Blockchain-based key-value store to support dynamic smart contract interaction in the agricultural sector

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ABSTRACT

In the era of supply chain digitalization, adaptability and transparency are key to enhancing efficiency and trust. Although blockchain technology and smart contract offer innovative solutions, the limitations of static smart contract hinder their full potential. This article introduces a new approach using dynamic smart contract capable of managing various commodities in the supply chain with a key-value store. While this advantage provides flexibility, it still poses challenges in managing increasingly complex interactions among various actors, especially when the number of commodities increases. To address these challenges, this study introduces the concept of smart contract interaction that facilitates the automation and management of interactions with high efficiency. The implementation results show that smart contract interaction outperforms conventional approaches in terms of speed, resilience, and ease of management. Through the combination of dynamic smart contract and smart contract interaction, demonstrating how efficiency, transparency, adaptability, and scalability can be achieved in the supply chain, providing new insights into the utilization of blockchain technology for the modern industry.

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1. INTRODUCTION

Indonesia is an archipelagic country with an abundance of natural resources. Indonesia stands as a leading producer in the commodities sector, especially in fish and coffee [1]. These two commodities have become the economic backbone for many local communities, driving growth and providing a distinctive identity for the country's culinary culture and trade [2]. However, behind this great potential, there are challenges arising from the supply chain of these commodities [3]. Price fluctuations, quality uncertainty, and difficulties in tracking product origins are some of the common issues [4]. These challenges affect consumer trust and hinder the economic growth potential of both commodities [5].

Blockchain is a technology that can solve various problems. It is a technology that enables distributed and encrypted data storage [6]. Known for it is security, transparency, and immutability, blockchain is resistant to alteration or hacking [7]. Operating through a peer-to-peer network, each transaction is verified and recorded in data blocks linked in a chain, providing full visibility and an unalterable record [8].

The application of blockchain has expanded to various fields, including finance [9], healthcare [10], education [11], and logistics. In the financial sector, blockchain is used for digital currency transactions like Bitcoin [12]. In healthcare, it aids in managing patient medical records and tracking medications [13]. In education, blockchain can be used for verifying diplomas and certificates [14]. Complementing these applications, recent advancements in blockchain technology have seen its integration with other cutting-edge technologies, such as artificial intelligence (AI), machine learning, and deep learning, opening new paradigms in various sectors. Innovative approaches have been explored in managing drone-based data with blockchain and optimizing through metaheuristic algorithms in secure environments [15]. The healthcare sector has witnessed the development of blockchain-enhanced network architectures for more efficient and secure systems [16]. Additionally, the collaborative use of blockchain with AI and the industrial internet of things (IoT) is transforming the digitalization of small and medium-sized enterprises, offering novel solutions and challenges [17]. The integration of blockchain technology with IoT has been critically reviewed to enhance security aspects, crucial for the evolving digital landscape [18]. Moreover, in the domain of digital forensics, the application of blockchain for a secure chain-of-custody process in IoT with multimedia investigation has been examined, showcasing it is potential in ensuring data integrity and security [19]. In the logistics sector, blockchain enhances supply chain transparency and efficiency [20]. These diverse applications and integrations of blockchain technology significantly contribute to the evolution of supply chain systems, making them more transparent, efficient, and secure [20].

In the agricultural sector, blockchain offers solutions to key challenges, including product origin tracking [21], quality verification [22], and transaction transparency [23]. The blockchain mechanism in agriculture involves recording every stage in the supply chain, from production, and processing, to distribution [24]. Each transaction or change in product status is recorded in a block and cannot be altered or deleted [25], as shown in Figure 1. This allows farmers, distributors, and consumers to track the product journey in real-time, enhancing trust and efficiency [26]. However, the implementation of blockchain in this sector faces significant challenges, particularly with static smart contracts. Static smart contracts are characterized by fixed parameters and rules that cannot be changed, limiting their ability to accommodate changes in market conditions, user needs [27], or adapt to policy or regulation changes [28]. This inflexibility is a critical issue in the agricultural sector, where conditions can change rapidly and unpredictably [29]. Furthermore, static smart contracts lack the necessary adaptability for dynamic and fluctuating contexts [29] and their scalability is limited, posing a serious obstacle to implementation and operational efficiency on a larger scale [30]. These limitations highlight the need for more dynamic and adaptable smart contract solutions in the agricultural blockchain applications [31].

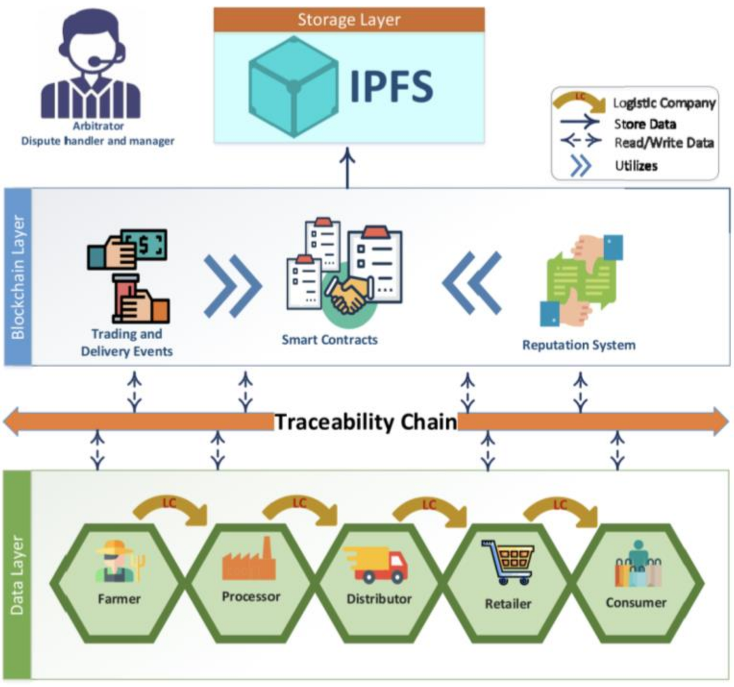

Figure 1. Blockchain workflow in agriculture [32]

As a solution to the limitations of static smart contract, the key-value store approach has been proposed [33]. This method enables more efficient storage, access, and modification of data [34], allowing for rapid adaptation to changes in the supply chain and providing the necessary flexibility in a dynamic industry [35]. However, new challenges arise due to the management of numerous commodities [36]. Efficient management of interactions between various smart contract becomes crucial [37]. The importance of smart contract interaction is evident here. In this context, previous research has explored various approaches. Exploring the multifaceted world of smart contract interactions, various researchers have delved into diverse methodologies and challenges. One study introduced flexible smart contract interaction with access control (FSCC), focusing on smart contract interaction with access control [38], while another proposed a distributed access control approach based on identity and role [39]. The complexities of cross-blockchain interactions were also examined [40], alongside an analysis comparing smart contract interactions with consensus status [41]. The potential of blockchain in enhancing supply chain collaboration was demonstrated through a specific framework [42], and the exploration of tools for identifying vulnerabilities in smart contract was also undertaken [43]. Discussions extended to the realm of multi-smart contract interactions [44] and the profiling of smart contract [45]. Further, the intricacies of smart contract interactions within Coq were explored [46], and the concept of SmartSync for cross-blockchain interactions was also brought to light [47]. These studies collectively shed light on critical aspects of smart contract interaction, encompassing access control, security, and interoperability across different blockchain platforms.

However, this study goes a step further by utilizing the key-value store to optimize interactions among smart contract, enabling more efficient data management [48]. This approach offers a more dynamic and responsive solution compared to existing methods, focusing on adaptability and flexibility in the face of emerging changes and needs. Thus, this study not only addresses the challenges of managing diverse commodities but also makes a significant contribution to improving the efficiency and effectiveness of smart contract interactions overall.

This study makes a significant contribution in integrating blockchain technology with the key-value store approach. The main contributions of this study include:

- Key-value store enhancement for agricultural dynamic smart contract: this study introduces a key-value store mechanism tailored for blockchain, enhancing dynamic smart contract in agriculture. It streamlines data handling for commodities like coffee and fish, boosting smart contract adaptability and efficiency in complex supply chains.
- Streamlining smart contract interactions with key-value store: the study integrates a key-value store into smart contract interaction, optimizing smart contract data management in agriculture. This fusion enhances data processing efficiency and smart contract interaction capabilities, creating a more agile and adaptable system for varied agricultural commodities.
- Case study on fish and coffee commodities: through in-depth analysis, this study highlights the challenges and opportunities in the supply chain of fish and coffee commodities in Indonesia, and how blockchain-based solutions can have a positive impact.
- Performance and reliability evaluation: this study is not only theoretical but also presents empirical evaluations regarding the performance and reliability of the proposed solutions, providing concrete evidence of the benefits and superiority of this approach in a real-world context.

2. METHOD

2.1. High-level requirements analysis

In this endeavour to develop blockchain-based solutions for supporting dynamic smart contract interactions in the agricultural sector, particularly for fish and coffee commodities, an in-depth analysis of specific functional needs was conducted [49]. The workflow analysis method was employed, crucial for understanding how information is managed and flows within the proposed system. In this context, a series of interviews with farmers, distributors, and consumers were conducted to identify challenges and obstacles encountered in the industry, which include:

- Hierarchy and structure of the supply chain: this analysis considered the hierarchy and structure of the supply chain in the agricultural sector, essential for understanding how entities interact and operate within the supply chain.
- Rules and regulations: the study explored the rules and regulations applicable to the supply chain of fish and coffee commodities to ensure that the developed solutions comply with the existing legal framework.
- Supply chain challenges: challenges faced by various entities were identified in the supply chain, including data mismatches, distribution delays, and product quality issues.

From this analysis, this study developed a workflow representing the distribution process of fish or coffee, as seen in Figure 2. This workflow illustrates how information moves from farmers to consumers, helping us identify various entities within the supply chain.

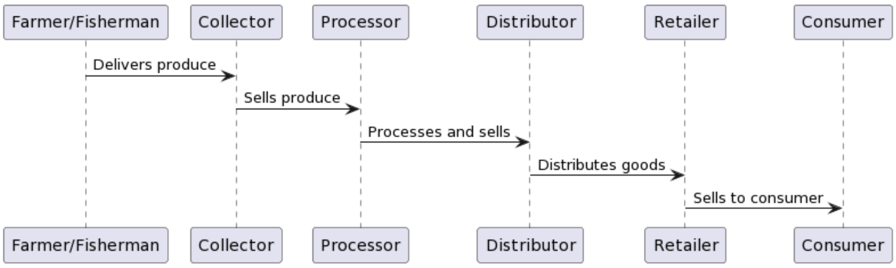

Figure 2. Simple workflow of the fish and coffee supply chain

Some of the challenges often expressed by supply chain participants include data mismatches, delays in the distribution process, and product quality issues [50]. Therefore, as shown in Figure 3, a blockchain-based solution with key-value store integration is proposed to address these challenges [51]. Based on the workflow analysis, the following functional requirements have been identified:

- Supply chain participant registration [FR1]: every entity, from farmers and distributors to consumers, should be able to easily register on the platform.
- Submission and update of data [FR2]: entities must be able to submit and update their data, such as harvest quantity, harvest date, selling price, and others.
- Dynamic smart contract interaction [FR3]: given the complexity of the supply chain, dynamic smart contract interaction is necessary.
- Integration with key-value store [FR4]: to support dynamic smart contract interaction, integration with a key-value store is required.
- Transparency and reliability of data [FR5]: all transactions and stored data must be transparent to all participants in the supply chain.
- Verification and validation mechanism [FR6]: any data or transaction submitted must be verified and validated by other entities in the supply chain.
- Notifications and alerts [FR7]: entities should receive notifications or alerts about changes or updates relevant to them.

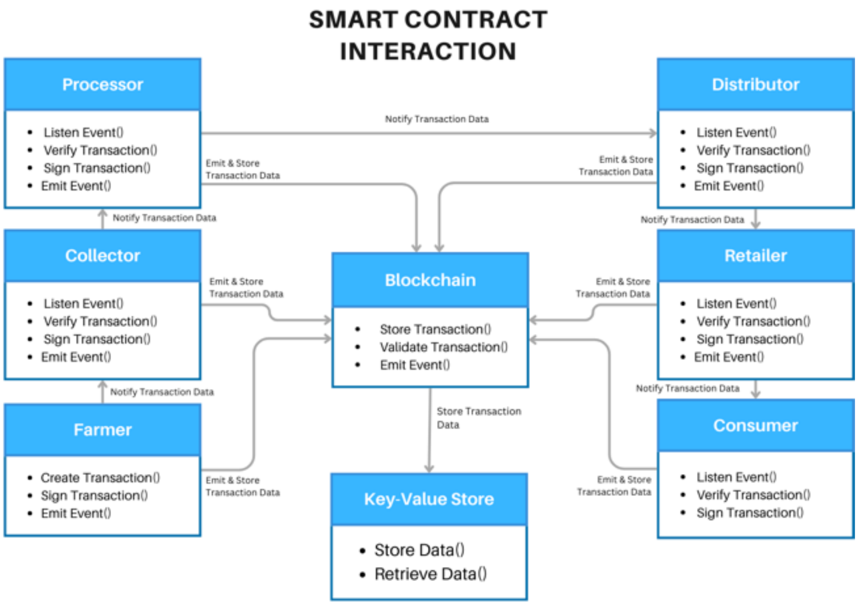

Figure 3. Smart contract interaction in supply chain

2.2. Pseudocode and algorithmic approach

In this section, the pseudocode is presented to elucidate the underlying logic of this blockchain-based system, making it accessible and understandable even for those not proficient in specific programming languages. It serves as a crucial tool for replication and validation, allowing future researchers to easily reproduce the methods and verify their correctness. By abstracting from the syntax of any programming language, the pseudocode provides a universal representation of the system's algorithms, facilitating adaptation and extension across various technological contexts [52]. It also offers a comprehensive view of how different components interact within the system, crucial for understanding its overall operation and identifying potential improvements. Additionally, the pseudocode has significant educational value, aiding in teaching complex algorithms in a more digestible format, thereby enhancing learning and comprehension in the field.

2.2.1. User registration

The cornerstone of this blockchain ecosystem is a robust user registration process, ensuring integrity and trust within the network. The following pseudocode as shown in Algorithm 1 details the user registration process, highlighting how new users are added to the system and how their registration triggers further interactions within the network. This algorithm is designed to ensure that each user in the blockchain network has a unique identity. The process of checking existing registrations prevents duplicate entries, maintaining the integrity of the system. The event emission upon successful registration is crucial for notifying other parts of the system, such as smart contract, about the new user, facilitating seamless interaction within the network.

Algorithm 1. User registration

```
Input: name(str), role(str), additionalAttributes(dict)
Output: User's unique ID, Role, and any additional attributes
1: Check if user is already registered
2: if (user is already registered) then
3:   Return "User is already registered"
4: else
5:  Store user's name, role, and additional attributes in the
database
6:  Generate a unique User ID for the new user
7: Emit an event indicating that a user with a specific name and
role has been successfully registered
8: Return User's unique ID, Role, and any additional attributes
9: end if
```

2.2.2. Add product by fisherman/farmer

The initial step in this supply chain is the recording of products by fishermen or farmers. Algorithm 2 describes this process, emphasizing how the addition of a product triggers notifications across the network, enhancing the flow of information and goods. This pseudocode represents the critical first step in the supply chain within this blockchain system. The validation of product ID uniqueness and the storage of product details are fundamental for maintaining accurate and reliable data. The emission of an event upon product addition is a key feature, alerting other entities in the supply chain about new products, thus facilitating efficient coordination.

Algorithm 2. Add product by fisherman/farmer

```
Input: productID(str), metadata(dict)
Output: Product's unique ID, Metadata
1: Check if product ID already exists
2: if (product ID exists) then
3:     Return "Product ID already exists"
4: else
5:  Store product details and metadata in the database
6:   Emit an event indicating that a new product has been
created by a Fisherman/Farmer
7:    Return Product's unique ID and its Metadata
8: end if
```

3. RESULTS AND DISCUSSION

3.1. Smart contract design and structure

In the intricate world of supply chain management for commodities, dynamic smart contract interaction is pivotal for handling the growing complexity of transactions and entity interactions. While a detailed exposition of every facet is beyond the scope of this study of smart contract use, it emphasizes those interactions that critically enhance supply chain efficiency and transparency. Key examples of smart contract interaction demonstrate the necessity of dynamic smart contract, supported by a key-value-based approach, for automated and efficient operation of modern supply chains. This approach ensures adaptability and resilience in the face of evolving demands and regulatory changes.

In the context of smart contract interaction 1 as shown in Algorithm 3, the `AddProduct` smart contract plays a pivotal role in integrating product information into the blockchain. This contract is specifically designed to handle the addition of new products by fishermen or farmers. When a product is added, its unique identification and metadata are securely recorded on the blockchain. The `addProduct` function within this contract is the key player here. It takes the product ID and metadata as inputs and performs a series of operations: it first checks if the product already exists in the system, then records the new product's details, and finally, it triggers the `ProductAdded` event.

When the `addProduct` function successfully records a new product, it emits the `ProductAdded` event, which includes the product's ID, owner's address, metadata, and timestamp. This event acts as a signal to other entities in the supply chain, such as collectors or processors, informing them about the new product's addition. This mechanism enhances the efficiency of the supply chain by enabling quicker responses and better coordination among different parties.

Algorithm 3. Smart contract interaction 1 add product

```
contract AddProduct {
    struct Product {
        string id;
        address owner;
        string metadata;
        uint timestamp;
    }
    mapping(string => Product) public products;
    event ProductAdded(string indexed productId, address indexed owner, string metadata,
uint timestamp);

    function addProduct(string memory _id, string memory _metadata) external returns (bool)
{
        require(products[_id].timestamp==0, "Product already exists");
        products[_id]=Product(_id, msg.sender, _metadata, block.timestamp);
        emit ProductAdded(_id, msg.sender, _metadata, block.timestamp);
        return true;
    }
}
```

In smart contract interaction 2 as shown in Algorithm 4, the `TransferProduct` smart contract plays a pivotal role in managing the transfer of product ownership within the blockchain system. This contract is integral to ensuring a transparent and traceable supply chain, particularly important in the agricultural sector for commodities like fish and coffee. The primary function of this contract, `transferProduct`, is designed to facilitate the transfer of products from one entity to another. It requires the product ID and the new owners address as inputs. When executed, this function updates the `transfers` mapping in the blockchain with comprehensive details of the product transfer. These details include the product ID, the address of the transferring entity (sender), the address of the receiving entity (recipient), and the timestamp of the transaction.

The ProductTransferred event is a critical aspect of this contract. Triggered by the successful execution of the transferProduct function, this event broadcasts important information across the blockchain network. It includes the product ID, the addresses of both the sender and the recipient, and the timestamp, providing a comprehensive overview of the transfer. This event serves as a real-time notification system, alerting all relevant parties in the supply chain about the change in product ownership. The implementation of this event is a subtle yet powerful feature of the smart contract, enhancing the overall transparency and efficiency of the supply chain. It ensures that every participant in the network is immediately informed about changes in product status, fostering a high level of trust and reliability in the system.

With the smart contract interaction-based approach, every interaction and transaction within the supply chain is recorded, analyzed, and managed with higher automation. This not only enhances operational efficiency but also ensures data integrity and transparency throughout the supply chain. For example, when a tuna fish product is added by a fisherman to the system, an automatic notification can be received by the distributor, allowing them to plan logistics more efficiently. Similarly, the transfer of products from the fisherman to the collector can be accurately tracked, ensuring that every entity in the chain has access to the latest information on the status and location of the product.

Algorithm 4. Smart contract interaction 2 transfer product
```
contract TransferProduct {
    struct ProductTransfer {
        string productId;
        address from;
        address to;
        uint timestamp;
    }
    mapping(string => ProductTransfer) public transfers;
    event ProductTransferred(string indexed productId, address indexed from, address
indexed to, uint timestamp);
    function transferProduct(string memory _productId, address _to) external returns (bool)
{
        transfers[_productId]=ProductTransfer(_productId, msg.sender, _to,
block.timestamp);
        emit ProductTransferred(_productId, msg.sender, _to, block.timestamp);
        return true;
    }
}
```

3.2. Testing and validation

To ensure the robustness and reliability of the smart contract, the Mocha testing framework was employed, a widely recognized tool in the blockchain development community [51]. The testing process was meticulously designed to cover a comprehensive range of scenarios, including function verification, error handling, and security checks. This work structured the tests to simulate real-world interactions with the smart contract, ensuring that each function performed as expected under various conditions. This involved creating a series of automated tests that would trigger and evaluate each function of the smart contract, scrutinizing their responses to both standard and edge-case scenarios.

The choice of the Mocha framework and adherence to Ethereum.org’s testing standards was driven by their proven effectiveness in the blockchain domain. Mocha is renowned for its flexibility and comprehensive reporting, which are crucial for debugging and validating complex smart contract interactions [53]. Aligning with Ethereum.org’s standards, the study ensured that the testing procedures adhered to industry best practices, thereby enhancing the credibility and security of the smart contract [54]. This alignment was particularly important for validating the security aspects of the contract, as Ethereum.org’s standards are specifically tailored to address the unique challenges and threats in the blockchain environment.

3.3. Evaluation

3.3.1. Smart contract test

Testing smart contract is an initial step to ensure that the contract created are by the specifications and function as intended. Adopting the testing standards recommended by Ethereum.org, this study use the Mocha framework to run a series of automated tests. These tests include verification of contract functions, error handling, as well as the security and reliability of the contract. The test results show that the developed smart contract operate accurately and consistently, meeting all the criteria set in the design phase.

3.3.2. Functional test

The testing of smart contract is designed to evaluate their responsiveness to various parameters and the integration of new rules, highlighting the adaptability of dynamic smart contract interaction over static smart contract, as detailed in Table 1. Dynamic smart contract interaction excels in managing commodity prices dynamically, adapting to market fluctuations without the need for contract amendments, and efficiently adding or removing commodities, which static smart contract cannot do without modifying the contract.

Dynamic smart contract interaction also enhances the supply chain at the actor level by streamlining the inclusion and exclusion of actors, improving access control with dynamic rules, and at the business flow level by swiftly adapting to regulatory changes. It responds promptly to market and regulatory shifts, ensuring efficient stock management and scalability. This allows for handling increased transaction volumes and business expansion with greater flexibility, without altering the existing smart contract, demonstrating dynamic smart contract interaction’s superior adaptability and efficiency in meeting the evolving demands of the market and business needs.

3.3.3. Aggregation test

Aggregation testing has revealed that dynamic smart contract interaction systems outperform static smart contract in handling user numbers, showcasing unlimited capacity versus the static smart contract’s inherent limitations. dynamic smart contract interaction's lower latency translates to quicker transaction processing, despite higher transaction costs, which likely accounts for its enhanced complexity and feature set. Additionally, dynamic smart contract interaction incurs slightly higher data storage costs, justified by its superior efficiency and volume handling capabilities, coupled with faster data access and code execution speeds, pointing to a more agile and capable system.

Dynamic smart contract interaction's initial setup costs are steeper, reflecting the investment in a more intricate system, yet it matches static smart contract in transaction verification speed. Across the board, dynamic smart contract interaction scores higher in flexibility, scalability, adaptability, and other key operational metrics, suggesting a more versatile and growth-ready system. Despite the increased financial outlay for transactions and setup, dynamic smart contract interaction's advantages in adapting to dynamic market conditions and integrating with diverse systems solidify its position as a robust, future-proof solution for complex user scenarios, as detailed in Table 2.

Dynamic smart contract interaction excels in adapting to market and regulatory changes, outperforming static smart contract by enabling swift modifications like price adjustments and commodity updates without altering the existing contract. This adaptability, along with the ability to handle larger volumes of transactions and users, suggests that the higher initial costs are offset by the system's enhanced operational efficiency and responsiveness to business evolution. Despite these benefits, the dynamic smart contract interaction's complexity necessitates a deeper understanding of the blockchain by end-users, highlighting the need for comprehensive education to ensure its successful adoption and maximize its potential in real-world applications.

Table 1. Functional test

No	Level	Testing point	Static smart contract	Dynamic smart contract interaction
1	Commodity level	Change prices	Yes	Yes
2		Add new commodity	No	Yes
3		Remove commodities	No	Yes
4		Add price attributes	No	Yes
5		Change measurement units	No	Yes
6	Actor level	Add new actors	No	Yes
7		Remove actors	Yes	Yes
8		Restrict actor access	Yes	Yes
9		Change roles	No	Yes
10	Business flow	Replace business rules	No	Yes
11		transaction processes	No	Yes
12		Add payment conditions	No	Yes
13		Provide shipping options	No	Yes
14		Add sanctions or incentives	No	Yes
15	Case handling	Handle sudden price changes	No	Yes
16		Handle product contamination	No	Yes
17		Handle stockouts	No	Yes
18		Handle regulatory changes	No	Yes
19		Handle seasonal fluctuations	No	Yes
20	Scalability level	Increase transaction volume	No	Yes
21		Reduce transaction time	No	Yes
22		Add new business branches	No	Yes
23		Handle high transaction loads	No	Yes
24		Adjust data storage capacity	No	Yes

Table 2. Aggregation test

Items	Static smart contract	Dynamic smart contract interaction
Number of Users	Limitted	Unlimitted
Response time	62	62
Transaction cost	4.25E-05	0.00015463
Latency	92	68
Data storage cost	0.00014589	0.00016434
Data access speed	179	77
Code execution speed	73	483
Initial setup cost	0.0025	0.0061
Transaction verification speed	76	76
Flexibility	2	5
Scalability	2	5
Adaptability	3	5
Code complexity	2	5
External integration	2	5
Reliability	3	5
Interoperability	2	5
Functional coverage	2	5

3.4. Discussion and implication

3.4.1. Interpretation of findings

This study demonstrates that dynamic smart contract interactions offer significant advantages over static smart contract, particularly in terms of adaptability and scalability. The use of dynamic smart contract interaction allows for quick and efficient changes in supply chain management without the need for complex contract modifications. This is crucial in the context of rapidly changing markets, where the ability to adjust prices, add or remove commodities, and dynamically change business rules becomes key to maintaining operational continuity and efficiency.

3.4.2. Comparison with traditional approaches

Compared to static smart contract, dynamic smart contract interaction provides greater flexibility in managing market changes and regulations. Although the initial setup and transaction costs are higher, this investment pays off with increased transaction handling capacity and adaptation to changing market conditions. However, the higher complexity of dynamic smart contract interaction demands a deeper understanding of blockchain technology, which can be a challenge in it is adoption.

3.4.3. Implications for the future

These findings have significant implications for the future of supply chain management in blockchain. With higher adaptability, dynamic smart contract interaction can support businesses in efficiently facing unexpected market challenges and regulatory changes. This indicates great potential for applications in various sectors, especially where the need for rapid response to market dynamics is crucial. However, further efforts in user education and training are needed to fully leverage the potential of this technology.

3.4.4. Limitations and future research directions

While this study presents promising results, it also highlights certain limitations that need attention. These include the necessity for a deeper technical comprehension of blockchain technology and the intricacies of dynamic smart contract interactions. Future research should therefore prioritize the development of user-friendly tools and methodologies that simplify the use and understanding of blockchain technology. Moreover, it is essential to explore it is practical applications across various industrial contexts, evaluating its real-world effectiveness and adaptability in diverse operational environments.

4. CONCLUSION

Dynamic smart contract represents a significant advancement in blockchain technology. Addressing the rigidity of static contract by enabling real-time adjustments and updates, streamlining processes within complex supply chains. This adaptability saves time, reduces costs associated with contract redeployment, supports intricate decision-making, adapts to regulatory changes, and integrates new entities and assets effortlessly. As a result, a resilient and market-responsive supply chain is maintained. Smart contract interaction complements these advancements by providing a structured and efficient framework for managing interactions within the supply chain. It ensures that every action and transaction is transparent and traceable in real time, enhancing communication and coordination among all parties. This synergy between dynamic smart contract and smart contract interaction paves the way for a robust and responsive supply chain, revolutionizing the industry with improved efficiency, transparency, and an unprecedented level of adaptability and scalability.

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