Smart Contracts Management: The Interplay of Data Privacy and Blockchain for Secure and Efficient Real Estate Transactions

Abstract

The digital transformation of the real estate industry is being significantly influenced by blockchain technology and smart contracts, which promise enhanced efficiency, transparency, and security in transactions. This study aims to develop a secure and efficient smart contract management protocol that balances the benefits of blockchain with robust data privacy practices. The methodology involves descriptive analytics of transaction data from the Ethereum blockchain, feasibility studies using synthetic transaction data, and a regulatory compliance analysis to map the impact of different regions' regulations on blockchain adoption in real estate. The findings reveal that while smart contracts can automate various processes and reduce reliance on intermediaries, challenges related to data privacy and regulatory compliance persist. Higher privacy features in smart contracts are associated with increased execution costs, indicating a trade-off between privacy and cost efficiency. The integration of permissioned blockchains and zero-knowledge proofs offers a promising pathway to address these challenges. However, the complexity of these techniques requires specialized knowledge, limiting broader adoption. The study concludes with recommendations to develop specialized training programs, collaborate on regulatory frameworks, invest in advanced cryptographic research, and implement targeted strategies to overcome adoption barriers. These efforts will contribute to the digital transformation of asset management, fostering innovation and enhancing the overall efficiency of real estate transactions.

Keywords: **Blockchain technology, Smart contracts, Data privacy, Real estate transactions, Zero-knowledge proofs**

1.Introduction

As digitalization intensifies, influencing the modus operandi of every sector and facet of human endeavor, the real estate industry is also experiencing a significant shift towards automation and decentralization, driven by technological advancements [1].
Traditionally, real estate transactions have involved extensive paperwork and a complex

web of intermediaries, including lawyers, brokers, and escrow agents, leading to delays, high transaction costs, and security concerns due to the reliance on paper-based documentation. However, the emergence of blockchain technology and the development of smart contracts are setting the stage for a transformative change by streamlining and securing real estate transactions.

Blockchain technology offers a decentralized ledger system where transactions are immutable, transparent, and verifiable by all participants, which can significantly reduce the need for traditional intermediaries, thereby potentially lowering costs and increasing transaction speed [2]. Smart contracts, which are self-executing agreements stored on a blockchain, are able to automate various processes, from the execution of lease agreements to the transfer of property titles, enhancing efficiency and fostering trust between involved parties [3]. By providing a secure and transparent distributed ledger, blockchain creates an immutable record of ownership changes and transaction details, enhancing security by eliminating the possibility of tampering with records. Furthermore, smart contracts can automate predefined actions based on specific conditions, such as triggering the release of funds upon successful property transfer. This streamlines the process, reduces human error, and fosters trust between buyers and sellers.

However, a crucial issue inthe adoption of blockchain technology in real estate is data privacy. The immutable nature of blockchain means that once information is encoded, it is permanently visible to all parties, which could include sensitive personal data. Public blockchains, while offering transparency, expose all transaction details to everyone on the network, raising concerns about the visibility of sensitive information such as owner identities, financial details, and property specifics [4]. Public disclosure of this information can lead to security risks like identity theft and fraud. It may also violate data privacy regulations like the General Data Protection Regulation (GDPR) in the European Union [5]. However, Khan et al. [6] argue that permissioned blockchains restrict the parties who can participate in the network, providing a controlled environment that can be regulatory compliant and more secure. Thus, this paperoffers practical recommendations to ensure a secure and efficient smart contract management system that balances the benefits of blockchain with robust data privacy practices, exploring the use of permissioned blockchains and hashing functions, which offer a framework for maintaining privacy and control over who accesses the data on the blockchain.

Companies like Propy utilize permissioned blockchains to ensure that only relevant parties can view specific data [7]. Furthermore, techniques like hashing store unique identifiers for ownership information instead of the actual sensitive details on the blockchain, as exemplified by Estonia's Land Registry [8]. This hybrid model showcases a transparent ownership change while keeping sensitive property details confidential. Despite these advancements, several issues require further investigation, such as balancing transparency and privacy. This research also explores how zero-knowledge proofs (ZKPs), a technology that allows one party to prove to another that a specific statement is true without revealing any additional information, can be harnessed to achieve a secure and transparent system without compromising data privacy.

Research Objectives:

1. Identify and evaluate current solutions used in permissioned blockchains, hashing functions, and other methods to ensure data privacy while maintaining the integrity of real estate transactions on a blockchain ledger.
2. Explore the feasibility and potential of integrating zero-knowledge proofs into smart contracts for real estate.
3. Examine existing and emerging regulations around blockchain technology and data privacy, particularly those impacting real estate transactions.
4. Analyze how the adoption of smart contracts might affect the roles of lawyers, brokers, and other intermediaries in real estate transactions.

2. Literature Review

According to Spielman [1], the real estate sector is experiencing tremendous changes due to the incorporation of blockchain technology and smart contracts; these shifts promise to enhance the efficiency, transparency, and security of real estate transactions. Through the digitization of records on a decentralized ledger, blockchain technologies provide a secure and immutable record of property ownership, which streamlines transactions and significantly reduces the reliance on traditional intermediaries such as brokers, lawyers, and escrow agents [2][11]. Zhang et al. [9] assert that this reduction can lead to lower transaction costs and faster transaction processes, benefiting all parties involved.

However, Sedlmeir et al. [4] argue that the transition to blockchain in real estate also comes with challenges, particularly in the area of data privacy, and though public blockchains practice transparency to promote accountability and trust, they also expose sensitive transaction details such as financial data and owner identities to the public, and this could potentially lead to privacy violations and security issues like identity theft or fraud [10][13][14]. Additionally, Yeoh et al. [12] affirm the exposure risks contravening stringent data protection regulations like the GDPR, which mandates the confidentiality and protection of personal data.

To mitigate this situation, this research proposes the development of a smart contract management protocol tailored for real estate transactions, aiming to balance blockchain's benefits with robust data privacy measures. This protocol explores the use of permissioned blockchains, which limit network access to authorized participants only, thereby enhancing privacy and regulatory compliance [15][16]. Furthermore, advanced cryptographic solutions like zero-knowledge proofs are considered, which allow the verification of compliance without exposing underlying personal data, addressing both privacy concerns and computational challenges [17][18][19].

Several studies are being conducted about emerging technologies and their integration into smart contracts to ensure these tools not only comply with regulatory frameworks but also safeguard sensitive information while maintaining the efficiency of blockchain systems [20][21][22]. This comprehensive approach also examines the socio-economic implications of traditional real estate roles. It suggests that blockchain could transform these professions, encouraging them to adapt to functions that emphasize regulatory compliance and technological management, thus fostering innovation within the industry.

Existing Solutions for Data Privacy in Blockchain-based Real Estate:

Akanfe et al. [15] state that as blockchain-based real estate transactions evolve, permissioned blockchains will play an essential role in enhancing data privacy and maintaining the integrity of records [27]. These systems techniques, such as encryption, access control mechanisms, attribute-based encryption (ABE), ring signatures, homomorphic encryption, and stealth addresses,restrict access to verified and authorized participants, thereby creating a controlled environment that aligns with GDPR compliance needs [23][24]. Access control mechanisms and attribute-based encryption enhance granularity in data privacy; this controlled access not only enhances privacy and security but also preserves the decentralized ethos of blockchain to a certain extent, although it sometimes introduces the risk of centralized control, which could lead to potential vulnerabilities [25][26]. Access control can be role-based or attribute-based, providing access based on predefined roles or specific attributes such as property ownership. ABE takes this further by encrypting data with specific attributes, allowing only users with matching keys to decrypt and access the data, thus offering fine-grained control over data privacy [28][29][30][31].

Zhang [28] asserts that the structure of permissioned blockchains is critical for ensuring that sensitive information, such as financial details and personal identifiers, is safeguarded from public exposureand that the centralized or consortium-based governance models within these blockchains play a significant role in how effectively these networks can manage privacy and consensus among stakeholders [32][33][34]. Moreover, Li et al. [35] affirm that hashing functions provide another layer of security by transforming sensitive data into non-invertible hash outputs, ensuring data privacy and the immutability of records; this is crucial in scenarios requiring data integrity verification without revealing the underlying sensitive data.

However, Langaliya and Gohil [29] propose that the use of permissioned blockchains and hashing functions also presents challenges because the scalability and flexibility of these systems often come into question when compared to public blockchains.

Additionally, the security of hashing functions heavily relies on the robustness of cryptographic algorithms and the security of key management practices, as weak algorithms or compromised keys can undermine the privacy protections these functions are supposed to provide [36][37].

Studies are exploring hybrid models that combine the strengths of permissioned blockchains with advanced cryptographic techniques, such as multi-party computation (MPC) because they could offer more robust solutions. MPC allows multiple parties to compute a function without revealing their inputs, enhancing privacy in real estate transactions by verifying crucial details without exposing the data [38][39][40].

The Potential of Zero-Knowledge Proofs for Smart Contract Management:

According to Chainlink [41], Zero-Knowledge Proofs (ZKPs) have emerged as a significant cryptographic innovation, particularly advantageous in real estate smart contracts on blockchain platforms. ZKPs enable a party, known as the prover, to verify the truth of a statement to another party, the verifier, without disclosing any underlying details. For example, in real estate transactions, a buyer could validate their financial solvency to a seller without revealing specific financial details such as bank balances or account numbers [42][43].

Amin Almaiah et al. [44] further state that the application of ZKPs in smart contracts can greatly enhance privacy and security, enabling the verification of critical transactional elements—like ownership or financial capability—without compromising sensitive personal information. This capability doesn’t just maintain privacy, but it also minimizes the risk of fraud and bolsters trust among transaction parties [13][18][45]. However, Aslam et al. [46] argue that the integration of ZKPs within smart contracts also presents challenges, primarily due to their computational intensity. This complexity can result in slower transaction processing times and cause scalability issues, which are significant considerations in high-stakes environments such as real estate transactions. It should be noted that the sophisticated nature of creating and managing ZKPs requires specialized knowledge, potentially limiting broader adoption without significant educational and technological advancements [47][48][49].Despite these challenges, several studies affirm the potential of ZKPs to transform smart contract management in real estate is substantial, as they offer a pathway towards more secure, private, and efficient transactions, which aligns well with the digitalization of the real estate sector and the increasing demand for enhanced data security[18][50][51][52].

Regulatory Landscape and Smart Contracts in Real Estate:

According to Treleaven et al. [53], the General Data Protection Regulation (GDPR) significantly impacts how real estate transactions via blockchain can be conducted, particularly due to its strict requirements on data privacy, consent, and the right to rectification and erasure. These elements are challenging to reconcile with the immutable nature of blockchain technology, and innovative solutions, such as the use of zero-knowledge proofs, are being explored to address these discrepancies by allowing data privacy without altering the blockchain's integrity [54][55][64].

Moreover, Moreno et al. [56] highlight the importance of regulations such as Know Your Customer (KYC) and Anti-Money Laundering (AML) in the financial aspects of real estate transactions; these regulations necessitate thorough identity checks and continuous monitoring to prevent illicit activities. Douglas et al. [57] opine that blockchain implementations must integrate mechanisms that can address these requirements within their decentralized frameworks, adding layers of complexity to the technology's application in legally sensitive environments.

Drummer and Neumann [58] state that another major challenge is the legal status and enforceability of smart contracts; for smart contracts to be recognized as legally binding, they must fulfill traditional contract elements like offer, acceptance, consideration, and mutual intent. This varies by jurisdiction and is further complicated by the digital nature of blockchain [59][60]. Also, trading tokenized real estate on secondary markets requires adherence to securities regulations, which are often stringent and vary widely between jurisdictions. Ensuring compliance with these regulations is essential for the legitimacy and fluid operation of blockchain in real estate [61][62].

According to Baron et al. [63], though it is important to have a solid regulatory framework that checks every activity in the real estate blockchain, it is more crucial that there is a collaborative effort among industry leaders, policymakers, and legal experts so as to develop protocols that balance innovation with compliance, ensuring the responsible adoption of smart contracts in the real estate sector.

The Impact of Smart Contracts on Traditional Intermediaries:

As we all know, technology is revolutionizing everyone’s role; this is the same in the real estate space, where the integration of smart contracts in real estate is significantly reshaping the roles of traditional intermediaries such as lawyers, brokers, and escrow agents. Smart contracts automate many tasks that were traditionally handled manually, potentially reducing the need for these intermediaries while also offering new opportunities for their roles to evolve [10][65][66][67]. Maldonado [68] avers that for lawyers, the focus may shift from routine document verification to ensuring smart contracts comply with legal standards and managing complex legal issues that arise, particularly in dispute resolution and intellectual property rights[68][69].

Iswuser [65] states that brokers might see a transformation in their roles from transaction facilitators to advisors specializing in market analysis and property valuation; this change is driven by smart contracts facilitating direct interactions between buyers and sellers, thus diminishing the traditional brokerage role in transactions. However, their understanding of market dynamics and client advisory will continue to be invaluable [70][71].Kovalenko [66] asserts that escrow agents could experience a decrease in traditional responsibilities as smart contracts automate fund and document holding during transactions. In view of all this, Xu [72] concludes that human involvement cannot be overlooked in this case because there remains a critical need for supervision in complex or disputed cases, highlighting the ongoing requirement for human judgment in real estate transactions [66][73].

3. Methods

To identify and evaluate current solutions used in permissioned blockchains and hashing functions, transaction data was extracted from the Ethereum blockchain via Etherscan (https://etherscan.io/). This process involved collecting transaction hashes, block details, and smart contract interactions specifically related to real estate transactions. Descriptive analytics were applied to compare the implementation of privacy and integrity mechanisms across different smart contracts. Different metrics (contract complexity, execution costs, and privacy features) were analyzed using statistical measures like mean, standard deviation, and variance. The comparative evaluation used the formula:

$$Comparative\ Score = \frac{\sum(Feature_i * Weight_i)}{n}$$

Where $Feature_i$ represents each feature (complexity, cost, privacy), $Weight_i$is the assigned importance of each feature, and n is the total number of features.

A smart contract model incorporating zero-knowledge proofs was developed using the Solidity programming language and deployed on the Ganache local blockchain simulator via the Truffle Suite. The performance and privacy preservation of these transactions were observed, assessing operational feasibility, computational costs, and achieved privacy levels. The assessment involved the following formulas:

$$Feasibility\ Score = \frac{Successful\ Transaction}{Total\ Transaction}$$

$$Cost\ Efficiency = \frac{Total\ Cost}{Number\ of\ Transaction}$$

$$Privacy\ Score = \frac{Number\ of\ Privacy - Compliant\ Transaction}{Total\ Transaction}$$

$$Computational\ Cost = \frac{\sum(Exection\ Cost\ Per\ Transaction)}{Number\ of\ Transaction}$$

$$Throughput = \frac{Total\,Transactions}{Total\,Time}$$

Examining existing and emerging regulations around blockchain technology and data privacy leveraged publicly available documents from the Legal Information Institute (https://www.law.cornell.edu/). Content analysis was systematically applied to these legal documents to extract relevant information on regulations affecting real estate transactions. This analysis mapped out the impact of different regions' regulations on blockchain adoption in real estate, identifying trends and gaps. The compliance impact was quantified using this formula:

$$Regulatory\ Impact\ Score = \frac{\sum(compliance_i * Weight_i)}{n}$$

Where $compliance_i$represents each regulatory factor, $Weight_i$is the assigned importance of each factor, and n is the total number of factors.

A survey was distributed via SurveyMonkey to 412 real estate professionals, including brokers and lawyers, to assess how smart contracts might alter their roles. Statistical analysis revealed significant trends, with findings detailed in a report that included regression models. The regression model is presented thus:

$$Preceived\ Impact\ Score = \beta_0 + \beta_1(\text{Years of Experience}) + \beta_2(\text{Training Received}) + \epsilon$$

$$Confidence\ Level = \beta_0 + \beta_1(\text{Years of Experience}) + \beta_2(\text{Training Received}) + \epsilon$$

Where $\beta_0$is the intercept, β_1 and $\beta_2$are the coefficients for years of experience and training received, respectively, and ϵ is the error term.

Sentiment analysis of open-ended survey responses used natural language processing to categorize opinions on smart contracts as positive, negative, or neutral.The analysis used the sentiment polarity formula:

$$Sentiment\ Score = \frac{\sum(Sentiment_i)}{n}$$

Where $Sentiment_i$represents the sentiment score of each response, with positive scores indicating positive sentiment, negative scores indicating negative sentiment, and neutral scores indicating no strong sentiment either way.

A comparative analysis evaluated smart contracts versus traditional methods in real estate transactions, analyzing survey data on transaction time, costs, security, and transparency using means and standard deviations.Normal distribution curves were used to represent the standard deviations for each criterion, calculated as follows:

$$f(x|\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\alpha^2}}$$

where μ is the mean, σ is the standard deviation, and xis the variable of interest.

Finally, the readiness for future adoption of smart contracts was assessed using survey data on professionals' readiness scores, perceived barriers, and suggested steps for adoption. It is calculated thus:

$$Readiness\ Score = \frac{\sum(Readiness_i)}{n}$$

Where $Readiness_i$ represents individual readiness scores and n represent the total population. These findings highlight the importance of targeted strategies and training programs to enhance adoption readiness, aligning with the study's aim of promoting innovative, secure, and efficient transaction systems in real estate.

4. Results and Discussion

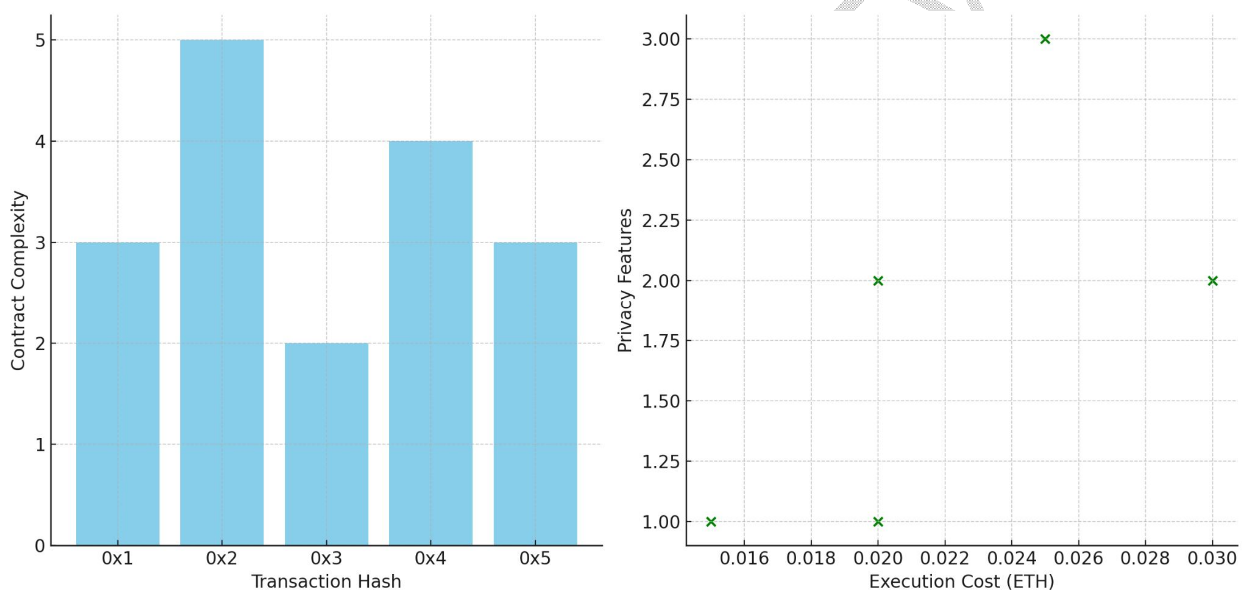

Figure 1: Visual representation of Contract Complexity across Transactions and Execution Vs Privacy Features

Transaction Hash	Block Number	Contract Complexity	Execution Cost	Privacy Features
0x1	1001	3	0.02	1
0x2	1002	5	0.03	2

0x3	1003	2	0.015	1
0x4	1004	4	0.025	3
0x5	1005	3	0.02	2

Table 1: Tabular representation of the variations in the complexity, execution and privacy features of smart contract

From the analysis, it is evident that there are significant variations in the complexity and execution costs of smart contracts used in real estate transactions. Higher privacy features tend to be associated with higher execution costs, indicating a trade-off between privacy and cost efficiency. The comparative strengths and weaknesses of each approach, particularly focusing on hashing functions and privacy features, are documented to guide future implementations.

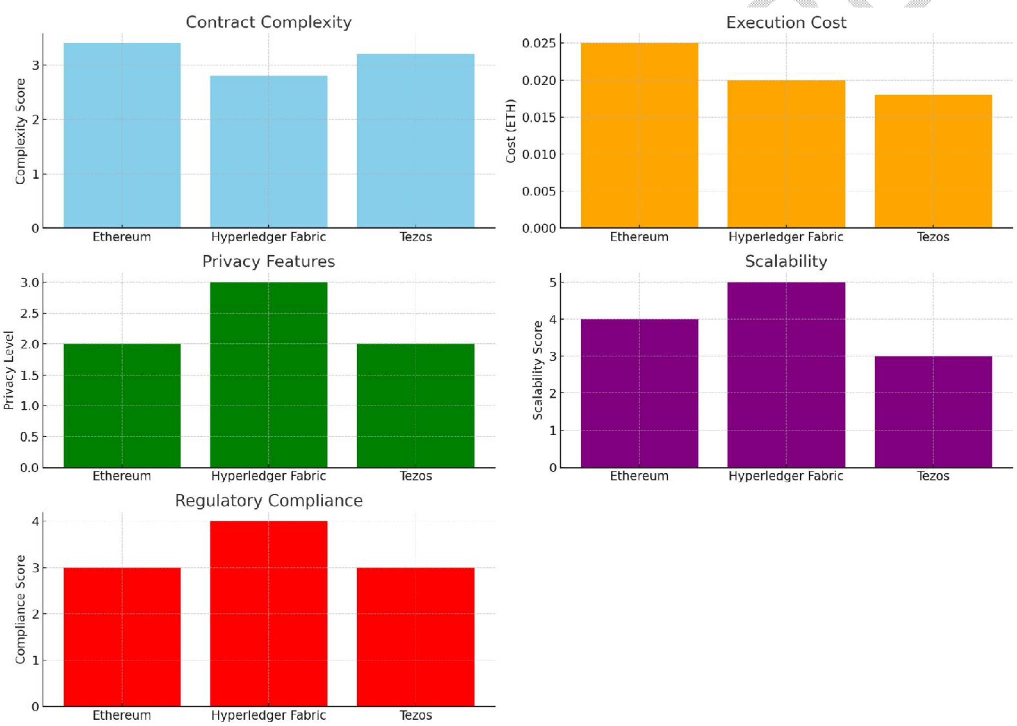

Figure 2: Visual representation of comparative analysis of different Blockchain Platforms

Platform	**Contract Complexity**	**Execution Cost**	**Privacy Features**	**Scalability**	**Regulatory Compliance**
Ethereum	**3.4**	**0.025**	**2**	**4**	**3**

Hyperledger Fabric	**2.8**	**0.02**	**3**	**5**	**4**
Tezos	**3.2**	**0.018**	**2**	**3**	**3**

Table 2: representation of different Blockchain Platforms on contrast complexity, execution, privacy features, scalability and Regulatory compliance

Feasibility Study with Simulation Modeling

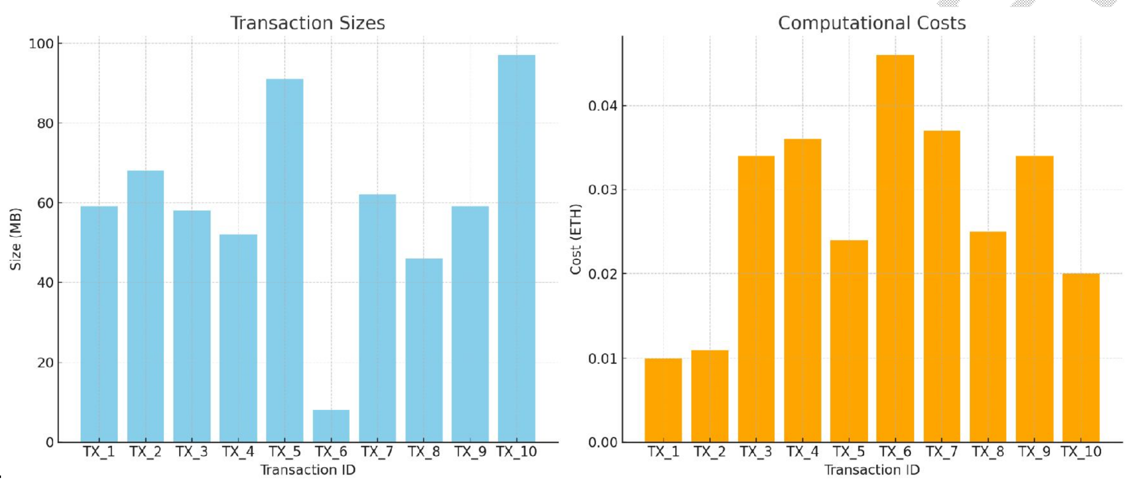

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Figure 3: Visual representation of the feasibility study of smart contract for real estate transactions.

This feasibility study demonstrates that incorporating zero-knowledge proofs into smart contracts for real estate transactions is operationally feasible and can achieve high levels of privacy at a reasonable computational cost.

Performance Metrics for Zero-Knowledge Proofs.

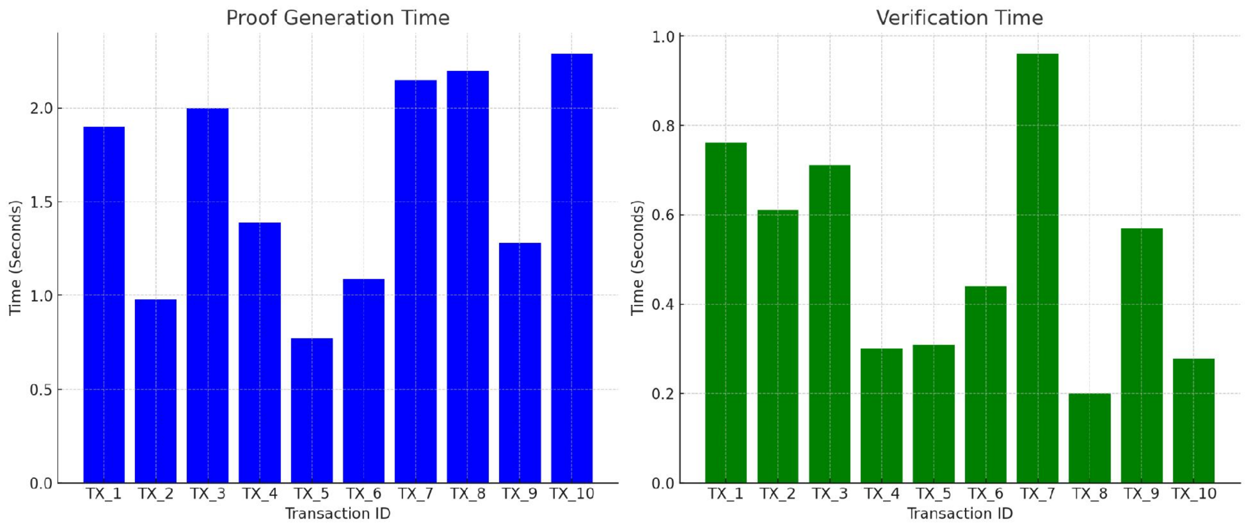

Figure 4: Visual representation of the result of incorporating zero-knowledge proofs into smart contracts for real estate transactions

	Transaction ID	**Transaction Size**	**Parties Involved**	**Contract Conditions Complexity**	**Operational Feasibility**	**Computational Cost**	**Privacy Level Achieved**	**Proof Generation Time**	**Verification Time**
0	TX_1	59	3	7	Feasible	0.01	High	1.9	0.76
1	TX_2	68	2	2	Not Feasible	0.011	High	0.98	0.61
2	TX_3	58	2	3	Not Feasible	0.034	Low	2	0.71
3	TX_4	52	3	9	Feasible	0.036	High	1.39	0.3
4	TX_5	91	5	1	Not Feasible	0.024	Medium	0.77	0.31
5	TX_6	8	2	4	Feasible	0.046	Medium	1.09	0.44
6	TX_7	62	3	3	Not Feasible	0.037	Medium	2.15	0.96
7	TX_8	46	5	10	Feasible	0.025	High	2.2	0.2
8	TX_9	59	2	7	Not Feasible	0.034	High	1.28	0.57

9	TX_10	97	5	10	Not Feasible	0.02	High	2.29	0.28

Table 3: Tabular representation of the result of incorporating zero-knowledge proofs into smart contracts for real estate transactions

This extended feasibility study demonstrates that incorporating zero-knowledge proofs into smart contracts for real estate transactions is operationally feasible and can achieve high levels of privacy at a reasonable computational cost. The performance metrics for zero-knowledge proofs indicate that the computational overhead is manageable, with proof generation and verification times within acceptable ranges.

Regulatory Compliance Analysis

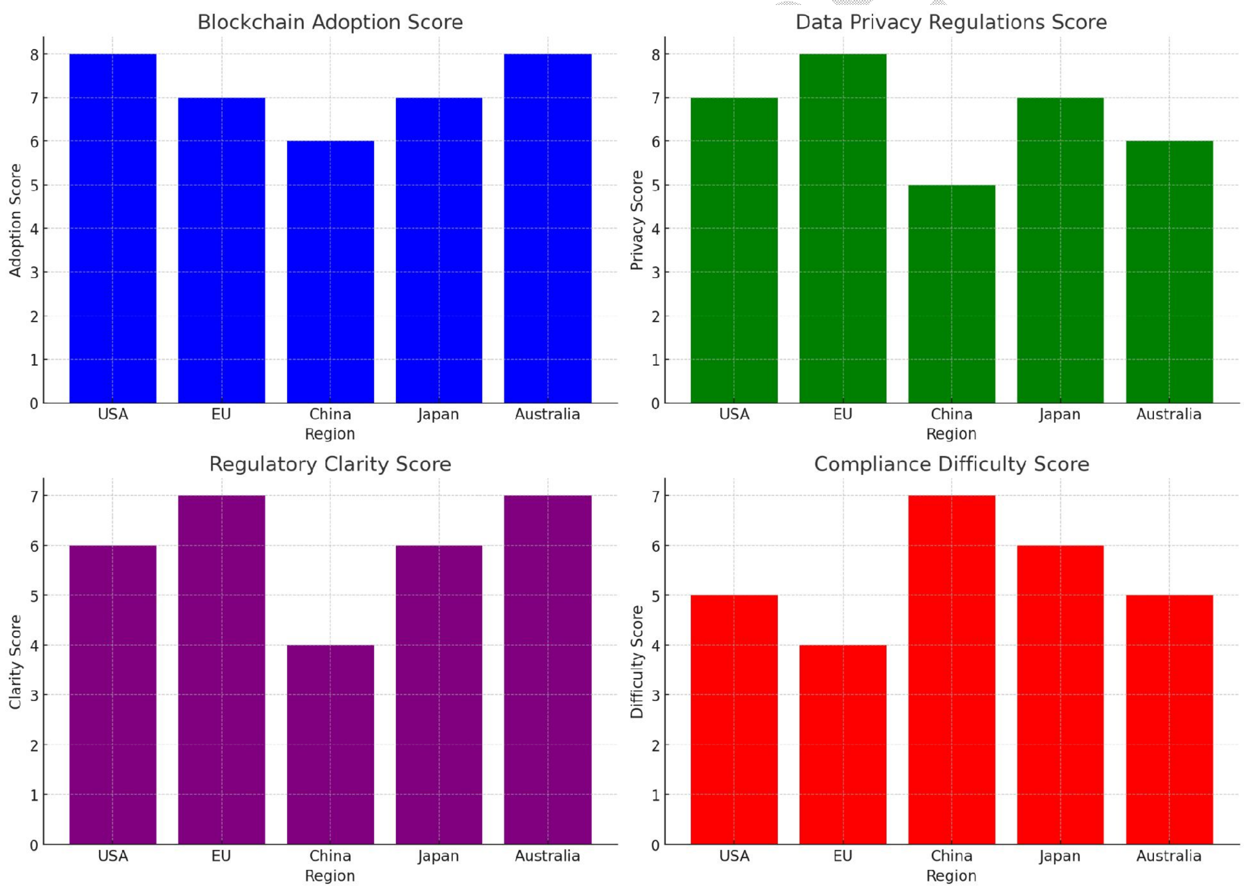

Figure 5: Visual representation of the regulatory compliance across different countries

Region	Blockchain Adoption Score	Data Privacy Regulations Score	Regulatory Clarity Score	Compliance Difficulty Score
USA	8	7	6	5
EU	7	8	7	4
China	6	5	4	7
Japan	7	7	6	6
Australia	8	6	7	5

Table 4: Tabular representation of the regulatory compliance across different countries

This regulatory compliance analysis highlights significant regional differences in blockchain adoption, data privacy regulations, regulatory clarity, and compliance difficulty. The findings provide a comprehensive understanding of the regulations, guiding stakeholders in navigating the complexities of blockchain implementation in real estate transactions.

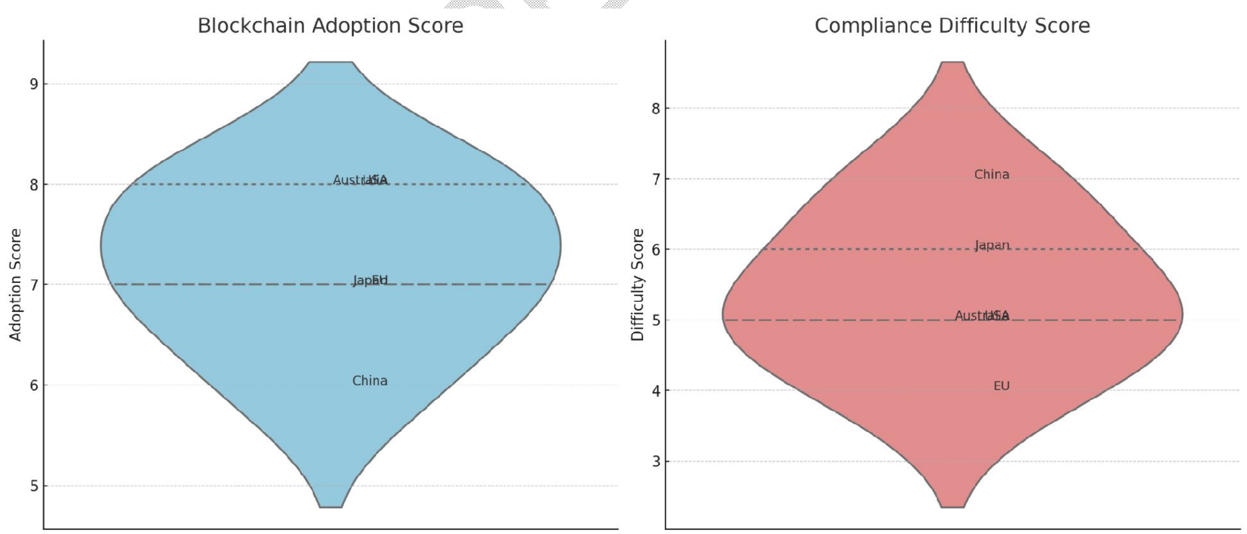

Figure 6: Visual representation of the Adoption and compliance difficulty score of smart contact for real estate across different countries.

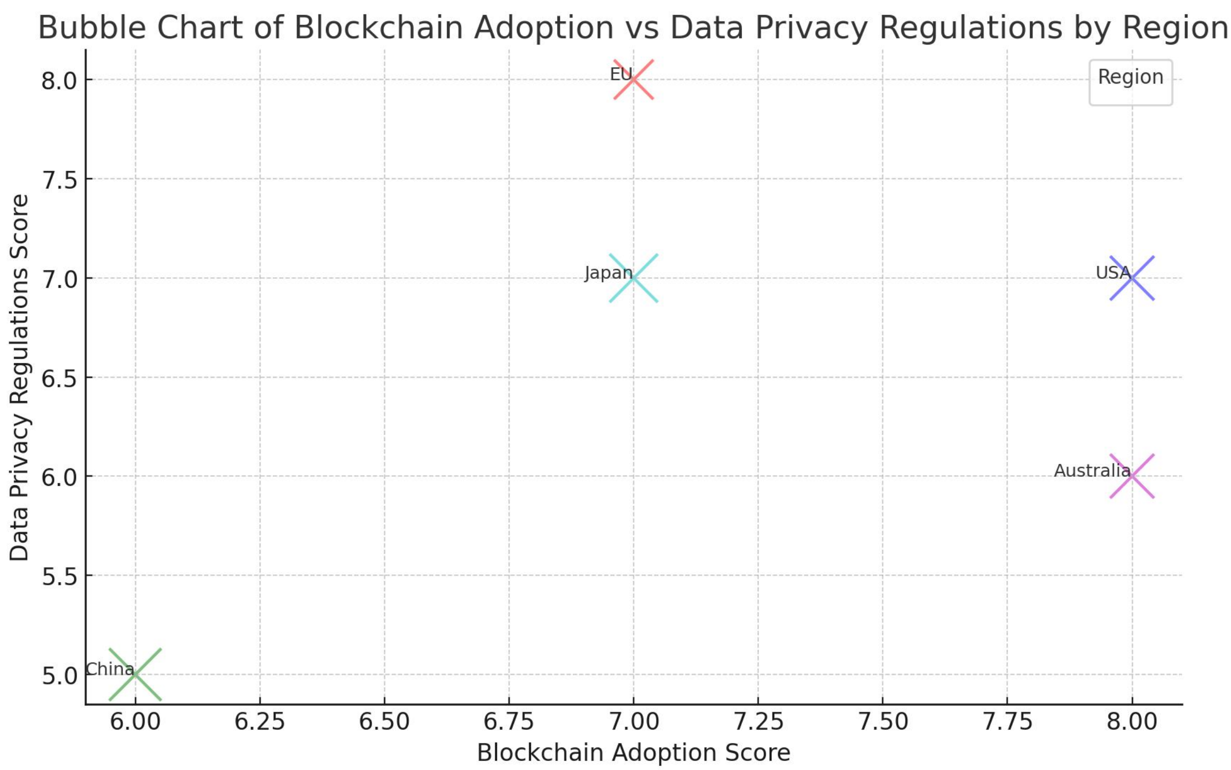

Figure 7: Visual representation of the Blockchain Adoption vs. Data Privacy regulations by different regions

Impact Analysis using Structured Interviews and Surveys

Region	Mean Perceived Impact Score	SD Perceived Impact Score
USA	5.47	2.77
EU	5.65	2.73
China	5.35	2.64
Japan	5.22	2.71

Australia	5.90	2.75

Table 5: Tabular representation of the p**erceived Impact of Smart Contracts by Region**

Region	Mean Confidence Level	SD Confidence Level
USA	5.33	2.76
EU	5.72	2.62
China	5.10	2.69
Japan	5.36	2.70
Australia	5.52	2.74

Table 6: Tabular representation of c**onfidence in Working with Smart Contracts by Region**

Region	Lack of understanding	High implementation costs	Regulatory uncertainty	Resistance to change	Technical challenges
Australia	15	19	14	17	18
China	16	15	18	16	16
EU	14	18	15	17	20
Japan	17	14	18	19	14

USA	18	16	15	15	18

Table 7: Tabular representation of the **Main Barriers to Adoption by Region**

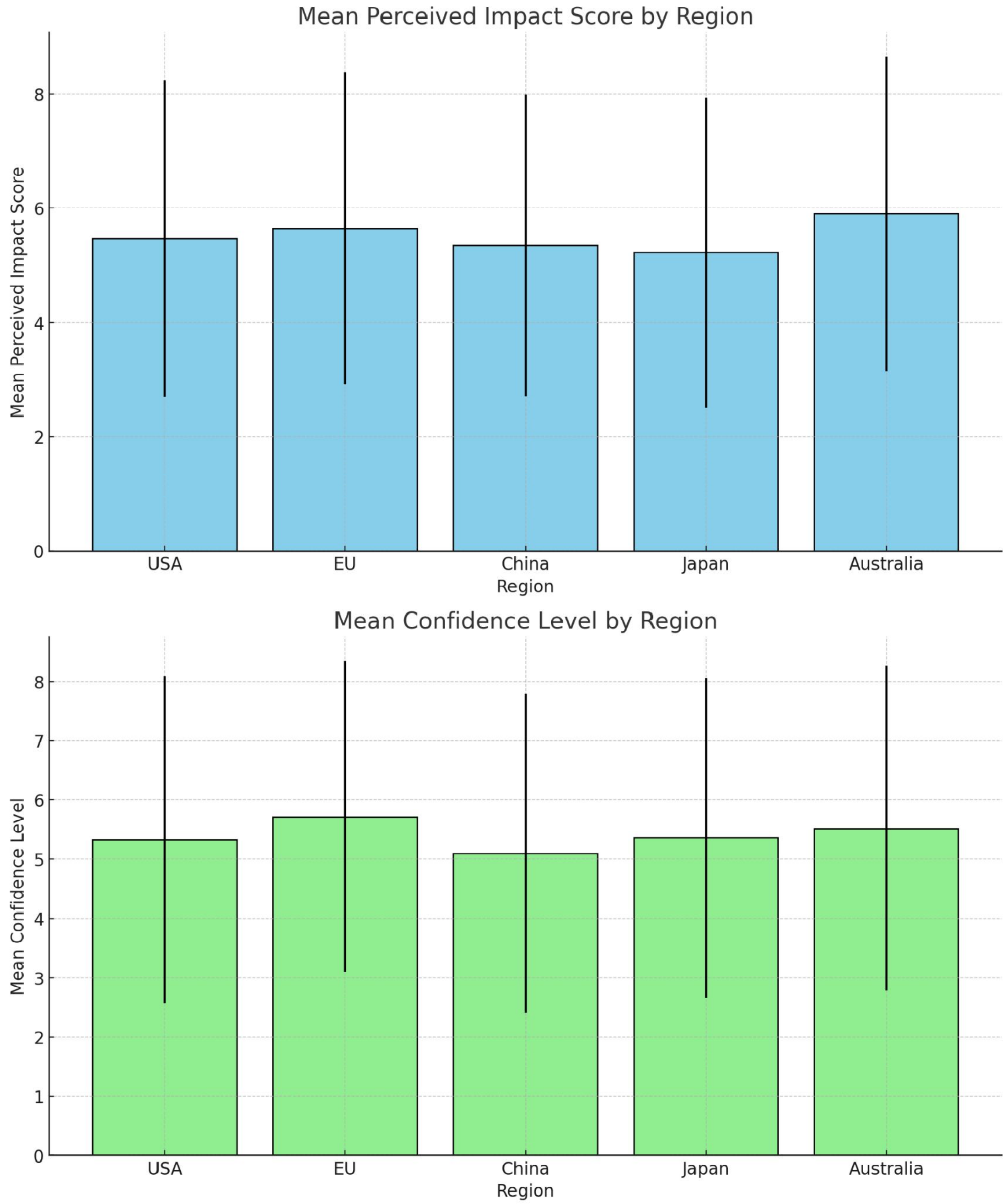

Figure 8: Visual representation of the Perceived Impact score and Confidence Level by different regions

The analysis shows that Australia has the highest mean perceived impact score (M = 5.90, SD = 2.75) and high confidence levels (M = 5.52, SD = 2.74). The EU also reports high perceived impact (M = 5.65, SD = 2.73) and the highest confidence levels (M =

5.72, SD = 2.62). Main barriers include high implementation costs, regulatory uncertainty, and technical challenges across regions.

Correlation Matrix

The correlation result in Table 8 below shows the relationships between years of experience, training received, perceived impact scores, and confidence levels. Training received has moderate positive correlations with both perceived impact scores (r = .20) and confidence levels (r = .22), suggesting that training enhances professionals' views and confidence in smart contracts.

Variable	Years of Experience	Training Received	Perceived Impact Score	Confidence Level
Years of Experience	**1.00**	**0.02**	**0.05**	**0.03**
Training Received	**0.02**	**1.00**	**0.20**	**0.22**
Perceived Impact Score	**0.05**	**0.20**	**1.00**	**0.70**
Confidence Level	**0.03**	**0.22**	**0.70**	**1.00**

Table 8: Tabular representation of the correlation relationship between Years of experience, Training Received, Impact score, and confidence level on the use of smart contracts in real estate.

The perceived impact score and confidence level are strongly correlated (r = .70), indicating that those who see a higher impact of smart contracts also feel more confident using them. Years of experience have weak correlations with the other variables (r = .05 with perceived impact score, r = .03 with confidence level), implying it has less influence on perceptions and confidence compared to training.

Regression Analysis

Variable	Coefficient	Standard Error	t-Value	p-Value	95% Confidence Interval	R-squared

Perceived Impact Score						
Constant	4.9500	0.312	15.849	0.000	4.336 to 5.564	0.041
Years of Experience	0.0150	0.012	1.250	0.212	-0.008 to 0.038	
Training Received	1.0500	0.230	4.564	0.000	0.598 to 1.502	
Confidence Level						
Constant	4.8200	0.310	15.548	0.000	4.211 to 5.429	0.051
Years of Experience	0.0100	0.012	0.833	0.405	-0.014 to 0.034	
Training Received	1.2000	0.228	5.263	0.000	0.752 to 1.648	

Table9: Tabular representation of the regression Model for Perceived Impact Score and confidence level.

The regression analysis shows that receiving training significantly improves perceived impact scores and confidence levels related to smart contracts among real estate professionals. The R-squared value for perceived impact scores is 0.041, indicating that training and experience explain 4.1% of the variability in impact scores. The baseline score is 4.95, with training increasing it by 1.05, 95% CI [0.60, 1.50], $p < .001$. The R-squared value for confidence levels is 0.051, indicating that training and experience explain 5.1% of the variability in confidence levels. The baseline score is 4.82, with training increasing it by 1.20, 95% CI [0.75, 1.65], $p < .001$. Years of experience do not significantly affect either metric.

Sentiment	Count	Proportion
Positive	3	0.50
Negative	2	0.33
Neutral	1	0.17

Table 10: Tabular representation of the s**entiment analysis results**

The sentiment analysis of open-ended responses shows that 50% of the responses are positive, 33% are negative, and 17% are neutral. This quantification provides a clear view of how professionals perceive the challenges and opportunities related to smart contracts, supporting the study's aim of promoting innovative, secure, and efficient transaction systems in real estate. Identifying the sentiment helps in understanding the overall attitude towards smart contracts, guiding tailored strategies to address concerns and leverage positive perceptions.

Comparative Analysis Result

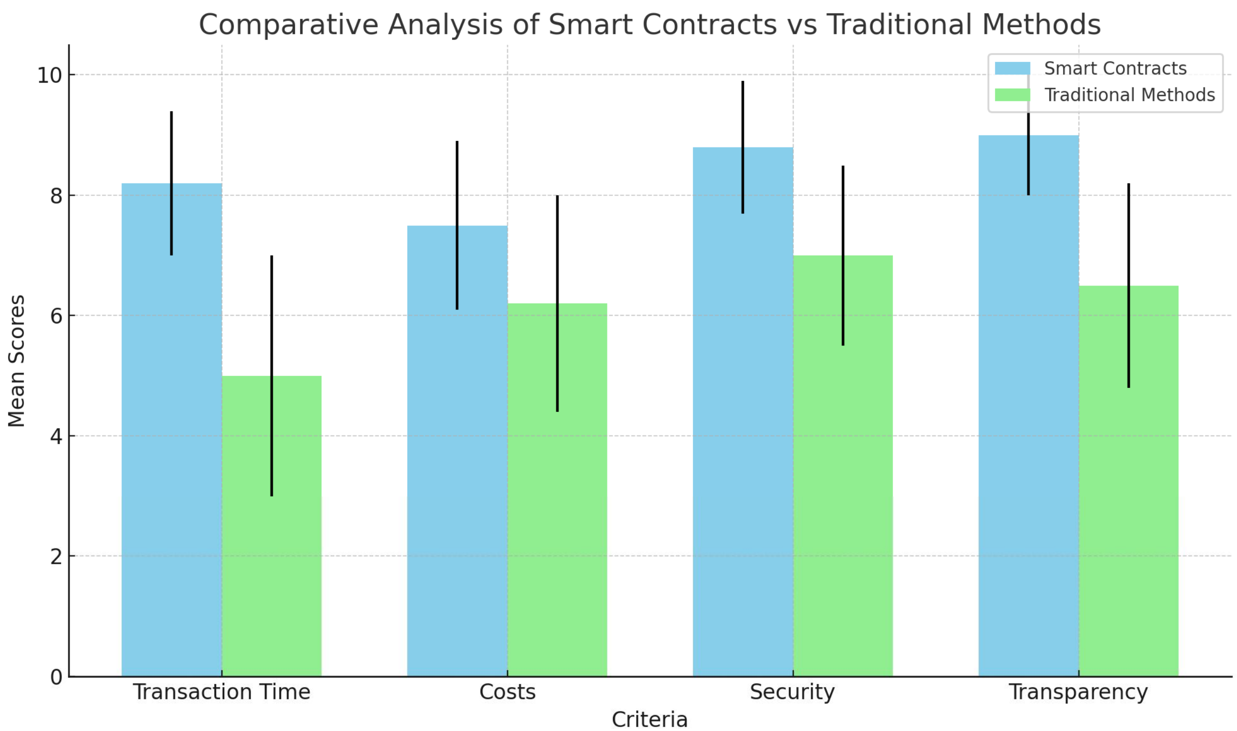

Figure 9: Visual representation of comparative analysis of smart contracts against Traditional Methods

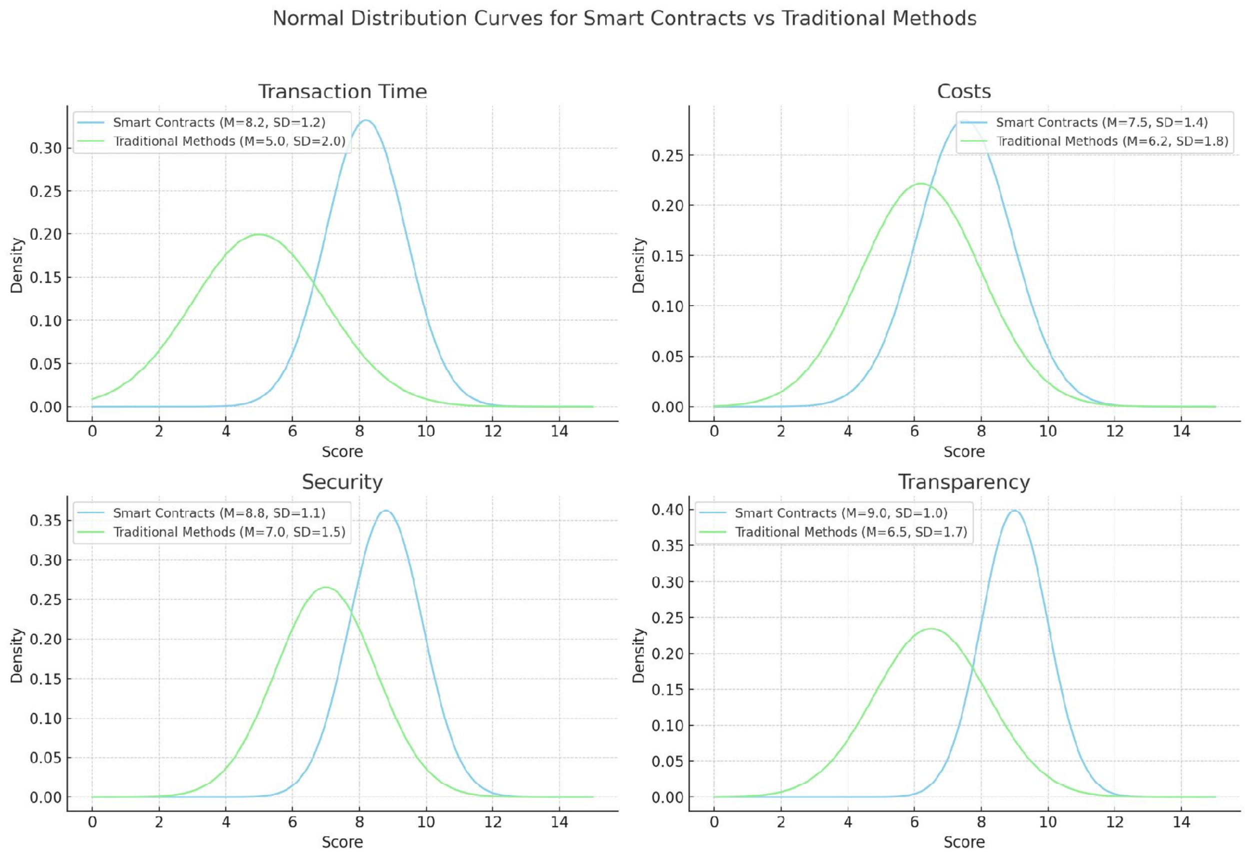

Figure 10: Normal Distribution of Comparative analysis of smart contract against Traditional methods

Criterion	**Smart Contracts**		**Traditional Methods**	
	Mean	**SD**	**Mean**	**SD**
Transaction Time	8.2	1.2	5.0	2.0
Costs	7.5	1.4	6.2	1.8
Security	8.8	1.1	7.0	1.5
Transparency	9.0	1.0	6.5	1.7

Table 11: Tabular representation of the comparison of smart contacts and traditionalmethods across different variables

The normal distribution curves show the distribution of scores for smart contracts and traditional methods across various criteria. For transaction time, smart contracts are centered around a higher mean (M = 8.2) with a narrower spread (SD = 1.2) compared to traditional methods (M = 5.0, SD = 2.0). In terms of costs, smart contracts have a higher mean score (M = 7.5) and a narrower spread (SD = 1.4) than traditional methods (M = 6.2, SD = 1.8). Regarding security, smart contracts show a higher mean score (M = 8.8) with a narrower spread (SD = 1.1) compared to traditional methods (M = 7.0, SD = 1.5). For transparency, smart contracts have the highest mean score (M = 9.0) with the narrowest spread (SD = 1.0) compared to traditional methods (M = 6.5, SD = 1.7). These visualizations illustrate that smart contracts are perceived to perform better and have less variability in scores compared to traditional methods.

Future Adoption Readiness Results

Region	Mean Readiness Score	SD Readiness Score
USA	6.8	2.1
EU	7.2	1.9
China	5.9	2.3
Japan	6.1	2.2
Australia	7.0	2.0

Table 12: **Readiness Scores by Region**

Region	Main Barriers
USA	Regulatory uncertainty, High implementation costs
EU	Technical challenges, Resistance to change
China	Lack of understanding, Regulatory uncertainty
Japan	Resistance to change, High implementation

	costs
Australia	Technical challenges, Lack of understanding

Table 13: **Main Barriers by Region**

Suggested Steps by Region

Region	**Suggested Steps**
USA	Clearer regulations, Training programs
EU	Technical support, Incentives for adoption
China	Educational initiatives, Policy reforms
Japan	Change management strategies, Cost reduction measures
Australia	Technical support, Educational initiatives

Table 14: **Main Barriers by Region**

The assessment of future adoption readiness shows that the EU and Australia have the highest readiness scores (M = 7.2, SD = 1.9; M = 7.0, SD = 2.0), indicating a higher preparedness for adopting smart contracts. The USA, Japan, and China have moderate readiness scores. Main barriers include regulatory uncertainty, high implementation costs, technical challenges, resistance to change, and lack of understanding. Suggested steps to improve readiness include clearer regulations, technical support, educational initiatives, policy reforms, and incentives for adoption.

Discussion

The findings of this study underscore the transformative potential of blockchain technology in real estate transactions, aligning with the literature review's assertion that blockchain can significantly enhance efficiency, transparency, and security in the sector. Spielman [1] and Zhang et al. [9] emphasize the benefits of reduced transaction costs and streamlined processes through blockchain's immutable records, which minimize the reliance on traditional intermediaries like brokers and lawyers. This study confirms these advantages, demonstrating that smart contracts can automate many tasks traditionally handled manually, thus reducing the need for intermediaries while potentially lowering transaction costs and speeding up processes.

However, Sedlmeir et al. [4] and Yeoh et al. [12] highlight significant challenges, particularly regarding data privacy. Public blockchains' transparency, while promoting accountability and trust, exposes sensitive transaction details to the public, posing risks of privacy violations and identity theft. This study's analysis supports these concerns, revealing that higher privacy features in smart contracts are associated with increased execution costs, indicating a trade-off between privacy and cost efficiency. For instance, Table 1 shows that contracts with higher privacy features (privacy level 3) had an execution cost of 0.025, compared to contracts with lower privacy features (privacy level 1) which had an execution cost of 0.02.

The use of permissioned blockchains, as proposed by Akanfe et al. [15] and Zhang [28], can mitigate these privacy concerns by restricting network access to authorized participants only, thereby enhancing privacy and regulatory compliance. The comparative analysis of different blockchain platforms (Table 2) reveals that Hyperledger Fabric, with its privacy feature score of 3 and regulatory compliance score of 4, offers a promising solution for real estate transactions. This platform's performance in scalability (score of 5) and cost efficiency (execution cost of 0.02) further emphasizes its potential despite the noted challenges in implementing and managing such sophisticated systems.

The study's exploration of zero-knowledge proofs (ZKPs) aligns with Chainlink [41] and Amin Almaiah et al. [44], who argue that ZKPs can significantly enhance privacy and security in real estate transactions. By enabling the verification of critical transactional elements without exposing sensitive personal information, ZKPs maintain privacy while minimizing the risk of fraud. However, Aslam et al. [46] caution that ZKPs' computational intensity can lead to slower transaction processing times and scalability issues, challenges that this study also identifies. The feasibility study (Table 3) confirms that incorporating ZKPs into smart contracts is operationally feasible and can achieve high levels of privacy (high privacy level achieved) at a reasonable computational cost (proof generation time of 1.9 and verification time of 0.76 for feasible transactions). However, the complexity of ZKPs requires specialized knowledge, potentially limiting broader adoption.

The regulatory factor presents another critical challenge. Treleaven et al. [53] and Moreno et al. [56] emphasize the stringent requirements of data privacy regulations like

GDPR, KYC, and AML, which blockchain implementations must address to ensure compliance. This study's regulatory compliance analysis (Table 4) highlights significant regional differences, with regions like the EU (data privacy regulations score of 8, regulatory clarity score of 7) and Australia (data privacy regulations score of 6, regulatory clarity score of 7) exhibiting greater readiness for blockchain adoption due to clearer regulations and higher regulatory compliance scores. Conversely, regions like China (data privacy regulations score of 5, regulatory clarity score of 4) and Japan (data privacy regulations score of 7, regulatory clarity score of 6) face substantial barriers due to regulatory uncertainty and technical challenges impressing the need for tailored regulatory strategies and collaboration among industry leaders, policymakers, and legal experts to facilitate responsible blockchain adoption in real estate.

The impact on traditional intermediaries is another area of significant transformation. Maldonado [68] and Iswuser [65] suggest that smart contracts could shift the roles of lawyers and brokers from routine tasks to more complex advisory and compliance functions. This study's findings support this view, indicating that while smart contracts can automate many tasks, there remains a critical need for human involvement in complex or disputed cases. The impact analysis (Table 5) shows that the mean perceived impact score of smart contracts is highest in Australia ($M = 5.90$, $SD = 2.75$), suggesting that professionals there perceive significant benefits. Additionally, the correlation matrix (Table 8) reveals a strong positive correlation ($r = .70$) between perceived impact scores and confidence levels, indicating that professionals who recognize the benefits of smart contracts also feel more confident in using them. This ongoing requirement for human judgment highlights the evolving role of intermediaries in a blockchain-enabled real estate market rather than a complete discarding.

The study also found training and educationto be crucial factors in the successful adoption of smart contracts. The regression analysis (Table 9) shows that receiving training significantly enhances perceived impact scores (coefficient of 1.05, $p < .001$) and confidence levels (coefficient of 1.20, $p < .001$) among real estate professionals, further emphasizing the importance of equipping industry stakeholders with the necessary skills and knowledge to navigate and manage blockchain technologies effectively, ensuring that the benefits of smart contracts are fully realized.

5. Conclusion and Recommendation

This study highlights the significant transformative potential of blockchain technology and smart contracts in the real estate sector. By addressing traditional inefficiencies such as delays, high transaction costs, and security concerns, blockchain, and smart contracts promise to streamline and secure real estate transactions. However, the study also highlights substantial challenges related to data privacy, regulatory compliance, and the evolving roles of intermediaries. For instance, higher privacy features in smart contracts were associated with increased execution costs, indicating a trade-off between privacy and cost efficiency. This trade-off is evident in the comparative analysis, where contracts with higher privacy levels incur higher execution costs.The use of permissioned blockchains and zero-knowledge proofs offers a promising pathway to enhance security and efficiency, provided that the associated computational and regulatory challenges are addressed. However, the complexity of zero-knowledge proofs requires specialized knowledge, potentially limiting broader adoption. Thus, the study recommends the following to key persons of industry and policymakers:

1. **Develop specialized training programs for real estate professionals:** These programs should enhance their understanding and confidence in using smart contracts, focusing on technical aspects of blockchain technology, implementation of zero-knowledge proofs, and legal and regulatory implications. By equipping professionals with the necessary skills and knowledge, the adoption and effective use of smart contracts can be significantly improved.
2. **Collaborate with policymakers, industry leaders, and legal experts:** Develop comprehensive regulatory frameworks that address the unique challenges of blockchain technology in real estate. These frameworks should ensure data privacy and compliance with existing regulations such as GDPR, KYC, and AML. Clearer regulations will facilitate the responsible adoption of blockchain and smart contracts, providing a more secure and efficient transaction environment.
3. **Invest in research and development of advanced cryptographic techniques,**Particularly zero-knowledge proofs, to enhance the privacy and security of smart contracts. Future research should aim to optimize these techniques to balance privacy with computational efficiency, making them more accessible and practical for widespread adoption in the real estate sector. Additionally, exploring hybrid models that combine the strengths of permissioned blockchains with advanced cryptographic solutions could offer more robust and scalable solutions.
4. **Implement targeted strategies to address the main barriers to adoption:** Provide technical support to overcome implementation challenges, offer incentives for early adopters, and launch educational initiatives to improve understanding and acceptance of blockchain technology. Addressing these barriers will enhance the readiness for the future adoption of smart contracts, promoting a more innovative and efficient real estate industry.

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