A Blockchain-Based Framework for Sustainable Supply Chain Management of the Mining Industry in Vietnam

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Abstract. The mining industry plays a crucial role in the global economy by providing essential resources such as coal, oil, gas, and metal ores. However, the complexity and diversity of the mining process present many challenges in supply chain management (SCM), including transparency, traceability, efficiency, and growing demands to adhere to environmental regulations and uphold sustainability practices. The emergence of Industry 5.0 has led to a transformation in supply chain dynamics, ushering in the era of sustainable supply chains. This paper proposes a Blockchain and Smart Contract framework to monitor sustainable mining SCM (SMSCM). Blockchain technology ensures a secure decentralized supply chain through a peer-to-peer network. By incorporating innovative tools like Unmanned Aerial Vehicles (UAVs), LiDAR, and remote sensing tools, the framework addresses key issues including provenance, trust, consensus, inventory management, volume verification, and SCM monitoring. A methodology based on the Ethereum blockchain is outlined, demonstrating functions through a case study on coal mining in Vietnam, with detailed Smart Contracts (SC) implementation analysis.

Keywords: Blockchain · Sustainable Supply Chain · Mining Supply Chain Management · IoT · Smart Contract

1 Introduction

The mining sector is crucial to the global economy, providing essential resources such as coal, oil, gas, and metal ores. Recently, there has been significant research on integrating blockchain technology into sustainable supply chain management (SSCM) within the mining industry to enhance risk reduction, environmental governance, supply continuity, and cost efficiency. Using blockchain features like traceability, transparency, SC, and decentralization in supply chain management significantly benefits the social, economic, and environmental aspects of SSCM. These features ensure product quality, sustainability certification, anti-corruption measures, and easy information access. Additionally, blockchain improves economic efficiency by cutting costs, reducing expenses,

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and enabling payment initiation based on product conditions. It also aids environmental efforts through carbon footprint monitoring, waste optimization, and energy efficiency [1, 2].

Nevertheless, the mining industry faces significant challenges in supply chain management, especially in product tracking, transfer management, and transparency. Issues such as the lack of transparency and traceability can result in fraudulent activities and resource smuggling, undermining industry integrity and environmental sustainability. Moreover, the industry struggles with managing and monitoring the mining process and handling fragmented information related to specifications, product quantities, quality data, maintenance, and repairs. Additionally, there is mounting pressure to meet environmental regulations and ensure sustainability [3]. To overcome these challenges, this study proposes a framework using blockchain, SC, and advanced technologies to monitor SMSCM in the mining sector. The framework enables reverse traceability, transparency, and efficiency, as demonstrated through a case study on the coal supply chain in Vietnam. Integration of IoT, particularly through sensors and UAVs, allows continuous monitoring and intelligent management in SMSCM, with detailed analysis of the implementation of SC showing potential benefits and impact on SMSCM practices. In this paper, the contributions are presented:

- The paper introduces a novel Blockchain framework for monitoring sustainable mining Supply Chain Management (SMSCM). This innovative framework incorporates advanced tools such as Unmanned Aerial Vehicles (UAVs), LiDAR, and remote sensing technologies within the framework to handle key issues like provenance, inventory management, volume verification for bulk cargo, and monitoring environmental compliance of SCM in the mining industry.
- Highlighted the implementation of SC enabled by Blockchain technology, facilitating self-executing agreements between stakeholders in mining SCM. This enhances transactional efficiency and automation, ensuring specific conditions related to product standards, compliance with environmental regulations, and sustainability practices are met before executing actions.

The remainder of this paper is structured as follows: Sect. 2 provides an overview of the related work. Section 3 designs the proposed framework. Section 4 implements and shows the outputs of the proposed framework. Finally, some conclusions are given in Sect. 5.

2 Related Works

2.1 Blockchain and Smart Contract in SSCM

Industry 5.0 emphasizes SSCM, integrating AI and IoT for continuous monitoring. Blockchain technology mitigates agent credibility risks with its transparency and immutability, leading to increased adoption in SSCM for enhanced sustainability practices transparency [4]. The global supply chain is increasingly leveraging blockchain with IoT to improve interoperability and governance of devices. This integration enhances connectivity, data generation, and governance for supply chain partners. IoT devices collect specific data during product transportation, while distributed ledgers ensure secure data storage, providing improved monitoring capabilities [5]. Blockchain and IoT integration provide partners with real-time, reliable supply chain information enhancing traceability, enabling quick recovery of goods, tracking product stages, and estimating delivery times. This scalable platform facilitates peer-to-peer financial transactions without trusted intermediaries, reducing financial and reputational risks through SC functionality [6].

SC which automatically executes under specified conditions is integral to blockchain technology. Initially designed to digitize and automate legal contracts, SC have evolved to be predominantly associated with blockchain-enabled contracts [7]. SC are executed on decentralized ledgers, primarily utilizing Ethereum, along with other platforms like EOS, Polkadot, Tron, and Tezos These platforms provide a wide range of functionalities relevant to supply chain management [8]. SC can verify digital profiles of entities and products, ensure quality assessments, govern procurement processes, and enhance financial efficiency by eliminating the need for intermediaries. In SSCM, SC powered by blockchain technology is crucial in ensuring transparency, enforcing regulatory policies, and improving economic and environmental sustainability. The application of SC extends to industries like food, beverage, and agriculture, offering traceability, preventing counterfeit operations, and enhancing economic performance through disintermediation. By providing auditability, traceability, and automated payment execution, SC and blockchain technology revolutionize supply chain management practices toward enhanced efficiency and transparency [9].

2.2 Blockchain-Based Integrates SSCM in Mining

In recent years, there has been significant attention and research focused on applying blockchain technology to sustainability supply chain management in the mining industry. Kshetri emphasizes the strengths of blockchain in mining supply chains through real-world projects but lacks a comprehensive framework for implementing blockchain-based mineral tracking mechanisms [1]. Mugurusi demonstrates the potential of blockchain in creating transparency and traceability in cobalt sourcing from small-scale mining companies, with a focus limited to this specific group and lacking a comprehensive study of the entire mining industry [10]. J. Liu et al. propose a blockchain-based model for improving the financial condition and income of enterprises in the coal supply chain. However, their research only explores one aspect of the financial system in the industry and lacks a comprehensive analysis [11]. Others research highlight the application of blockchain in traceability and enhancing the sustainability of the mineral supply chain, but these studies are still in the early stages and lack a comprehensive approach for implementation across the entire mining industry [12, 13].

In conclusion, existing blockchain-based frameworks prioritize traceability and transparency in supply chains with insufficient attention to environmental monitoring. The integration of robust mechanisms to incorporate environmental data into blockchain and IoT systems is vital for sustainable mining supply chain management. Addressing gaps in integrating diverse environmental monitoring systems with these frameworks is crucial, necessitating standardized protocols and interfaces for seamless connectivity and efficient data collection and analysis. Particularly in scenarios involving bulk cargo like coal, ensuring volume verification in the supply chain before trading among stakeholders becomes imperative for accurate transactions and accountability.

3 Blockchain-Based for SSCM of Coal Mining

3.1 Application Scenario

In this section, we will detail the application of our framework in the coal supply chain of Vietnam National Coal – Mineral Industries Holding Corporation Limited (Vinacomin). Vinacomin, as the prominent coal supplier in the nation, plays a crucial role in ensuring a steady and sufficient coal supply for the economy, especially for the electricity generation activities of the Vietnam Electricity Group (EVN). According to the contract agreement with EVN, Vinacomin is responsible for delivering and supplying enough coal continuously, meeting the volume, quality, type, and delivery schedule specified in the contract terms. Therefore, establishing coal product traceability is essential in the coal supply chain, focusing on the accuracy of quantity and quality parameters. This necessitates comprehensive information sharing, optimized supply management, and traceability of coal products across various stakeholders in the supply chain, including mining operations, distributors, processing companies, and consumers (EVN). Ensuring environmental compliance and sustainability standards during mining operations is imperative, requiring Vinacomin to navigate through intricate regulations related to mining activities, environmental impact assessments, land usage rights, and rehabilitation obligations within the coal supply chain operations [14].

In response to these requirements, a new framework for SSCM has been proposed based on the coal supply chain of Vinacomin for EVN, with key application components: enhance traceability of coal products, facilitate proactive production planning through inventory information sharing, and ensure environmental compliance through real-time monitoring of mining activities.

3.2 Proposed System Architecture

In this paper, a new framework for sustainability is proposed based on an analysis of coal supply chain management in Vietnam. Figure 1 illustrates the architecture of the proposed framework, which comprises five layers: the perception layer, off-chain layer, blockchain layer, application layer, and user layer.

The perception layer is responsible for real-time data collection in the coal supply chain, gathering information from IoT devices such as environment sensors, GPS, and UAV-LiDAR. These IoT devices are linked to an autonomous agent registered within the blockchain network.

The off-chain layer plays a vital role in addressing scalability issues, improving performance, ensuring data privacy, reducing costs, and complying with regulations within blockchain systems. It involves storing private or large data in the cloud or InterPlanetary File System (IPFS), with the hash value of the data stored in the blockchain. For instance, the off-chain layer handles data such as mine status images obtained using UAV and remote sensing tools. Data that are less sensitive or of standard size are directly

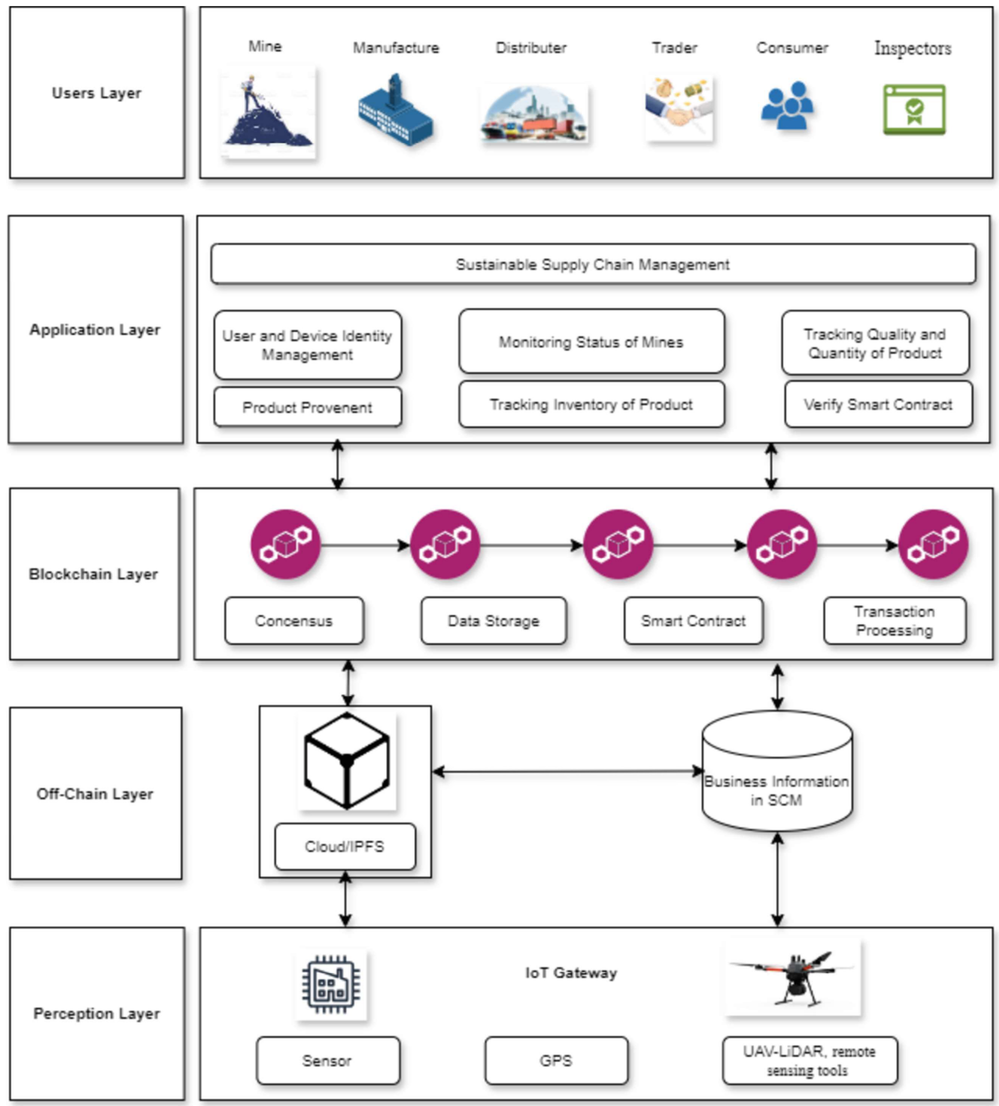

Fig. 1. Proposed System Architecture

placed on-chain, such as location, temperature, and the origin of raw coal. The input data to the blockchain comes from two sources: IoT devices and business information in the supply chain. The input data format is predefined using a JavaScript Object Notation (JSON) file to ensure consistency and compatibility with the system.

The blockchain layer as the foundation of the framework, contains consensus, SC, data storage, and transaction processing. The framework is established within a private Ethereum blockchain network, where mining nodes across the network utilize the proof of authority (PoA) consensus algorithm to mine and append blocks of instructions to the blockchain ledger. Any device capable of collecting, validating, and executing transactions can operate as a mining node. These nodes are responsible for storing data, and transaction results, and maintaining a common blockchain ledger accessible to all nodes. SC within the blockchain enables transaction facilitation via function calls and events, empowering stakeholders to oversee, trace, and receive relevant updates when needed [15]. The SC is generated and implemented, with each participant holding a distinct Ethereum address as their registered account. These stakeholders are identified within the network through their specific Ethereum addresses. Moreover, the Ethereum address encompasses public and private keys utilized for digitally signing and validating transaction data authenticity and linking transactions to the relevant Ethereum account [16].

The application layer consists of user and device identity, quality, and quantity certificate, product provenance, monitoring mining status, tracking inventory, verify SC. The sustainable supply chain provides interfaces for stakeholders to inquire about relevant product data, and information in the supply chain, which interacts with the blockchain network through application programming interfaces (APIs).

The user layer involves various stakeholders like miners, manufacturers, distributors, traders, consumers, and inspectors in the coal supply chain. Miners obtain licenses and conduct assessments before mining raw coal. Manufacturers process and classify raw coal to create clean coal products, which distributors sell to traders. Traders facilitate contracts with consumers for products. The inspector conducts stringent quality inspections at all stages of production and consumption, employing quantity inspection techniques to verify compliance with set standards. UAV-LiDAR technology is utilized for volume checks, and environmental monitoring is done using UAVs and sensors. IoT devices manage factors like temperature and humidity during transportation and storage. A decentralized blockchain system with SC connects all participants, enabling traceability and proactive production planning for stakeholders.

3.3 Smart Contract

Within the context of SCM, stakeholders engage in the establishment of SC. These contracts serve as a collection of digital commitments, representing a digital agreement among stakeholders that resides within the blockchain network and is linked to a specialized blockchain address. When the fulfillment of predefined conditions by the involved parties, the SC is activated. The implementation of this process enhances trust among stakeholders, deriving from the inherent reliability and integrity of blockchain technology. The algorithm of SC outlines the steps involved in buying raw coal and the product of coal from the mine to the consumer in the coal supply chain, as shown in Algorithm 1 to Algorithm 5.

Initially, the SC is created and deployed, with each stakeholder having a registered address, the process begins when the MNF requests to purchase raw coal from the Mine, following Algorithm 1. The SC verifies MNF's registration status, raw material suitability, quantity and quality checks, mining inventory volume, UAV validation of volume, and correct payment amount. If conditions are satisfied, the system updates tracking and inventory, transfers payment to MINE, updates contract status, and broadcasts notifications. Otherwise, the system reverts to the initial contract state and displays the corresponding error message. Following this, MNF processes and screens the raw coal to produce coal, as described in Algorithm 2. The SC verifies specific conditions, including MNF's registration and the passing of quantity and quality controls. Upon successful validation, the system updates the tracking of the coal product, changes the product's state to MNFPro, updates the contract status, and broadcasts notifications.

Otherwise, the system reverts to the initial contract state and displays the corresponding error. When the coal product is ready, the DTB submits a request to purchase the coal product from MINE as shown in Algorithm 3. The SC confirms various conditions, including DTB's registration, product state, quantity and quality controls, volume availability in MNF's inventory, UAV confirmation, and payment matching. If conditions are satisfied, the system updates the tracking of the coal product, adjusts inventories, transfers payment, updates contract status, and notifies relevant parties. Otherwise, the system reverts to the initial contract state and displays the corresponding error message. Afterward, TRA purchases coal products from DTB following Algorithm 4. The SC verifies TRA's registration, product state, quantity and quality controls, volume availability in DTB's inventory, UAV confirmation, and correct payment amount. If all conditions are satisfied, the system updates product tracking, adjusts inventories, transfers payment, updates contract status, and notifies relevant parties. Otherwise, the system reverts to the initial contract state and displays the corresponding error message. Finally, CSM buys coal products from TRA as described in Algorithm 5. The SC validates CSM's registration, product state, quantity and quality controls, volume availability in TRA's inventory, UAV confirmation, and payment matching. If all criteria are satisfied, the system updates product tracking, adjusts inventories, transfers payments, updates contract status, and sends notifications. Otherwise, the system reverts to the initial contract state and displays an error message.

Algorithm 1. MNF buys raw coal from MINE

Input: Address of MINE
    Address of MNF
    rmid, rmcid, volumeRM, priceRM

1. ContractState Created
2. Status of MNF: Request buy raw coal
3. Status of MINE: Read
4. *If MNF = registed and stateRM = MinedRM and checkQuantityCtrl = true and checkQuanlityCtrl = true and mineInvs > = volumeRM and checkUAV-VolumePR=true and msg.value = priceRM Then*
5. Update tracking raw coal: *mnfaddr→msg.address, stateRM → ManufacturedRM*
6. Updated inventory of raw coal*: minusMineInv -= volumeRM, addMnfInv += volumeRM*
7. Update payment: *mineaddr.transfer = priceRM*
8. Contract status → Buy successfully
9. Broadcast a notification message
10. End
11. Else
12. Return to the initial contract state and display the error
13. End

Algorithm 2. MNF process and screen product of coal

Input: Address of MNF
Address of MINE
proid, coalid, proName, proCID, mineDatePro, volumePro, pricePro, statePro

1. ContractState Created
2. Status of MNF: Process and Screen product of coal
3. *If MNF = registed and checkQuantityCtrl = true and checkQuanlityCtrl = true Then*
4. Update tracking coal product: *mnfaddr→msg.address, statePro →MNFPro*
5. Updated inventory of coal product*: addMnfInv += volumePro*
6. Contract status → Product of coal
7. Broadcast a notification message
8. End
9. Else
10. Return to the initial contract state and display the error
11. End

Algorithm 3. DTB buys product of coal from MNF

Input: Address of DTB
proid, coalid, volumePro, pricePro

1. ContractState Created
2. Status of DTB: Request buy product of coal
3. *If DTB = registed and statePro = MNFPro and checkQuantityCtrl = true and checkQuanlityCtrl = true and mnfInvs > = volumePro and checkUAV-VolumePR=true and msg.value = pricePro Then*
4. Update tracking coal product: *dtbaddr→msg.address, statePro →DTBPro*
5. Updated inventory of coal product*: minusMnfInv -= volumePro, addDtbInv += volumePro*
6. Update payment: *mnfaddr.transfer = pricePro*
7. Contract status → Buy successfully
8. Broadcast a notification message
9. End
10. Else
11. Return to the initial contract state and display the error
12. End

Algorithm 4. TRA buys a product of coal from DTB

Input: Address of TRA
proid, coalid, volumePro, pricePro

1. ContractState Created
2. Status of TRA: Request buy product of coal
3. *If TRA = registed and statePro = DTBPro and checkQuantityCtrl = true and checkQuanlityCtrl = true and dtbInvs > = volumePro and checkUAV-VolumePR=true and msg.value = pricePro Then*
4. Update tracking coal product: *traaddr* → *msg.address, statePro* → *TRAPro*
5. Updated inventory of coal product*: minusDtbInv -= volumePro, addTraInv += volumePro*
6. Update payment: *dtbaddr.transfer = pricePro*
7. Contract status → Buy successfully
8. Broadcast a notification message
9. End
10. Else
11. Return to the initial contract state and display the error
12. End

Algorithm 5. CSM buys product of coal from TRA

Input: Address of CSM
proid, coalid, volumePro, pricePro

1. ContractState Created
2. Status of CSM: Request buy product of coal
3. *If CSM = registed and statePro = TRAPro and checkQuantityCtrl = true and checkQuanlityCtrl = true and traInvs > = volumePro and checkUAV-VolumePR=true and msg.value = pricePro Then*
4. Update tracking coal product: *traaddr* → *msg.address, statePro* → *DLVPro*
5. Updated inventory of coal product*: minusTraInv -= volumePro, addCsmInv += volumePro*
6. Update payment: *traaddr.transfer = pricePro*
7. Contract status → Buy successfully
8. Broadcast a notification message
9. End
10. Else
11. Return to the initial contract state and display the error
12. End

4 Implementation of Smart Contracts and Output

For the testing purposes, we conducted with solidity on Remix IDE [17]. Remix is an online IDE that enables developers to use Ethereum wallets with dummy cryptocurrency. We utilize the MetaMask Ethereum Wallet and Chrome extension [18] to interact with Ethereum networks. The Remix IDE environment offers capabilities for compiling and deploying SC on the blockchain. Furthermore, the Sepolia Testnet was employed as an alternative tool to simulate the blockchain for testing purposes [19] (Fig. 2). While testing and validating the suggested framework, we conducted tests on the modifiers and function calls in the SC to guarantee that only the authorized Ethereum address holder could execute the functions. Additionally, we also verified the activities to ensure the correct flow of information and data. The SC deployed is detailed in Fig. 3. Additionally, the advancement of our proposed framework with the current blockchain-based frameworks and traditional coal mining supply chain is shown in Table 1.

Fig. 2. Remix IDE connects with the Meta mask wallet.

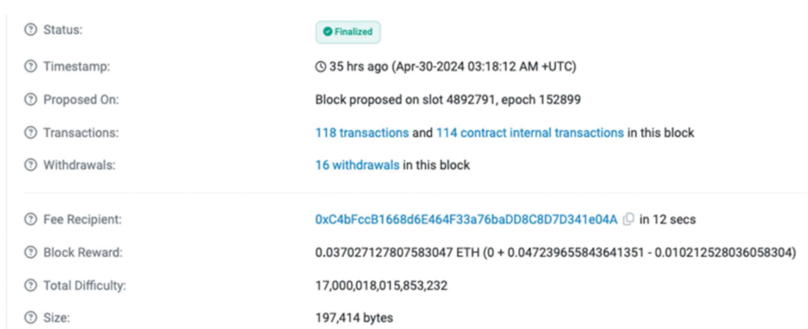

Fig. 3. SC deployed on Sepolia Testnet [20].

Table 1. The Advantages of Proposed Blockchain-based Framework

Attributes	Traditional Model	Current Blockchain-based Framework	Proposed Framework
Provenance	Historical info not recorded	History of transactions available	History of transactions available
Immutability	Administrators can manipulate info	Transactions cannot be changed	Transactions cannot be changed
Trust	Trust issues in centralized approach	Increased trust in a collaborative environment	Increased trust in a collaborative environment
Consensus	No such feature is available	Agreement among stakeholders	Agreement among stakeholders
Tracking inventory of each stakeholder	No information	No information	Available along the supply chain, supporting production planning
Verify the volume of SC	No feature	No feature	Utilizing UAVs with LiDAR technology for volume estimation
Monitor the status of mines	No feature	No feature	Using UAVs with LiDAR and remote sensing tools for mine status

5 Conclusion

Following the analysis of the challenges in coal mining in Vietnam, the necessity of implementing blockchain technology becomes evident. The proposed blockchain-based framework based on the Ethereum blockchain and SC addresses key issues such as provenance, immutability, trust, consensus, inventory management, verification of cargo volumes, and periodic monitoring of coal mines. By leveraging blockchain technology and integrating innovative solutions of IoT such as UAVs, LiDAR, and remote sensing tools, the proposed framework offers a comprehensive approach to enhance transparency, efficiency, and sustainability in the coal mining supply chain. This conclusion emphasizes the significance of embracing blockchain technology to overcome the existing challenges and show the way for a more innovative, environmentally conscious, and technologically advanced coal mining industry in Vietnam. However, it is important to note that implementing and integrating blockchain on a large scale remains a complex task. Future research will validate and implement the proposed framework to evaluate its execution costs.

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