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RISK ANALYSIS OF BLOCKCHAIN TECHNOLOGY IN CROSS-BORDER E-COMMERCE DRUG TRACEABILITY USING ANALYTIC HIERARCHY PROCESS

(*Analisis Risiko Teknologi Blok Rantai dalam Pengesanan Ubatan E-Dagang Rentas Sempadan Menggunakan Proses Hierarki Analitik*)

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ABSTRACT

As blockchain technology develops, it is crucial to create a cross-border e-commerce traceability method for imported pharmaceuticals in response to consumer demand for the safety and reliability of medical items. This method promotes the adoption of blockchain technology in the field of traceability as well as the development of a new cross-border e-commerce model for imported pharmaceuticals. However, there are still some technical difficulties and dangers associated with using blockchain in traceability methods. Based on the Analytic Hierarchy Process (AHP), the dangers associated with using blockchain technology for cross-border e-commerce medical traceability were examined in this study. The results show that the difficulty of system integration, the consequences of data breaches, mix-boundary data transfer regulations, market acceptance, and operating costs have the most important impact on the application of blockchain technology in the traceability of pharmaceuticals in cross-border e-commerce within their risk categories.

Keywords: blockchain; drug traceability; AHP method; risk analysis

ABSTRAK

Seiring dengan perkembangan teknologi blok rantai (*blockchain*), adalah penting untuk mewujudkan satu kaedah pengesanan e-dagang rentas sempadan bagi ubat-ubatan yang diimport bagi memenuhi permintaan pengguna terhadap keselamatan dan kebolehpercayaan produk perubatan. Kaedah ini bukan sahaja menggalakkan penggunaan teknologi blok rantai dalam bidang pengesanan, malah menyumbang kepada pembangunan model baharu e-dagang rentas sempadan untuk ubat-ubatan yang diimport. Walau bagaimanapun, masih terdapat beberapa kesukaran teknikal dan risiko dalam menggunakan teknologi blok rantai bagi kaedah pengesanan. Berdasarkan kaedah Proses Hierarki Analitik (AHP), kajian ini menilai risiko yang berkaitan dengan penggunaan teknologi blok rantai bagi pengesanan ubat-ubatan dalam e-dagang rentas sempadan. Hasil kajian menunjukkan bahawa kesukaran dalam integrasi sistem, akibat daripada kebocoran data, peraturan pemindahan data rentas sempadan yang kompleks, penerimaan pasaran, dan kos operasi adalah faktor risiko utama yang memberi kesan ketara terhadap aplikasi teknologi blok rantai dalam pengesanan ubat-ubatan e-dagang rentas sempadan.

Kata kunci: blok rantai; pengesanan ubat; kaedah AHP; analisis risiko

1. Introduction

Blockchain has attracted a lot of attention in a variety of industries since its establishment as the basic technology for Bitcoin (Nakamoto 2008). In recent years, the application of blockchain technology has expanded beyond economic services to contain consumer and industrial materials, communications, transportation, healthcare, and open services (Deloitte 2019). In terms of market share, blockchain technology has increased by 17.6 % in manufacturing and circulation, by 14.6 % in services, and by 4.2 % in the public sector, according to Deloitte's 2019 Global Blockchain Survey (Deloitte 2019). Despite more people using blockchain, the tech is still in its early stages of development and facing many obstacles to widespread adoption (Pilkington 2016; Tapscott & Tapscott 2016).

There are some restrictions on blockchain growth. Governance mechanisms and legal frameworks are however evolving in the technology (Yli-Huumo *et al.* 2016; Iansiti & Lakhani 2017). However, the implementation of blockchain introduces numerous social risks, such as data security, privacy concerns, and the difficulty of structure integration (Zheng *et al.* 2017; Kshetri 2017). traditional risk control approaches can address some of these issues, but they frequently fail to address blockchain's special challenges (Beck *et al.* 2017; Christidis & Devetsikiotis 2016).

Blockchain technology has been recognized for its potential to enhance transparency, security, and decentralization in supply chains (Tian 2016). However, its adoption in cross-border pharmaceutical traceability remains limited due to several challenges, including regulatory uncertainty, interoperability constraints, and security risks (Zheng *et al.* 2017; Kshetri 2017).While previous studies have examined blockchain's role in general supply chains (Wang *et al.* 2021), ESG frameworks (Gong *et al.* 2024), and green building assessments (Dhingra 2024), research on its application in cross-border pharmaceutical e-commerce and the associated risks remain scarce. Most existing studies primarily focus on the technical feasibility of blockchain but do not provide a comprehensive risk assessment framework that addresses the unique challenges of pharmaceutical trade across international borders.

In order to address this gap, this study attempts to answer the question: What are the primary risks of blockchain adoption in cross-border pharmaceutical e-commerce traceability, and how can the risks be assessed in a systematic way using a structured decision-making framework?

To answer this question, the Analytic Hierarchy Process (AHP) is employed in this research to identify and rank critical risk factors. This process provides quantitative answers that can help policymakers, supply chain managers, and pharmaceutical stakeholders to develop efficient risk mitigation strategies. To evaluate complex systems like blockchain-based drug traceability.

This study employs the AHP to evaluate the risks of blockchain technology in cross-border e-commerce drug traceability systematically, integrating it with quality measurement and decision analysis. By integrating expert judgment and quantitative analysis, this study develops a systematic risk ranking model that enhances quality management and decision-making in blockchain-based pharmaceutical traceability. Compared to traditional qualitative analysis, this study makes it possible to use AHP to build a data-driven quality measurement model, making blockchain risk analysis objective and quantifiable. The proposed risk assessment model is a decision support system for policymakers and pharmaceutical supply chain managers, enabling them to simplify quality control measures in blockchain-enabled drug traceability systems and ensure the successful implementation of blockchain technology.

The remainder of this paper is structured as follows: Section 2 is the literature review of the application of blockchain technology to supply chains and risk assessment models. Section 3 is a research methodology, with the description of how the AHP model was constructed. Section 4 is the results and discussion, with a focus on ranking of risk factors and implications. Section 5 is the conclusions and policy implications.

2. Literature Review

Existing blockchain risk analysis research generally has some limitations. Most of the literature tends to address individual perspectives, e.g., data security or compliance with regulations, without taking into account the wider spectrum of risks (Casino, Dasaklis, and Patsakis 2019; Li *et al.* 2020). For instance, from a data security perspective, Li *et al.* (2020) highlighted the vulnerabilities in blockchain systems. They consist of consensus protocol weaknesses and potential smart contract exploitation. Reyna *et al.* (2018) presented blockchain integration challenges with the Internet of Things (IoT), specifically data privacy, network latency, and energy consumption.

For regulatory compliance, Hughes *et al.* (2019) discussed the difficulty of using blockchain in cross-border transactions due to the variations in legal and regulatory frameworks across countries. Such variations make it difficult to implement blockchain-based traceability systems across borders. Iansiti and Lakhani (2017) also clarified that for large-scale adoption of blockchain, a consistent and clear legal framework must be established to guarantee the functionality and security of the technology.

The use of blockchain continues to be a significant issue in terms of economic utility. Despite the fact that blockchain has the potential to increase supply chain efficiency (Saberi *et al.* 2019). Glaser (2017) states that many small and medium-sized businesses (SMEs) are hesitant to adopt the technology due to its high initial costs. Additionally, Tapscott and Tapscott (2016) noted that the separation of blockchain raises operating expenses, particularly when it comes to system liberty and maintenance.

Even more problems arise as a result of blockchain's professional integration with existing systems. Xu *et al.* (2016) emphasized the difficulty of integrating blockchain with the country's most novel supply chain techniques as a form of modern connectivity. Critical is interoperability of data models and construction interoperability. To analyze blockchain and IoT connections. Christidis and Devetsikiotis (2016) studied blockchain integration with IoT. Freedom and security issues persist, due to them, even though smart contracts have probable advantages for technology and transparency.

Blockchain-related research is also improving in terms of network security and privacy security. Kshetri (2017) emphasized the value of Bitcoin in improving network security and privacy, notably by enhancing transparency and reducing information interference. Mougayar (2016) suggested that blockchain does help reduce data breach risks by reducing the need for next-party providers.

Lu *et al.* (2024) examined the probable uses of blockchain techniques in combined-border drug traceability and proposed conditions. Rathore and Gupta (2022) developed a framework that combines the Fuzzy Analytic Hierarchy Process (FAHP) with preference ranking to assess safety risks in Indian hospitals during the pandemic. Liu *et al.* (2024) revisited the impact of perceived satisfaction on consumer attitudes and impulse purchases, laying a foundation for understanding how consumers accept and utilize blockchain technology. Yu (2022) analyzed the opportunities and challenges of cross-border e-commerce using Social, Legal, Economic, Political, and Technological Analysis, providing crucial insights into blockchain's role in this context.

In the pharmaceutical supply chain context, several recent reports have highlighted blockchain's ability and difficulties. Akram *et al.* (2024) reviewed blockchain applications for pharmaceutical supply chain management, emphasizing its effectiveness in increasing finish-to-end tracking, protecting the supply chain against counterfeit products, and increasing transparency throughout the product lifecycle. In addition, Ahmed and MacCarthy (2023) developed an evidence-based framework to assess the appropriate breadth and depth of blockchain-enabled traceability systems. They identified key elements that affect blockchain adoption across supply chains, such as regulatory requirements and product quality considerations (Ahmed & MacCarthy 2023). In addition, Vu *et al.* (2025) provided quantitative evidence from the food industry on how blockchain application impacts supply chain performance, exhibiting gains in operational efficiency, inventory management, and cost reduction while also advising against challenges related to over-efficiency of safety stocks.

Blockchain also has the potential to foster the development of decentralized service systems, driving innovation across related sectors (Seebacher & Schüritz 2017). This decentralized characteristic makes blockchain widely applicable in supply chain management, IoT, smart contracts, and other areas (Zhang & Wen 2017). Coyne and McMickle (2017) examined whether blockchain could serve accounting purposes, concluding that its transparency and immutability could effectively enhance the reliability of financial records.

Zhou *et al.* (2023) conducted an evolutionary game analysis on blockchain technology adoption in cross-border e-commerce, proposing a strategic framework for stakeholders involved in its adoption. Teng (2021) meanwhile, discussed blockchain's trustworthiness within virtual organizations from a normative perspective, emphasizing its potential to enhance supply chain transparency. Furthermore, Zamani *et al.* (2020) analyzed blockchain's security risks, noting that while it offers long-term cost-saving potential, issues like high installation costs, energy consumption, and slow processing speeds remain significant concerns.

Wenhua et al. (2023) explored blockchain usage in healthcare and identified the security threats at the data, network, consensus, and incentive levels that are of the utmost significance to the security of the technology. Ali *et al.* (2020) conducted a systematic review of blockchain usage in the financial sector, its advantages, and security threats as a financial tool. Abbasi *et al.* (2019) explored credit risk assessment in IoT-based supply chain finance, focusing on the potential of blockchain to enhance transparency in supply chain finance.

Ahmadi *et al.* (2020) analyzed the advantages of blockchain-based IoT technology in the pharmaceutical supply chain, demonstrating that blockchain provides a novel framework for pharmaceutical traceability solutions. Similarly, Botcha *et al.* (2019) proposed a blockchain-integrated IoT model where IoT devices collect critical data from different pharmaceutical supply chain stages, and the data is stored on the blockchain in an immutable ledger format, ensuring transparent supervision of all stakeholders.

To enhance supply chain efficiency and monitoring, Grest *et al.* (2019) developed a blockchain-based supply chain traceability meta-model that integrates various supply chain systems into a unified platform, effectively addressing the lack of timely information sharing between different supply chain participants. Kumar and Tripathi (2019) further proposed a secure pharmaceutical supply chain system combining blockchain with QR code technology, significantly improving data security against tampering and cyberattacks. These studies highlight blockchain's growing role in enhancing drug traceability, improving data security, and ensuring real-time visibility in pharmaceutical logistics.

Overall, existing research shows that blockchain has significant advantages in improving transparency, security, and decentralization in supply chains. It also faces several technical and expert difficulties, though. There are still a dozen studies on the use of blockchain for supply chain history, particularly in cross-border digital commerce drug traceability. In place of the current research area, this research seeks to adequately assess the risks associated with applying blockchain technology for cross-border online banking drug traceability.

3. Materials and Methods

3.1. *Research design*

The dangers associated with the use of blockchain technology in cross-border electronic health tracking products are examined in this study using AHP. To evaluate the relative importance of several risk factors, survey data, and the AHP strategy were combined using a mixed-methods method. The research primarily relies on the Technology Acceptance Model (TAM), which establishes a hierarchy of risks and evaluates decision-weight information, using the TAM model and expert opinions.

Data on perceived threats associated with blockchain in the clinical monitoring field was gathered through the "perceived option" part of the study. The final analysis and comparison of the perceived danger components were done using AHP. To determine the respondents' understanding of the numerous issues in this method, a comprehensive method was used. As a result, we identified the high-risk groups in blockchain-based health documents that require prioritization.

3.2. *Data collection and survey design*

A questionnaire was utilized in this research to capture the user belief about blockchain technology in pharmaceutical traceability. In order to ensure that the survey was representative and comprehensive, we invited cross-border e-commerce, pharmaceutical supply chain, and blockchain technology experts to complete the survey. The survey was divided into two sections: the first section collected demographic and professional background information, and the second section collected perceived usefulness, perceived ease of use, trust, perceived risk, and external environmental factors in the adoption of blockchain. A five-point Likert scale ranging from "strongly disagree" to "strongly agree" was utilized.

150 questionnaires were collected, covering the pharmaceutical sector, cross-border e-commerce websites, logistic companies, and customs companies. An online survey was conducted, where regional factors were also considered to ascertain the influence of the use of blockchain on the cross-border traceability of drugs.

Apart from the survey, the study employed the AHP to measure the relative importance of blockchain-related risks. Three experts with great experience in pharmaceutical logistics, blockchain systems, and cross-border trade regulation were selected for the AHP study. The number of experts is not large, yet as seen in previous studies, it has been proven to produce consistent and significant results in organized decision-making studies (Okoli & Pawlowski 2004; Hallowell & Gambatese 2009).

In AHP research, Saaty (1980) emphasized that expert judgment consistency is more important than sample size. Given that the Consistency Ratio (CR) should be less than or equal to 0.1, even a small panel of experts can produce strong and stable results (Saaty 1980). Furthermore, existing literature indicates that 3–10-member expert panels are sufficient to achieve stable rankings of decision factors, particularly in specialized fields (Rowe & Wright 1999). Accordingly, in the present study, caution was exercised to select experts based on relevant industry experience and consistency of judgments, to enable prioritization of blockchain-related risks in pharma traceability in a structured and accurate way.

3.3. *AHP model*

The several risk factors that were associated with the use of blockchain in cross-border online business drug traceability were evaluated in the AHP type. By separating the imperative component, five needs layers, and seventeen sub-criterion layers into a planned model, Then, a judgment matrix was constructed. Next, the relative weights of the criteria and sub-criteria were calculated. After that, the consistency of the judgment matrix was checked. Finally, the overall risk weights and priorities were determined. Figure 1 shows the process flow.

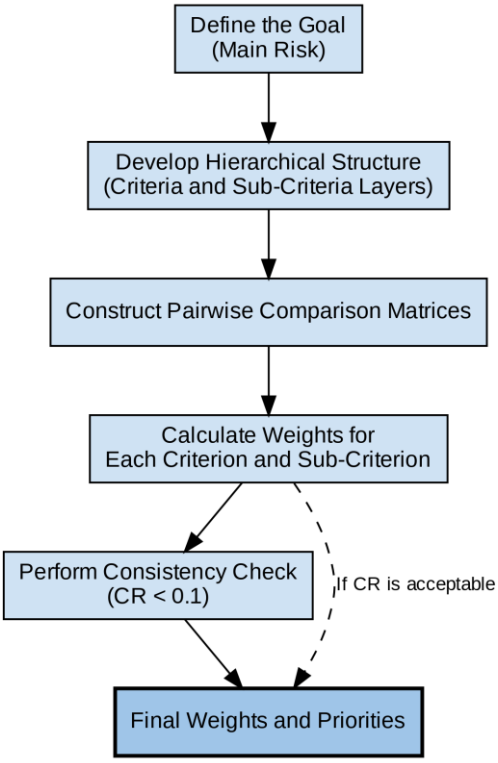

Figure 1: AHP process flowchart

3.3.1. *Hierarchical structure development*

The risk assessment program for the use of blockchain in cross-border e-commerce for drug traceability is broken down into five specific amounts and five condition sections, each with 18 sub-criterion, according to the rules of accuracy, success, systematic approach, and buy. The study design program that was modified for this study is relatively included and divided using the sign parts. In terms of drug traceability, Goal Layer A emphasizes the main risk factors for cross-border e-commerce using blockchain technology. The criteria layers B are divided into five categories: technical and operational risks, security and privacy risks, legal and regulatory risks, economic and financial risks, and supply chain and logistics risks. The sub-criteria C includes 18 indicator factors: scalability issues, maintenance and upgrade requirements, complexity of system integration, technical support and services, consequences of data breaches, risks of malicious attacks, technical requirements for regulatory compliance, user identity management and verification, cross-border data transfer regulations, legal status of smart contracts, international trade agreements, uncertainty of return on investment, market acceptance, initial investment, complexity of cross-border supply chains, standardization issues, and operational costs, as seen in Table 1.

Table 1: Risk evaluation index system for the use of blockchain in cross-border e-commerce drug traceability

Goal Layer	Criteria Layer	Sub-Criteria
Priority of the Main Risk Factors in the Application of Blockchain for Drug Traceability in Cross-Border E-Commerce (A)	Technical and Operational Risks (B1)	Scalability Issues (C1)
		Maintenance and Upgrade Requirements (C2)
		Complexity of System Integration (C3)
		Technical Support and Services (C4)
	Security and Privacy Risks (B2)	Consequences of Data Breaches (C5)
		Risks of Malicious Attacks (C6)
		Technical Requirements for Regulatory Compliance (C7)
		User Identity Management and Verification (C8)
	Legal and Regulatory Risks (B3)	Cross-Border Data Transfer Regulations (C9)
		Legal Status of Smart Contracts (C10)
		International Trade Agreements (C11)
	Economic and Financial Risks (B4)	Uncertainty of Return on Investment (C12)
		Market Acceptance (C13)
		Initial Investment (C14)
	Supply Chain and Logistics Risks (B5)	Complexity of the Cross-Border Supply Chain (C15)
		Standardization Issues (C16)
		Operational Costs (C17)

3.4.1. *Construction of judgment matrix A*

In AHP, the information on the weight of indicators is obtained by comparing indicators in the established hierarchical model by decision-makers and assigning relative importance, that is, the weight of the indicators. To better evaluate decision-making weight information, this study employs a relative scale (1 to 5) and its reciprocals to display judgments. A ratio scale table is shown in Table 2, where scale values are obtained by pairwise comparisons of related factors at the same level. This paper invited three industry experts to determine the importance of each indicator relative to the others through a questionnaire survey (Appendix A), thus constructing the judgment matrices, as shown in Tables 3, 4, 5, 6, 7, and 8.

The elements a_{ij} of the judgment matrix A possess the following properties:

$a_{ij} > 0$, reciprocal matrix,

where $a_{ji} = 1/a_{ij}$. The scale of the judgment matrix elements a_{ij} is shown in Table 2.

Table 2: Ratio scale table

Scale	Meaning
1	Indicates equal importance of both elements
2	Indicates *i* is slightly more important than *j*
3	Indicates *i* is clearly more important than *j*
4	Indicates *i* is strongly more important than *j*
5	Indicates *i* is extremely more important than *j*

Table 3: Judgment matrix for goal layer A

	Technical and Operational Risk	Security and Privacy Risk	Legal and Regulatory Risk	Economic and Financial Risk	Supply Chain and Logistics Risk
Technical and Operational Risk	1.000	2.622	3.635	3.303	5.000
Security and Privacy Risk	0.381	1.000	3.000	2.000	4.309
Legal and Regulatory Risk	0.275	0.333	1.000	0.382	5.000
Economic and Financial Risk	0.303	0.500	2.621	1.000	3.302
Supply Chain and Logistics Risk	0.200	0.232	0.200	0.303	1.000

Table 4: Judgment matrix for criteria layer B1

	Scalability Issues	Maintenance and Upgrade Requirements	Complexity of System Integration	Technical Support and Services
Scalability Issues	1.000	0.500	0.255	0.303
Maintenance and Upgrade Requirements	2.000	1.000	0.232	0.382
Complexity of System Integration	3.915	4.309	1.000	2.621
Technical Support and Services	3.302	2.621	0.382	1.000

Table 5: Judgment matrix for criteria layer B2

	Consequences of Data Breach	Risk of Malicious Attacks	Technical Requirements for Regulatory Compliance	User Identity Management and Verification
Consequences of Data Breach	1.000	2.290	5.000	3.634
Risk of Malicious Attacks	0.437	1.000	3.302	2.289
Technical Requirements for Regulatory Compliance	0.200	0.303	1.000	0.382
User Identity Management and Verification	0.275	0.437	2.621	1.000

Table 6: Judgment matrix for criteria layer B3

	Cross-Border Data Transfer Regulations	Legal Status of Smart Contracts	International Trade Agreements
Cross-Border Data Transfer Regulations	1.000	2.289	2.885
Legal Status of Smart Contracts	0.437	1.000	2.000
International Trade Agreements	0.347	0.500	1.000

Table 7: Judgment matrix for criteria layer B4

	Uncertainty of Return on Investment	Market Acceptance	Initial Investment
Uncertainty of Return on Investment	1.000	0.303	0.500
Market Acceptance	3.302	1.000	2.289
Initial Investment	2.000	0.437	1.000

Table 8: Judgment matrix for criteria layer B5

	Complexity of Cross-Border Supply Chains	Standardization Issues	Operating Costs
Complexity of Cross-Border Supply Chains	1.000	2.885	0.437
Standardization Issues	0.347	1.000	0.275
Operating Costs	2.289	3.634	1.000

3.4.2. *Calculation of indicator weights*

After organizing the scoring results of each expert, the weight values for each indicator are calculated using the AHP. The calculation is performed according to the following steps (taking the calculation process for criteria layer indicators as an example):

(1) "A" is a 5th order matrix.

$$A=(a_{ij})=\begin{bmatrix} 1 & 2.622 & 3.635 & 3.303 & 5.000 \\ 0.381 & 1 & 3.000 & 2.000 & 4.309 \\ 0.275 & 0.333 & 1 & 0.382 & 5.000 \\ 0.303 & 0.500 & 2.621 & 1 & 3.302 \\ 0.200 & 0.232 & 0.200 & 0.303 & 1 \end{bmatrix} \tag{1}$$

Normalize matrix 'A' by columns:

$$\overline{b}_{ij}=\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{2}$$

$$B=(b_{ij})=\begin{bmatrix} 0.463 & 0.559 & 0.348 & 0.473 & 0.269 \\ 0.177 & 0.213 & 0.287 & 0.286 & 0.232 \\ 0.127 & 0.071 & 0.096 & 0.055 & 0.269 \\ 0.140 & 0.107 & 0.251 & 0.143 & 0.177 \\ 0.093 & 0.050 & 0.019 & 0.043 & 0.054 \end{bmatrix} \tag{3}$$

(2) Calculate the average weight, $\overline{w_i}$

$$\overline{w_i}=\sum_{j=1}^{n}\overline{b_{ij}}=\begin{bmatrix} 2.112 \\ 1.195 \\ 0.617 \\ 0.818 \\ 0.258 \end{bmatrix} \tag{4}$$

(3) Normalize to obtain w_i

$$w_i=\frac{\overline{w_i}}{\sum_{i=1}^{n}\overline{w_i}}=\begin{bmatrix} 0.422 \\ 0.239 \\ 0.123 \\ 0.164 \\ 0.052 \end{bmatrix} \tag{5}$$

(4) Calculate the maximum eigenvalue

$$\lambda_{max}=\sum_{i=1}^{n}\frac{\sum_{j=1}^{n}a_{ij}w_j}{nw_i}=5.365 \tag{6}$$

(5) Calculate the Consistency Index, CI

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{7}$$

(6) Calculate the Consistency Ratio, CR

$$CR=\frac{CI}{RI}=0.081 \tag{8}$$

In the above formula, RI is the given Random Consistency Index, as shown in Table 9.

Table 9: Random Consistency Index (*RI*) Table

n order	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Under normal circumstances, the smaller the *CR* value, the better the consistency of the judgment matrix. Generally, if the *CR* value is less than 0.1, then the judgment matrix is considered to have passed the consistency test. If the *CR* value is greater than 0.1, it indicates inconsistency, and the judgment matrix should be appropriately adjusted before re-analysis. In this case, for the 5th order judgment matrix, the calculated *CI* value is 0.091, and referring to the *RI* value from the table as 1.12, the *CR* value is therefore calculated to be $0.081<0.1$. This means that the judgment matrix of this study satisfies the consistency check, and the calculated weights are consistent.

4. Results and Discussion

Based on the AHP model, the results of this study prioritize the key risk factors associated with the application of blockchain technology for drug traceability in cross-border e-commerce, highlighting the relative importance of different categories of risks and providing insights into key areas that require attention for effective implementation. The assigned weights for each criterion were validated through consistency checks to ensure the reliability of the assessments.

4.1. *Results*

The results indicate that among the five-criteria layer indicators, technical and operational risks have the highest weight at 42.23%, followed by security and privacy risks (23.89%), economic and financial risks (16.36%), legal and regulatory risks (12.35%), and supply chain and logistics risks (5.17%). Thus, it can be concluded that among the main risk factors in the application of blockchain for drug traceability in cross-border e-commerce, technical and operational risks have the highest priority, followed by security and privacy risks, economic and financial risks, and legal and regulatory risks, with supply chain and logistics risks having the lowest priority. Figure 2 below illustrates the priority of these key risk factors.

Technical and operational risks consist of four sub-criteria, with the complexity of system integration having the highest weight at 50.95%, followed by technical support and services (26.77%), maintenance and upgrade requirements (13.18%), and scalability issues (9.10%). This indicates that within technical and operational risks, the complexity of system integration, as well as technical support and services, significantly impact the successful implementation of blockchain.

Security and privacy risks include four sub-criteria, with the consequences of data breaches having the highest weight at 50.20%, followed by risks of malicious attacks (26.68%), user identity management and verification (15.23%), and technical requirements for regulatory compliance (7.90%). This indicates that within security and privacy risks, the consequences of data breaches and the risk of malicious attacks have a significant impact.

Legal and regulatory risks comprise three sub-criteria, with cross-border data transfer regulations having the highest weight at 55.16%, followed by the legal status of smart contracts (28.29%) and international trade agreements (16.55%). This suggests that within legal and regulatory risks, the impact of cross-border data transfer regulations is the greatest.

Economic and financial risks include three sub-criteria, with market acceptance having the highest weight at 56.76%, followed by initial investment (27.75%) and uncertainty of return on investment (15.49%). This indicates that within economic and financial risks, the impact of market acceptance is the greatest.

Supply chain and logistics risks consist of three sub-criteria, with operating costs having the highest weight at 56.57%, followed by the complexity of cross-border supply chains (30.47%) and standardization issues (12.97%). This indicates that within supply chain and logistics risks, operating costs have the most significant impact. Table 10 below provides a detailed breakdown of the weights for each criterion and sub-criterion.

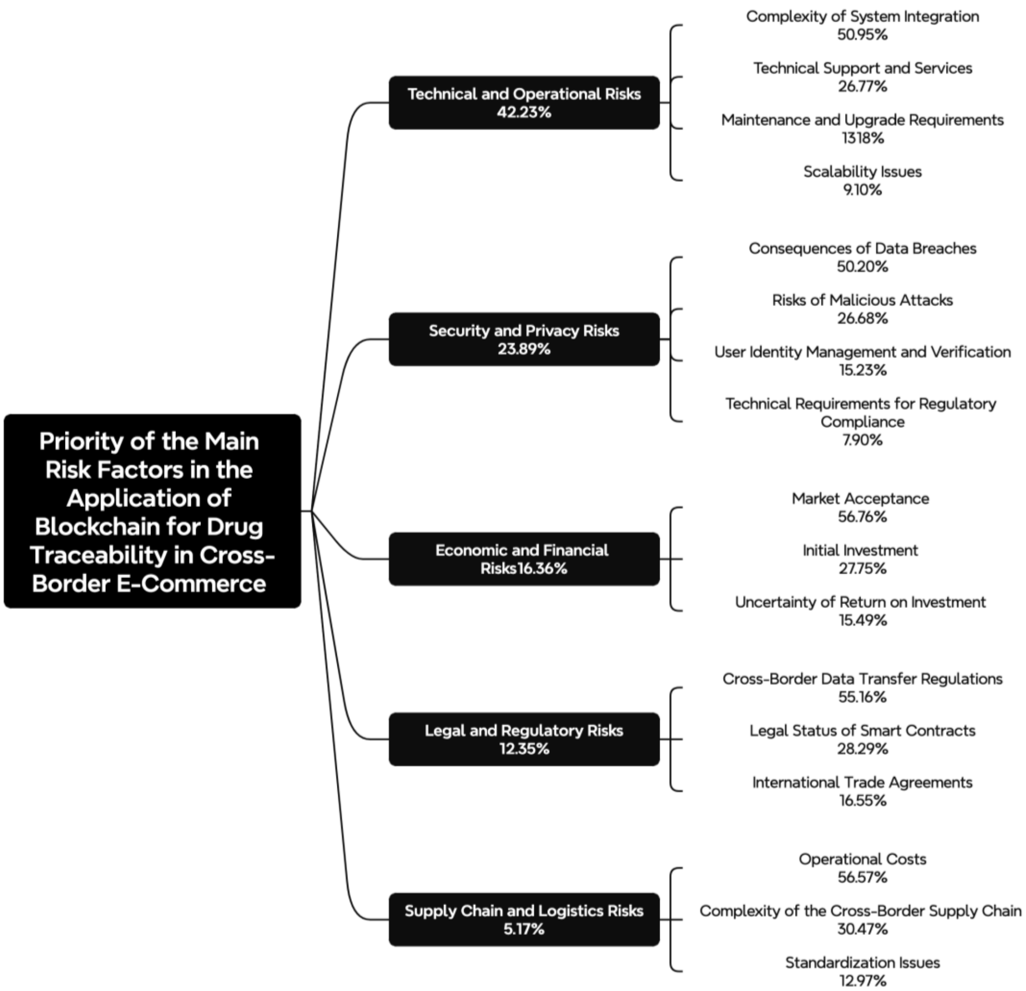

Figure 2: AHP analysis Application of blockchain for pharmaceutical traceability in cross-border e-commerce major risk factors

All judgment matrices constructed during the AHP process underwent rigorous consistency checks, with results indicating that all consistency ratios (*CR*) were below 0.1, thereby confirming the reliability of expert evaluations. Table 11 summarizes the consistency check results for each judgment matrix.

Table 10: Evaluation indicator weights.

Goal Layer	Criteria Layer	Weight	Sub-criteria	Weight	Composite Weight
The priority of the main risk factors in the application of blockchain for drug traceability in cross-border e-commerce.	Technical and Operational Risks	42.23%	Scalability Issues	9.10%	3.84%
			Maintenance and Upgrade Requirements	13.18%	5.57%
			Complexity of System Integration	50.95%	21.52%
			Technical Support and Services	26.77%	11.30%
	Security and Privacy Risks	23.89%	Consequences of Data Breaches	50.20%	11.99%
			Risks of Malicious Attacks	26.68%	6.37%
			Technical Requirements for Regulatory Compliance	7.90%	1.89%
			User Identity Management and Verification	15.23%	3.64%
	Legal and Regulatory Risks	12.35%	Cross-Border Data Transfer Regulations	55.16%	6.81%
			Legal Status of Smart Contracts	28.29%	3.49%
			International Trade Agreements	16.55%	2.04%
	Economic and Financial Risks	16.36%	Uncertainty of Return on Investment	15.49%	2.54%
			Market Acceptance	56.76%	9.29%
			Initial Investment	27.75%	4.54%
	Supply Chain and Logistics Risks	5.17%	Complexity of the Cross-Border Supply Chain	30.47%	1.57%
			Standardization Issues	12.97%	0.67%
			Operational Costs	56.57%	2.92%

Table 11: Summary of one-time test results

Empirical Number	Maximum Eigenvalue	CI	RI	CR	Consistency Test Result
1	5.365	0.091	1.12	0.081	PASS
2	4.107	0.036	0.89	0.04	PASS
3	4.069	0.023	0.89	0.026	PASS
4	3.024	0.012	0.52	0.023	PASS
5	3.012	0.006	0.52	0.012	PASS
6	3.04	0.02	0.52	0.038	PASS

Overall, complex and operational risks, as well as security and privacy risks, are the main obstructions to the use of blockchain technology for cross-border drug traceability. The two main issues that require immediate attention are the difficulty of joining applications and the effects of information vulnerabilities. While the global aspects of supply chain and logistics threaten less imminent, it is no less important to focus on controlling costs in operations while regulating business practices across the entire supply chain. With these analytical problems in mind, the stakeholders can make intelligent decisions regarding which are actually preventing blockchain death. It did help with the growth and dissemination of technology.

5. Discussion

The findings emphasize the imperatives of technical and operational risks and security and privacy concerns in blockchain implementation for cross-border pharmaceutical traceability. The stakeholders face severe limitations in aligning their systems with blockchain technologies, particularly technical interfacing and operational adaptation. Meeting these requires specific investments in professional competencies and designing ordered blockchain adoption strategies for hedging against operational risks.

In relation to security and privacy risks, the paper highlights data vulnerabilities and adversarial attacks as pertinent issues despite the inherent security aspects of blockchain. Parties are able to circumvent the application of blockchain in the event comprehensive cybersecurity frameworks are not available in terms of risks related to data infringement and illegal access. The findings indicate the necessity of setting blanket cybersecurity frameworks and industry-wide blockchain security laws with an aim to instill confidence in blockchain-enabled traceability systems.

Economic and financial factors, also, have an important role to play in the adoption of blockchain. Market acceptance is identified by the research as a factor for the success of blockchain—if the value of blockchain is not firmly felt, stakeholders will not be incentivized to invest. It is thus important to prove the quantifiable advantages of blockchain technology, e.g., transparency of the supply chain, efficiency, and assurance of pharmaceutical safety.

Moreover, legal and regulatory risks pose major challenges, especially with respect to cross-border data transfer legislation. The lack of harmonized regulatory regimes across borders poses a challenge to the implementation of blockchain. This necessitates international regulatory harmonization and open legal frameworks to facilitate easy implementation of blockchain-based tracking systems.

While supply chain and logistics risk was found to be less significant compared to other categories of risk, operational cost is a problem of significant impact. Seamless integration of blockchain requires more refined logistics protocols and industry-standardized guidelines, in particular for small and medium-sized enterprises (SMEs) which may view blockchain adoption as a costly undertaking.

This study informs decision optimization and quality measurement in blockchain-based supply chain management. The AHP model, as constructed, presents a replicable and unbiased way of risk evaluation that aligns with prevailing quality control systems in pharmaceutical traceability. These conclusions equip stakeholders with data-driven and quality-driven solutions to blockchain integration in cross-border pharmaceutical supply chains.

6. Conclusion

Effective use of blockchain technology for cross-border pharmaceutical traceability must overcome a number of critical challenges. They are technical integration, data protection, regulatory adherence, market acceptance, and cost reduction. These are the factors determining the success of blockchain deployment in pharmaceutical supply chains. By acknowledging and mitigating these risks, stakeholders can take concrete measures to facilitate blockchain deployment, thus improving supply chain security, efficiency, and transparency.

Using the AHP, this study conducted a systematic analysis of the risks involved in the adoption of blockchain in cross-border pharmaceutical e-commerce. Technical and operational risks, namely system integration and technological adaptability, are among the most critical issues. Security and privacy risks such as data vulnerability and cyber threats are still important issues that call for strict protective measures. Economically and financially, blockchain adoption is not only dependent on technology feasibility but also on market acceptability and regulatory compatibility across borders for effective and sustainable implementation. While supply chain and logistics risks were found to be of lower importance, operational efficiency and cost-effectiveness remain the secret to long-term sustainability.

The findings of the research in this work highlight the potential of blockchain in ensuring supply chain security, transparency, and quality control in pharmaceutical traceability. The AHP-based risk assessment model introduced in this work provides a structured and quantitative method for evaluating blockchain-related risks. This work adds to research in quality measurement and decision sciences by introducing a structured method for determining and ranking significant risk factors. Actionable suggestions have also been introduced in this research for supply chain managers, policymakers, and industry stakeholders to enable informed decisions on the adoption of blockchain in pharmaceutical traceability systems.

By using principles of quality measurement in blockchain risk analysis, the research helps create data-driven answers to improve pharmaceutical supply chain security, efficiency, and regulatory adherence. Future research can explore advanced risk analysis models such as predictive modeling and real-time data analysis to further improve blockchain-based risk management in pharmaceutical traceability.

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