Blockchain Technology in Supply Chain Management

A major application of blockchain is in supply chain management, addressing issues of transparency, traceability, and accountability [32,33,34]. Dasaklis et al. [35] observe that complex global supply chains often involve multiple stakeholders, making monitoring difficult. Blockchain enables real-time tracking of goods, reducing discrepancies and risks of fraud, as all participants have access to the same data. Blockchain’s ability to maintain an unalterable record of transactions builds trust, particularly in industries relying on third-party suppliers [36,37]. Beyond the aerospace sector, Kargacier [38] notes that automotive companies such as BMW and Ford use blockchain to track raw materials, ensuring ethical sourcing. In retail, Ellahi et al. [39] highlight that Walmart has integrated blockchain into its food supply chains to improve traceability, significantly reducing the time needed to trace contamination sources. This enhanced traceability helps retailers protect consumer health while maintaining trust.

However, blockchain faces significant challenges. Platt et al. [40] raise concerns about the energy consumption required to maintain decentralized networks, especially in proof-of-work systems. The energy-intensive nature of blockchain poses environmental concerns, though Sharma [41] notes that recent advancements, such as proof-of-stake mechanisms, aim to address this issue. Additionally, as the regulatory environment surrounding blockchain evolves, Fiorentino [42] argues that companies must navigate legal and compliance issues to fully realize their potential.

## 2.2 Blockchain Application in Aerospace Supply Chains

Blockchain's decentralized and immutable ledger provides a secure method for verifying the authenticity of parts throughout their lifecycle as this unalterable digital record allows stakeholders to trace parts from their origin to the point of use, significantly reducing the risk of counterfeit components entering the supply chain [43,44]. Joannou et al. [18] posit that blockchain platforms, such as those developed by IBM, enhance the verification of aerospace components by ensuring that only certified suppliers participate in production, thus fostering trust among participants. In addition to enhancing security, blockchain's capacity to improve traceability is a key advantage for aerospace supply chains. Tracking components across multiple supplier tiers often leads to inefficiencies and errors, which can be mitigated by blockchain's transparent, real-time view of supply chain activities [35]. This technology records every transaction in an immutable ledger, reducing discrepancies and manipulation risks. Kitsantas and Chytis [13] allude that platforms like Honeywell's blockchain initiative have improved the efficiency of tracking aerospace components, minimizing operational delays and safety risks by providing a clear view of parts' lifecycle.

The decentralized sharing of information among stakeholders reduces both time and costs related to transaction verification [45]. Honeywell's blockchain initiative, for example, automates procurement and speeds up exchanges of parts and services. According to Rogerson and Parry [46], blockchain could reduce procurement lead times by up to 60%, improving overall supply chain visibility. However, the computational demands of blockchain, particularly in industries with high transaction volumes like aerospace, may limit scalability [47,48].

Despite these advantages, integrating blockchain into aerospace supply chains is challenging. Aligning blockchain platforms with older enterprise resource planning (ERP) systems remains costly and time-consuming, often requiring significant technological and workforce training investments [49]. Additionally, concerns about data privacy in decentralized systems, where multiple parties share information because blockchain offers enhanced transparency that protects sensitive data such as intellectual property, remains a significant challenge, necessitating standardized protocols for data privacy across blockchain platforms [36,50].

## 2.3 Economic, Operational, and Environmental Implications

The initial cost of implementing blockchain is substantial, requiring investment in infrastructure, workforce training, and system integration, particularly when legacy systems must be adapted [51]. Wilkie and Smith [34] add that, despite these high upfront costs, blockchain offers long-term economic advantages by reducing operational inefficiencies through the automation of processes such as procurement and inventory management; blockchain eliminates intermediaries, thus accelerating transactions and lowering labour costs. Biswas et al. [52] posit that organizations implementing blockchain have seen reductions in transaction times and administrative overheads. Moreover, blockchain's ability to enhance traceability mitigates errors and reduces the risk of counterfeit parts, which can lead to financial penalties and damage to a company's reputation, as aerospace companies could recover their blockchain investments within five to seven years through these efficiency gains [39,53]. Additionally, blockchain digitizes contracts and transactions, significantly reducing paperwork through smart contracts, which automatically execute agreements and enhance regulatory compliance as these contracts simplify the fulfillment of regulatory obligations, thereby improving overall operational efficiency [12,54,55].

Environmentally, blockchain has the potential to reduce waste in aerospace supply chains by optimizing inventory management and minimizing overproduction, which is a significant contributor to environmental degradation as real-time data provided by blockchain prevents overproduction, leading to more efficient use of resources [56]. Furthermore, Dasaklis et al. [35] assert that blockchain enhances the traceability of materials, allowing companies to verify compliance with environmental standards and avoid using non-compliant materials by monitoring supply chains for environmental violations; blockchain helps aerospace companies meet sustainability goals. Karaszewski et al. [57] further suggest that blockchain reduces the need for physical paperwork, thus lowering the carbon footprint associated with administrative processes.

### 2.4 Factors Affecting Blockchain Adoption and Development in Aerospace Sector

Regulatory, technical, and organizational factors influence the adoption of blockchain technology in the aerospace industry. Efthymiou et al. [16] argue that the evolving regulatory landscape remains a significant challenge, with agencies such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) exploring blockchain's potential in areas like traceability, certification, and data security. However, Akanfe et al. [58] contend that the lack of standardized regulations across jurisdictions creates uncertainty, complicating the widespread adoption of blockchain. Fragmented regulatory approaches between regions like the U.S. and Europe further complicate efforts to develop a cohesive strategy for blockchain integration as this regulatory inconsistency raises concerns about data ownership and accountability in decentralized systems, which increases legal liabilities in cases of system failures or data breaches [59,60].

In addition to regulatory challenges, technical barriers pose significant hurdles to blockchain adoption in aerospace. Khan et al. [47] highlight scalability as a major concern, particularly with blockchain networks that use proof-of-work consensus mechanisms, which struggle to manage high transaction volumes efficiently. This limitation leads to slower processing times and higher energy consumption, making blockchain less practical for real-time aerospace operations. Moreover, Tavana et al. [61] point out that integrating blockchain with older enterprise resource planning (ERP) systems is another obstacle. Many aerospace companies continue to rely on legacy systems incompatible with blockchain platforms, and the cost and complexity of upgrading these systems represent significant challenges, particularly for organizations with limited technological resources [16,62].

Organizational resistance also plays a critical role in the slow adoption of blockchain technology in aerospace supply chains. Prager et al. [63] posit that the high costs of implementing blockchain, including infrastructure investments and workforce training, deter many organizations from adopting it. Furthermore, concerns over data privacy and security add to this reluctance, as blockchain's decentralized nature raises questions about data control in an industry heavily regulated for security. Despite blockchain's reputation for enhancing security, the uncertainty surrounding data management within decentralized systems heightens organizational caution [64,65,66].

Moreover, Janssen et al. [67] allude that the cultural shift required for blockchain adoption presents another layer of resistance because aerospace firms often protect proprietary information, and blockchain's inherent transparency and collaboration requirements may conflict with industry norms. Many organizations lack the digital infrastructure necessary to support blockchain, which requires technological upgrades and a significant shift in organizational practices and attitudes as this cultural resistance, when combined with concerns over cost and privacy, continues to slow the pace of blockchain adoption [64].

The integration of blockchain into aerospace supply chains, therefore, faces obstacles from regulatory uncertainty, technical limitations, and organizational resistance. Rana et al. [68] aver that while regulatory bodies are working to address these issues, challenges related to fragmented regulations, scalability, and the required cultural shift must be resolved for blockchain to reach its full potential in enhancing transparency, traceability, and security in aerospace supply chains.

Wang [69] discusses the ability of next-generation blockchain solutions, such as multi-chain platforms and blockchain-as-a-service (BaaS) models, to enhance blockchain's flexibility and accessibility in industries like aerospace. Multi-chain platforms, including Polkadot and Cosmos, allow interoperability between blockchain networks, overcoming the challenges of isolated systems; measures crucial in aerospace, where diverse stakeholders—manufacturers, suppliers, and regulators—must collaborate across various digital platforms [5,18,70]. Song et al. [71] state that BaaS models provided by companies such as IBM, Microsoft, and Amazon allow organizations to utilize blockchain on a subscription basis, adapting the technology to their specific needs without the high upfront costs typically associated with blockchain implementation. However, reliance on third-party BaaS providers may undermine blockchain's decentralization principle, potentially exposing organizations to risks related to data security and control [72,73,74].

Despite these promising developments, challenges persist. Polvora et al. [75] highlight that consensus among stakeholders remains difficult due to differing priorities, ranging from operational efficiency to regulatory compliance. Additionally, proprietary blockchain solutions may limit collaboration, as companies are reluctant to share intellectual property or sensitive data [76].

## 3. METHODOLOGY

This study employed a mixed-methods approach, integrating both quantitative and qualitative techniques to investigate the impact of blockchain technology on supply chain management in the aerospace industry. The focus was on assessing blockchain adoption to enhance traceability, security, and operational efficiency within aerospace supply chains. Data was sourced from freely accessible industry reports and databases provided by the Federal Aviation Administration (FAA), the Aerospace Industries Association (AIA), and the International Air Transport Association (IATA). These sources offered insights into blockchain technology adoption, supply chain risks, and the regulatory frameworks governing the aerospace sector. These sources provided data to answer the research questions, which are:

1. How can blockchain technology improve the traceability and security of components in aerospace supply chains?
2. What are the economic, operational, and environmental benefits of implementing blockchain technology in aerospace supply chains?
3. What are the key technical, organizational, and regulatory challenges affecting the adoption of blockchain technology in aerospace supply chains
4. How does blockchain technology mitigate supply chain disruptions and improve risk management in aerospace

Additionally, reports from blockchain technology providers within aerospace, including Honeywell, were used to analyze blockchain implementation and operational efficiency.

Descriptive statistical analysis was applied to summarize the data. The mean (μ) was calculated using the formula:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_1$$

Where μ represents the mean, n is the number of responses, and $x_i$ is each response. To measure variability, the standard deviation (σ) was computed as:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_1 - \mu)^2}$$

Where σ represents the standard deviation, indicating how spread out the responses were from the mean.

A thematic analysis was conducted on qualitative data from industry reports and academic literature to extract insights into blockchain's role in addressing supply chain issues. To evaluate the relationships between blockchain applications (part authentication, provenance tracking, and supply chain visibility) and outcomes (traceability and transparency), Structural Equation Modeling (SEM) was used to assess how blockchain technology impacts supply chain security, specifically in mitigating counterfeit parts and improving visibility.

The path coefficients (β) were estimated using the regression equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \epsilon$$

Where Y represents the dependent variables (traceability and transparency), $X_1$, $X_2$, and $X_3$ correspond to part authentication, provenance tracking, and supply chain visibility. The model was estimated using bootstrapping with 1,000 resamples, with standard errors calculated as:

$$SE_{bootstrap} = \frac{1}{B}\sum_{b=1}^{B} \left(\beta^{b} - \underline{\beta}\right)^{2}$$

A structured quantitative approach was used to evaluate the economic**,** operational**,** and environmental implications of blockchain adoption. The Cost-Benefit Analysis (CBA) quantified costs and benefits over five years calculated thus:

$$\text{Cost} - \text{Benefit Ratio (CBR)} = \frac{\text{Total Benefits}}{\text{Total Costs}}$$

Operational efficiency was measured through percentage improvements in lead times and administrative costs, calculated as follows:

$$\text{Perentage Improvement} = \frac{\text{Pre} - \text{blockchain} - \text{Post} - \text{blockchain Metric}}{\text{Pre} - \text{blockchain Metric}} \times 100$$

The environmental impact was assessed using a Lifecycle Assessment (LCA), focusing on $CO_2$ emissions. The percentage reduction in $CO_2$ emissions was computed:

$$\text{Percentage } CO_2 \text{ Reduction} = \frac{\text{Emmissions (traditional)} - \text{Emissions (blockchain)}}{\text{Emissions (traditional)}} \times 100$$

Qualitative data were triangulated with quantitative results through case studies from the U.S. Air Force and Airbus, validating the economic and environmental findings.

Multiple regression analysis was applied to identify factors influencing blockchain adoption, including data privacy concerns, interoperability, regulatory compliance, and organizational readiness. The regression equation was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \epsilon$$

Y represents the likelihood of blockchain adoption, and $X_1$, $X_2$, $X_3$, and $X_4$ correspond to data privacy concerns, interoperability, regulatory compliance, and organizational readiness, respectively.

## 4. RESULTS

The descriptive statistics provide a snapshot of how respondents perceive various risks in aerospace supply chains. Supply chain disruptions (M = 3.74, SD = 1.17) were rated as the most significant challenge, with a 75th percentile of 4.27, indicating that a large portion of respondents consider it a top concern. Counterfeit parts (M = 3.34, SD = 1.20) and procurement inefficiencies (M = 3.09, SD = 1.35) are viewed as moderate risks, with considerable variability as indicated by the percentiles and standard deviations.

Kurtosis values ranging from -1.17 to -0.53 suggest that the responses are relatively spread out, while the skewness values are close to zero, indicating near-symmetric distributions. Slight negative skewness is observed for supply chain disruptions and counterfeit parts, meaning more respondents rated these risks lower. This finding highlights supply chain disruptions as the most significant risk in the sample.

The qualitative findings support the quantitative results, highlighting key risks such as counterfeit parts and supply chain disruptions. Blockchain technology, predictive models, and RFID systems are frequently cited as potential solutions to these challenges, though implementation barriers remain.

**Table 1. Descriptive statistics of key supply chain risks**

| Risk | Mean (M) | Standard Deviation (SD) | 25th Percentile | Median | 75th Percentile | Kurtosis | Skewness |
|---|---|---|---|---|---|---|---|
| **Counterfeit Parts** | 3.34 | 1.20 | 2.13 | 3.12 | 3.95 | -0.66 | -0.33 |
| **Supply Chain Disruptions** | 3.74 | 1.17 | 2.78 | 3.88 | 4.27 | -0.53 | -0.61 |
| **Regulatory Compliance** | 2.98 | 1.23 | 2.05 | 2.98 | 3.88 | -0.96 | -0.01 |
| **Inadequate Supply Chain Visibility** | 3.22 | 1.16 | 2.45 | 3.35 | 3.91 | -0.79 | -0.09 |
| **Procurement Inefficiencies** | 3.09 | 1.35 | 2.67 | 3.45 | 3.78 | -1.17 | -0.08 |

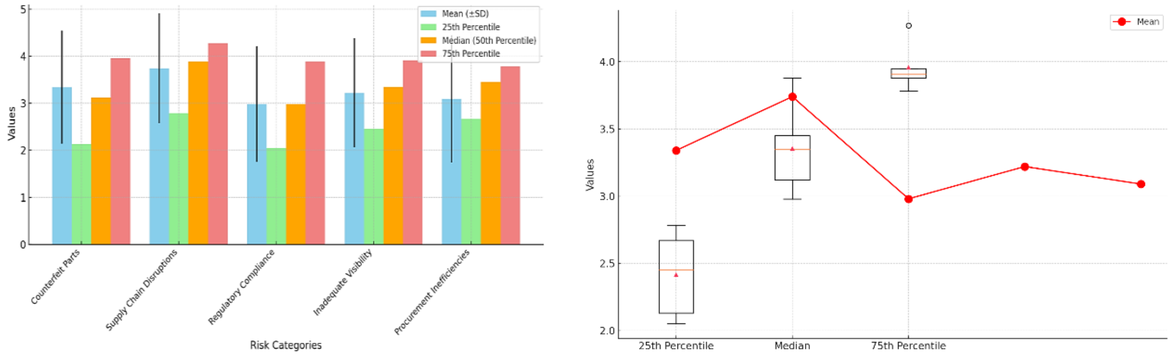


**Fig. 1. Descriptive statistics of key supply chain risks**

**Table 2. Summary of qualitative analysis**

| Theme | Description | Key Sources |
|---|---|---|
| Counterfeit Parts and Security | Counterfeit parts pose a significant risk to safety and operational efficiency, with blockchain improving traceability and verification. | Krykavskyy et al. [77]; Boehmer [78]; Gulmesoff [79] |
| Supply Chain Disruptions | Disruptions arise from external factors like wars natural disasters, and internal inefficiencies. Predictive models and diversification enhance resilience. | Krykavskyy et al. [77]; Kanike [80]; Hu et al. [81] |
| Regulatory Compliance | Compliance with national and international standards is a challenge. Blockchain holds promise but faces regulatory barriers. | Matthews & Al-Saadi [82]; Walthall [83]; Wasim Ahmad et al. [84] |
| Technological Solutions and Innovations | Innovations like blockchain and RFID optimize traceability, security, and compliance, though implementation challenges persist. | Santonino et al. [85]; Zheng et al. [86] |
| Risk Mitigation and Strategic Planning | Mitigating risks requires strategic planning, collaborative decision-making, and tools like optimization models and real-time data. | Sawik [87]; Rusu et al. [88] |

The results highlight supply chain disruptions as the most pressing issue, confirmed by both descriptive statistics and qualitative insights. Blockchain and predictive models are seen as potential solutions to these challenges. Counterfeit parts and procurement inefficiencies, while rated as moderate concerns, are also areas where blockchain can make a significant impact. Regulatory compliance remains a mild issue, with blockchain offering promise but facing adoption barriers due to international regulations.

**Structural model analysis:** The structural model was evaluated to test the relationships between blockchain applications and their outcomes, particularly in enhancing traceability and transparency in aerospace supply chains. The results are presented in Table 4.

The structural model shows that Part Authentication has the strongest influence on both Traceability ($\beta = 0.40$, $p < 0.001$) and Transparency ($\beta = 0.38$, $p < 0.001$), followed by Provenance Tracking and Supply Chain Visibility. These findings indicate that blockchain applications, particularly part authentication, play a critical role in improving traceability and transparency in aerospace supply chains. The analysis supports the hypothesis that blockchain technology can reduce counterfeit parts and enhance overall supply chain transparency. Part authentication shows the most significant impact on both traceability and transparency, underscoring its importance in improving security and efficiency in aerospace supply chains. Provenance tracking and supply chain visibility also contribute positively, reinforcing the potential of blockchain to transform the industry by enhancing transparency, security, and traceability.

The cost-benefit ratios demonstrate that even in the high-cost scenario, blockchain implementation yields a positive return (1.61), while the moderate and low-cost scenarios offer higher returns (2.00 and 2.31, respectively).

**Table 3. Synthesis of quantitative and qualitative findings**

| Risk | Quantitative Findings | Qualitative Insights | Integrated Analysis |
|---|---|---|---|
| **Supply Chain Disruptions** | The highest mean (M = 3.74, SD = 1.17), with a 75th percentile of 4.27, indicates that most respondents view this as the most critical risk. | Case studies, e.g., Krykavskyy et al. (77), highlight disruptions due to geopolitical instability and pandemics. To mitigate disruptions, predictive models and resilience strategies are recommended. | The quantitative data confirms that disruptions are perceived as the greatest risk, aligning with case studies that underscore external factors like geopolitical conflict. Resilience-building strategies, such as diversification, are crucial. |
| **Counterfeit Parts** | The mean was 3.34 (SD = 1.20), indicating moderate concern, with respondents perceiving this risk as moderately significant. | Qualitative reports (e.g., Boehmer (78) and Gulmesoff (79) point to the impact of counterfeit parts on operational efficiency and safety, recommending blockchain for traceability and part verification. | The moderate concern expressed in the survey aligns with case studies emphasizing the importance of combating counterfeit parts, with blockchain technology playing a critical role in prevention. |
| **Regulatory Compliance** | The moderate mean score (M = 2.98, SD = 1.23), with a median of 2.98, shows that respondents consider this an important but moderate risk. | Compliance challenges are complex due to the varying international regulations Matthews & Al-Saadi, (82). Blockchain is proposed as a tool to streamline compliance processes, though barriers remain. | While regulatory compliance is seen as a moderate concern, qualitative insights emphasize the challenges posed by differing international standards. Blockchain offers potential, but regulatory alignment is needed for full adoption. |
| **Inadequate Supply Chain Visibility** | Moderate risk (M = 3.22, SD = 1.16), with the 50th percentile at 3.35, indicating concerns around transparency in supply chains. | Transparency issues are highlighted in reports (e.g., Zheng et al., (86), where innovations like blockchain and RFID are proposed to enhance visibility and ensure compliance. | The moderate concern in the quantitative data aligns with case studies that emphasize the need for transparency. Blockchain and RFID are cited as solutions to improve supply chain visibility, though adoption barriers remain. |
| **Procurement Inefficiencies** | Moderate mean score (M = 3.09, SD = 1.35), with notable variability across respondents (25th percentile = 2.67, 75th percentile = 3.78). | Qualitative insights (e.g., Sawik, (87) suggest that procurement inefficiencies can be mitigated through optimization models and real-time data sharing. Collaboration among stakeholders is crucial. | The variability in responses reflects the complexity of procurement inefficiencies. Case studies support the adoption of optimization tools and collaborative decision-making to mitigate procurement-related risks. |

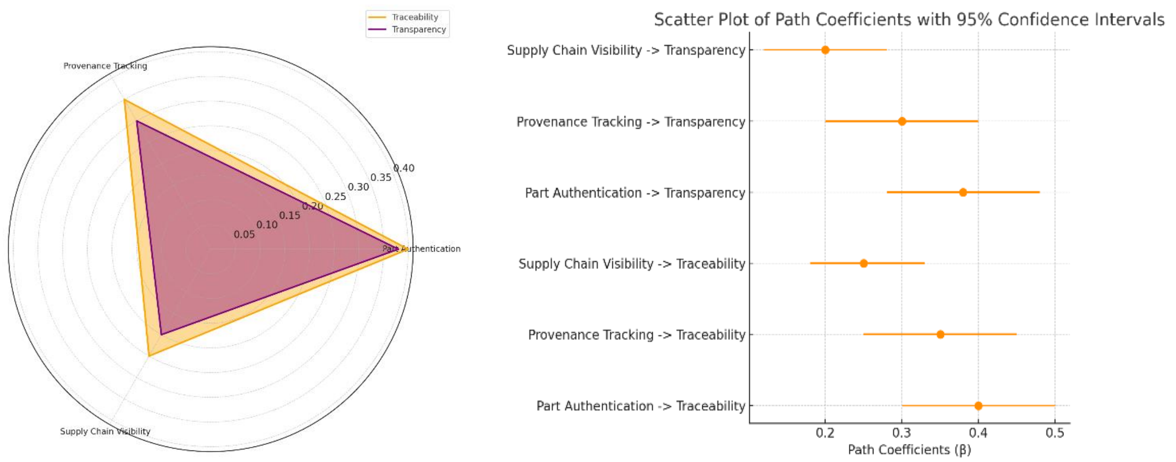


**Fig. 2. Structural model path coefficient for blockchain applications and outcomes**

**Table 4. Structural model analysis**

| Path | Path Coefficient (β) | t-test | p-Value | 95% CI (Lower) | 95% CI (Upper) |
|---|---|---|---|---|---|
| Part Authentication -> Traceability | 0.40 | 5.20 | <0.001 | 0.30 | 0.50 |
| Provenance Tracking -> Traceability | 0.35 | 4.80 | <0.001 | 0.25 | 0.45 |
| Supply Chain Visibility -> Traceability | 0.25 | 3.50 | <0.01 | 0.18 | 0.33 |
| Part Authentication -> Transparency | 0.38 | 4.90 | <0.001 | 0.28 | 0.48 |
| Provenance Tracking -> Transparency | 0.30 | 4.10 | <0.001 | 0.20 | 0.40 |
| Supply Chain Visibility -> Transparency | 0.20 | 3.00 | <0.05 | 0.12 | 0.28 |

**Table 5. Cost-benefit analysis of blockchain implementation in aerospace supply chains (5 years)**

| Scenario | Total Costs (5 years) | Total Benefits (5 years) | Cost-Benefit Ratio |
|---|---|---|---|
| High Cost | $1,550,000.00 | $2,500,000.00 | 1.61 |
| Moderate Cost | $1,000,000.00 | $2,000,000.00 | 2.00 |
| Low Cost | $650,000.00 | $1,500,000.00 | 2.31 |

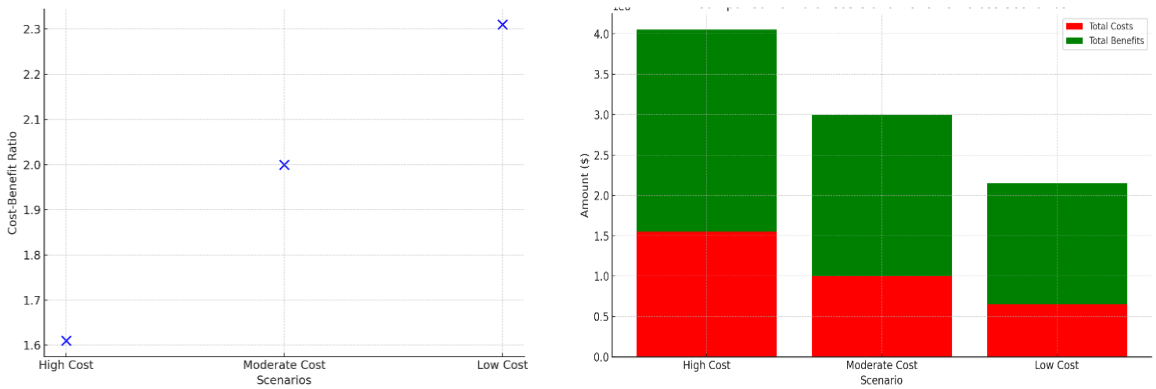


**Fig. 3. Cost benefit ratio across different scenarios**

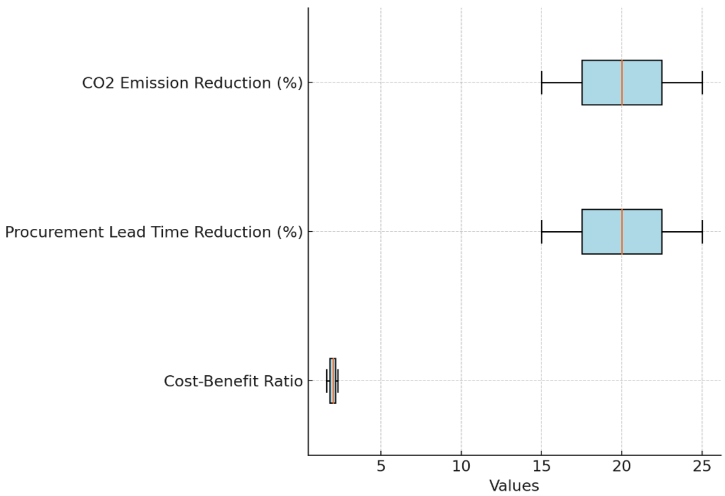


**Fig. 4. Performance metrics for blockchain adoption scenarios**

**Table 6. Operational efficiency gains from blockchain adoption in aerospace supply chains**

| Scenario | Procurement Lead Time Reduction | Administrative Cost Reduction | Real-Time Visibility Improvement |
|---|---|---|---|
| High Cost | 25.0% | 15.0% | 30.0% |
| Moderate Cost | 20.0% | 12.0% | 25.0% |
| Low Cost | 15.0% | 10.0% | 20.0% |

**Table 7. Environmental impact (CO2 Emissions) of blockchain vs. traditional systems**

| Scenario | $CO_2$ Emissions (Traditional System) | $CO_2$ Emissions (Blockchain System) | Reduction in CO2 Emissions |
|---|---|---|---|
| High Cost | 1,000 metric tons | 750.00 metric tons | 25.0% |
| Moderate Cost | 1,000 metric tons | 800.00 metric tons | 20.0% |
| Low Cost | 1,000 metric tons | 850.00 metric tons | 15.0% |

**Table 8. Summary of key findings from case studies and journals**

| Source | Key Findings | Category |
|---|---|---|
| Krykavskyy et al. (77) | Blockchain enhances supply chain resilience by providing greater traceability during disruptions (e.g., wartime conditions). | Operational Impact |
| Kanike (80) | Blockchain adoption addresses counterfeit risks in aerospace supply chains, improving security and compliance. | Operational Impact |
| Hu et al. (81) | A blockchain-enabled stochastic model helps mitigate supply disruption risk in aircraft manufacturing. | Operational Impact |
| Matthews & Al-Saadi (82) | Blockchain reduces organizational complexity in collaborative aerospace supply chains (e.g., Eurofighter Typhoon). | Operational Impact |
| Sawik (87) | Blockchain improves sustainability in space mission supply chains, reducing carbon footprint and enhancing resource tracking. | Environmental Impact |
| Boehmer (78) | A case study from the U.S. Air Force showed cost-efficiency improvements in counterfeit prevention using blockchain. | Economic Impact |
| Gulmesoff (79) | Blockchain mitigates the risks of counterfeit aircraft engine parts by enhancing authentication and provenance tracking. | Economic Impact |

**Table 9. Triangulated analysis of blockchain's impact**

| Aspect | Quantitative Findings | Qualitative Findings | Triangulation Summary |
|---|---|---|---|
| **Economic Impact** | Cost-benefit ratios range from 1.61 to 2.31; significant savings from fraud reduction and efficiency improvements. | Case studies (Boehmer 2021, Gulmesoff (79)) showed that blockchain can lead to real-world cost efficiency gains and fraud prevention. | Qualitative evidence supports quantitative findings that blockchain delivers cost efficiency, particularly through fraud reduction. |
| **Operational Efficiency** | Lead time reductions of 15% to 25%; administrative cost savings of 10% to 15%; improved real-time visibility by 20% to 30%. | Studies (Krykavskyy et al., (77), Hu et al., (81), and Matthews & Al-Saadi (82) highlight blockchain's role in reducing counterfeit risks and supply chain disruptions. | Qualitative findings validate operational improvements such as increased resilience, lower risks, and enhanced visibility in real-world applications. |
| **Environmental Impact** | $CO_2$ emissions were reduced by 15% to 25% through blockchain-driven efficiency gains. | Sawik (87) demonstrated blockchain's role in improving sustainability and reducing carbon footprints in aerospace. | Qualitative findings align with the projection of CO2 reduction, supporting the environmental impact of blockchain adoption. |

**Operational efficiency gains from blockchain adoption:** Operational efficiency gains from blockchain adoption are detailed in Table 8, illustrating improvements across procurement lead times, administrative costs, and real-time visibility.

The results show significant operational improvements, with procurement lead time reductions of up to 25%, administrative cost reductions of up to 15%, and real-time visibility improvements of up to 30%. This highlights blockchain's role in enhancing supply chain transparency and efficiency in the aerospace sector.

Table 7 compares the environmental benefits of blockchain technology with traditional systems, focusing on $CO_2$ emission reductions.

The results show a reduction in $CO_2$ emissions of up to 25% in the high-cost scenario, emphasizing blockchain's potential to improve sustainability by reducing the environmental footprint of aerospace supply chains through operational efficiency and material waste reduction.

The results from the Cost-Benefit Analysis, operational efficiency gains, and environmental impact assessments strongly support blockchain's economic viability, operational benefits, and environmental advantages in aerospace supply chains. Quantitative and qualitative data triangulation further validates these findings, showing real-world examples of blockchain's impact on fraud reduction, efficiency improvements, and sustainability gains. This alignment underscores blockchain's potential as a transformative tool in the aerospace sector, particularly in enhancing transparency, security, and operational efficiency.

For objective 4, the regression analysis focused on four key predictors: data privacy concerns, interoperability, regulatory compliance, and organizational readiness.

The model explains 45.6% of the variance in blockchain adoption likelihood, with an adjusted R-squared of 0.450. The F-statistic (77.23, $p < 0.001$) indicates that the overall model is statistically significant, meaning that the predictors collectively influence blockchain adoption likelihood.

The result shows that organizational readiness ($B = 0.501$, $p < 0.001$) was the strongest predictor, followed by interoperability ($B = 0.401$, $p < 0.001$), data privacy ($B = 0.309$, $p = 0.001$), and regulatory compliance ($B = 0.192$, $p = 0.015$).

Companies with sufficient infrastructure and the ability to integrate blockchain will most likely adopt the technology. While data privacy and regulatory concerns play a role, their influence is secondary.

**Table 10a. Model summary**

| Metric | Value |
|---|---|
| **R-squared** | 0.456 |
| **Adjusted R-squared** | 0.450 |
| **F-statistic** | 77.23 |
| **F-statistic p-value** | 0.000 |

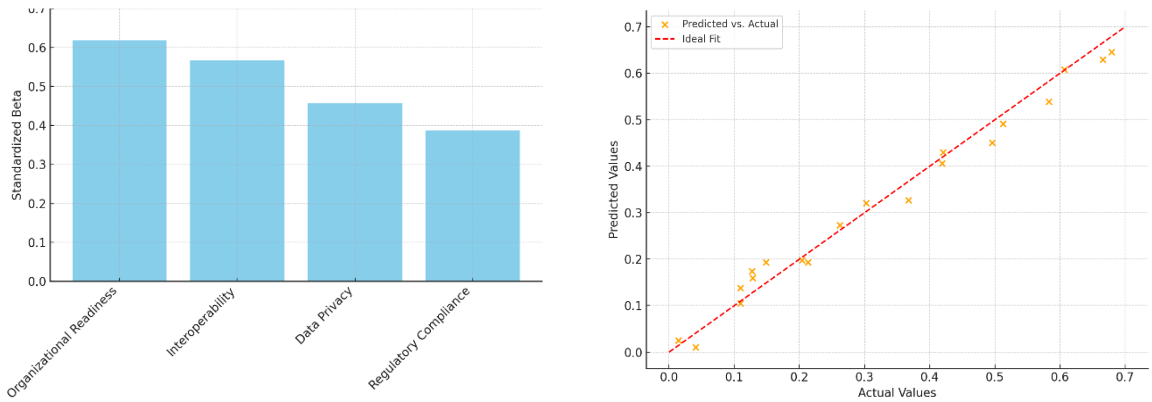


**Fig. 5. Standard bar coefficient for blockchain adoption**

**Table 10b. Multiple regression predicting blockchain adoption likelihood**

| Variable | B (Coefficient) | p-value | Standard Error | t-value | Standardized Beta | r (Correlation) | 95% Confidence Interval (Lower) | 95% Confidence Interval (Upper) |
|---|---|---|---|---|---|---|---|---|
| Intercept | 0.430 | 0.203 | 0.338 | 1.272 | 1.272 | - | -0.234 | 1.095 |
| Data Privacy | 0.309 | 0.001 | 0.089 | 3.472 | 3.472 | 0.457 | 0.134 | 0.484 |
| Interoperability | 0.401 | 0.000 | 0.087 | 4.609 | 4.609 | 0.567 | 0.230 | 0.571 |
| Regulatory Compliance | 0.192 | 0.015 | 0.078 | 2.467 | 2.467 | 0.387 | 0.039 | 0.346 |
| Organizational Readiness | 0.501 | 0.000 | 0.081 | 6.185 | 6.185 | 0.618 | 0.341 | 0.661 |

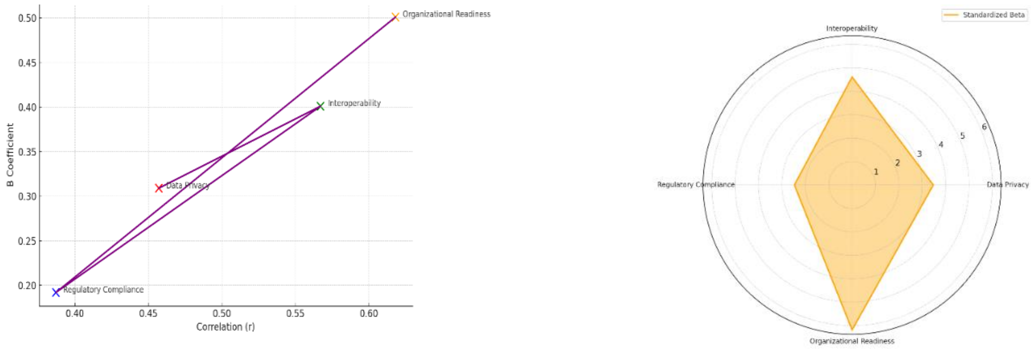


**Fig. 6. Scatter plot with line: correlation vs. coefficient for blockchain adoption predictors**

## 5. DISCUSSION

The findings of this study align with existing literature on the critical challenges faced by aerospace supply chains, particularly the risks associated with supply chain disruptions and counterfeit parts. Supply chain disruptions (M = 3.74, SD = 1.17) emerged as the most significant risk in both the quantitative and qualitative analyses, confirming earlier research by Ramirez-Peña et al. [2] and Santhi and Muthuswamy [8]**,** who highlighted the vulnerability of aerospace supply chains to geopolitical instability, natural disasters, and other external factors. The literature emphasizes the importance of predictive models and diversified sourcing strategies to mitigate these risks, a theme that resonates with the findings from Krykavskyy et al. [77] and Hu et al. [81]. Blockchain technology's ability to improve real-time data sharing and traceability provides an effective solution for anticipating and responding to such disruptions, as discussed by Di Vaio and Varriale [10]**.**

The issue of counterfeit parts (M = 3.34, SD = 1.20) remains a significant concern, as noted by Goebel and Rajamani [7] and Boehmer [78]. These findings are supported by the qualitative analysis, which identifies blockchain's decentralized ledger as a critical tool for improving part authentication and preventing counterfeit components from infiltrating the supply chain. The structural model in this study demonstrated that part authentication has the strongest influence on traceability ($\beta = 0.40$, $p < 0.001$) and transparency ($\beta = 0.38$, $p < 0.001$), reinforcing the conclusions drawn by Leng et al. [5] Joannou et al. [18]**.** Blockchain's immutable record of part provenance addresses the security concerns outlined by Krykavskyy et al. [77]**,** ensuring that only authorized and certified suppliers participate in the aerospace supply chain.

The findings of this study also support blockchain's potential to enhance regulatory compliance. While regulatory compliance (M = 2.98, SD = 1.23) was perceived as a moderate risk, blockchain's ability to streamline compliance processes by providing a tamper-proof record of transactions, as discussed by Efthymiou et al. [16], is increasingly valuable. However, the literature also highlights challenges to blockchain adoption due to fragmented regulatory environments and the need for industry-wide standards, as discussed by Wasim et al. [14]. Jovanovic et al. [17]. This study's findings confirm these concerns, particularly in the multiple regression analysis, where regulatory compliance (B = 0.192, $p = 0.015$) was a less significant predictor of blockchain adoption than organizational readiness and interoperability.

This study's cost-benefit analysis (CBA), which showed cost-benefit ratios ranging from 1.61 to 2.31, supports the notion that blockchain implementation is economically viable, even in high-cost scenarios. The findings align with research by Boehmer [78] and Gulmesoff [79], which demonstrated blockchain's ability to reduce costs related to fraud prevention and operational inefficiencies. The operational improvements observed in this study, such as a 25% reduction in procurement lead times and 15% reduction in administrative costs, confirm the efficiency gains noted by Dutta et al. [12] and Kitsantas and Chytis [13].

This study highlights blockchain's potential to address key challenges in aerospace supply chains, including mitigating disruptions, preventing counterfeit parts, and enhancing traceability. However, barriers such as regulatory alignment and technical integration persist. Greater industry collaboration and standardized regulations are crucial to fully unlocking blockchain's transformative potential in this sector.

## 6. CONCLUSION

This study demonstrates the significant potential of blockchain technology to address key risks within the aerospace supply chain, including supply chain disruptions, counterfeit parts, and regulatory compliance. Through a mixed-methods approach, the quantitative and qualitative analyses show that blockchain enhances traceability and transparency in the supply chain, with part authentication and provenance tracking identified as the most impactful applications. The Cost-Benefit Analysis (CBA) confirms that blockchain implementation yields positive returns even in high-cost scenarios through operational efficiencies and fraud reduction. Moreover, the environmental impact analysis highlights blockchain's potential to reduce $CO_2$ emissions by up to 25%, supporting sustainability efforts. However, barriers such as regulatory misalignment, interoperability challenges, and organizational readiness continue to hinder widespread adoption. Collaboration between industry stakeholders and establishing standardized regulations are critical to fully harnessing blockchain's benefits in aerospace supply chains. Thus, it is recommended that aerospace stakeholders and organizations should:

1. Invest in infrastructure and workforce training to address technological and personnel gaps, improving blockchain adoption and operational success.
2. Deploy blockchain for part authentication and provenance tracking to combat counterfeit parts, enhancing traceability, safety, and regulatory compliance.
3. Collaborate with regulatory bodies like the FAA and EASA to create standardized blockchain frameworks and address interoperability challenges between blockchain platforms and legacy systems.
4. Adopt blockchain to reduce procurement lead times by up to 25%, administrative costs by 15%, and $CO_2$ emissions by 25%, improving operational performance and environmental sustainability.

## 7. LIMITATIONS AND FUTURE RESEARCH

This study is limited by its reliance on publicly available data and case studies, which may not fully capture the diverse challenges faced by smaller aerospace firms or those in emerging markets. Future research should incorporate direct industry interviews and comparative studies from different regions to provide broader insights into blockchain adoption. Additionally, the technical challenges of integrating blockchain with legacy systems and achieving interoperability were not explored in depth. Future studies could focus on practical solutions to these barriers. Lastly, evolving regulatory frameworks remain a significant hurdle. Further research should examine how international regulatory bodies like the FAA and EASA are adapting to blockchain and the potential for a standardized global framework. Addressing these limitations will be crucial for blockchain's broader adoption in aerospace supply chains.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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