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AI-Enhanced Blockchain for Scalable IoT-Based Supply Chain

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Abstract: *Purpose*: The integration of AI with blockchain technology is investigated in this study to address challenges in IoT-based supply chains, specifically focusing on latency, scalability, and data consistency. *Background*: Despite the potential of blockchain technology, its application in supply chains is hindered by significant limitations such as latency and scalability, which negatively impact data consistency and system reliability. Traditional solutions such as sharding, pruning, and off-chain storage introduce technical complexities and reduce transparency. *Methods*: This research proposes an AI-enabled blockchain solution, ABISChain, designed to enhance the performance of supply chains. The system utilizes beliefs, desires, and intentions (BDI) agents to manage and prune blockchain data, thus optimizing the blockchain's performance. A particle swarm optimization method is employed to determine the most efficient dataset for pruning across the network. *Results*: The AI-driven ABISChain platform demonstrates improved scalability, data consistency, and security, making it a viable solution for supply chain management. *Conclusions*: The findings provide valuable insights for supply chain managers and technology developers, offering a robust solution that combines AI and blockchain to overcome existing challenges in IoT-based supply chains.

Keywords: blockchain; artificial intelligence; swarm intelligence; block pruning; scalability

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1. Introduction

Traceability is one of the most crucial aspects of supply chain management, involving the identification and tracking of products and services as they move through the supply chain. Given the complexity of modern supply chains, effective management is essential to ensure smooth operations and address the challenges that arise. The supply chain is the backbone of any organization, overseeing the flow of services and products across the enterprise.

With the constant evolution of technology, the Internet of Things (IoT) has become one of the most influential concepts in modern innovation, contributing significantly across various fields, including IoT-based supply chains [1]. The IoT serves as the backbone of IoT-based supply chains and is regarded as a paradigm for the connection between communicating peripherals [2]. Smart houses, smart vehicles, and intelligent automobiles are all part of this ecosystem [3]. The IoT offers solutions in a multitude of sectors for more effective manufacturing; nevertheless, IoT-based supply chains face several challenges, including security, big data management, centralization, hardware capabilities, and connectivity issues [4].

C.-M. Chung et al. [5] have stated that networks, such as supply chain networks, generate enormous amounts of data from IoT applications at high speeds. Thus, data centralization and non-transparency are significant issues for supply chains. Many experts have suggested the use of blockchain technology for supply chain management as a solution to this problem [6]. Blockchain is a distributed, decentralized, and secure database technology [7]. Every node in this technology is designed to track and communicate all transactions and timestamps without the need for a third party. Blockchain technology provides adequate solutions for numerous industries, such as healthcare, banking, data security, and agriculture [8]. A hash function connects the data contained in blocks into a chain. As every block in the blockchain is connected to the previous block, it is highly resistant to tampering by malicious entities in the network [7].

However, blockchain has some characteristics that are not entirely compatible with supply chain requirements [9]. To mitigate these problems, artificial intelligence (AI) can be employed, which has been increasingly used in recent years to solve various research challenges by performing human-like functions, such as decision-making and speech recognition [10]. Thinking, learning, and self-correction are all elements of this system. Learning is gaining knowledge and principles from data, whereas reasoning is the process of using those rules to draw approximate or definite conclusions.

- Research Gap and Contribution: This study addresses the gap in integrating artificial intelligence (AI) with blockchain technology to optimize performance in IoT-based supply chains. Existing research often overlooks the synergy between AI and blockchain, particularly in overcoming the specific challenges of latency, scalability, and data management. By proposing the ABISChain platform, this research introduces a novel approach that combines AI with blockchain to enhance supply chain efficiency. This approach not only addresses existing limitations, but also contributes to the theoretical understanding of AI-enabled blockchain systems.
- Scientific Discipline and Novelty: The present research contributes to the field of supply chain management and blockchain technology by presenting a new system model that leverages AI to optimize blockchain performance. The ABISChain platform represents a significant advancement in integrating AI with blockchain, offering improved scalability, data consistency, and security. This study also extends the application of AI in blockchain environments, providing a deeper understanding of how AI can enhance decentralized systems.
- Increased Cognitive Value: This research expands the analysis of blockchain and AI integration within supply chains, offering a comprehensive review of the existing literature and identifying gaps in current solutions. Through incorporating AI-driven optimization techniques, the study enhances the cognitive value of supply chain management research and provides a robust platform for future advancements.
- Methodology: We conducted a systematic review of the literature by searching major databases with keywords related to the IoT, blockchain, and AI in supply chain management. Relevant articles were selected based on their contribution to understanding the integration of these technologies and addressing supply chain challenges.

While blockchain and AI have been combined in an effort to assist supply chains, some hurdles still remain. In supply chains, IoT devices collect massive amounts of data. Therefore, security and space issues are affecting data storage [11]. This study accordingly offers a detailed analysis of AI-based blockchain for IoT-based supply chains, identifies key challenges, and presents a robust solution.

The rest of the paper is organized as follows: Section 2 provides an overview of AI-, blockchain-, and IoT-based supply chains. Section 3 examines blockchain-based supply chain projects, discussing their benefits, limitations, and challenges, and presents solutions for addressing these issues. Section 4 presents ABISChain, detailing its system model, design, and implementation. Section 5 analyzes the performance of ABISChain, benchmarking it against existing work and evaluating its storage complexity, processing time, and other relevant factors to verify the validity of the proposed solution. Finally, Section 6 concludes the paper with a summary of key findings and recommendations for future research.

2. Overview of AI, Blockchain, and IoT-Based Supply Chains

This section discusses artificial intelligence and blockchain for IoT-based supply chains and their efficiency contribution for supply chain systems. Blockchain technology and AI are core technologies of the last decade. Therefore, many applications have been developed based on their combination. Blockchain can be applied in the form of a platform that is distributed and decentralized for both apps and businesses, whereas AI is generally used for analysis of data for an intelligent decision-making capability.

2.1. Supply Chain Challenges

Connecting the IoT to traditional supply chain systems is difficult, as these systems are not equipped to manage the large volumes of data generated by the IoT, leading to the potential loss of information and reduced efficiency [12]. The current distribution system involves multiple suppliers, each managing its own section of the supply chain independently using their own centralized platforms [13]. These platforms store data in different formats and protocols, each with its own standards [14]. As a result, sharing information between these platforms is challenging. The IoT has greatly contributed to global industry [15]. In general, IoT systems are varied, and can be divided into categories: semantic-oriented for employing knowledge features, inter-oriented for acting as middleware, and things-oriented for sensing [16]. These IoT systems are associated with various administrative areas [17] (e.g., energy and transport). In the industrial field, there are five IoT techniques: cloud computing, RFID, middleware, IoT software, and WSN. With the help of the IoT, the IoT application may gather precise information, such as determining true color degrees and temperature differences [18]. While IoT technology can support technological development, manufacturing, and production, it also has steep equipment costs and high data load for servers [19]. The existing infrastructure for networks cannot use the entire potential of IoT technologies [12]. The IoT also has its own drawbacks. One of them is that centralized solutions fail to recognize and control the huge amount of incoming data and information [12]. There are currently no trustworthy infrastructures or frameworks that link the huge number of IoT objects or their interconnected services together and that connect those objects to data aggregation and analysis services [20]. At present, it is challenging to meet some of the necessary elements of trusted third-parties using standalone supply chain systems [12]. Furthermore, due to the decentralized structure of participants, scalability is a major challenge. A digital document is distributed geographically and consists of multiple copies that require multiple communication channels to meet the different requirements in each region. A study [21] has found that to conclude a single delivery, more than a hundred connections are required. Therefore, the supply chain tends to have important traffic. The existing systems provide no assurance of security, integrity, or confidence. As a result, data are lost, and confusion arises. Moreover, due to security issues, present systems are prone to attacks and exploitation in highly scaled solutions due to their widespread nature and lack of control [13].

2.2. Blockchain

The concept of blockchain refers to a digital ledger that efficiently and openly documents transactions and the transfer of value. This idea has given rise to various cryptocurrencies and blockchain applications, such as Bitcoin and Ethereum. Through employing blockchain technology, transaction records can be shared in a secure, decentralized, and reliable manner [22]. Each block within the blockchain consists of four components: information about the exchange of assets or transactions, the hash of the previous block, the current block's hash, and the timestamp of the block. In scenarios where a huge volume of data is required, solutions employ decentralized database platforms such as IPFS, LitecoinDB, and DBchain. The IPFS is a decentralized, distributed database and P2P System which connects peers that share common media. IPFS is a huge storage medium created based on blockchain technology. It is designed to handle high throughput, such as that in IoT applications. Large amounts of data raise challenges in the form of security vulnerabilities, privacy, and fault tolerance in Internet of Things apps [16]. Considering these issues in managing and protecting many IoT devices, many researchers have proposed blockchain technology for the IoT. With blockchain technology, cryptography, and other security techniques, there is the significant implication of high computational power requirements [23]. IoT security and privacy are protected through blockchain in many apps, including those related to healthcare, smart cities, and smart homes [24]. Blockchain provides authenticity in a P2P network. The integration of blockchains and IoT applications in the supply chain is holistic and aimed at solving data management issues. This integration can radically improve the quality of supply chain services.

2.3. Artificial Intelligence

Intelligent technology is the future of the world. AI is a branch of computer science concerned with the development of machines with human-like intelligence. It consists of super intelligence, narrow AI, and general AI. Based on new analysis, it is estimated that intelligent machines will replace human activities in a variety of applications including medical science, self-driving cars, and even agricultural pilots [25]. Artificial intelligence (AI) is a mechanism or computer code that determines what information to provide, how to process it, and what type of response to give a particular instruction or question [26]. The challenges associated with the "Internet of Things" include energy efficiency, big data analytics, security, privacy, and traffic congestion. The use of artificial intelligence for the IoT can address these challenges. With the use of automation technology, energy efficiency can be completely solved in a smart city because AI will be able to identify and predict parameters like real-time energy consumption patterns, weather conditions, traffic flow, building occupancy, or energy demand trends. Thus, the data collected by AI will be included in city energy management in a sophisticated manner to help creators choose the best control strategy for energy consumption. The new fields of "machine learning" and "connected devices" allow us to collect and analyze huge quantities of data and use the data to make predictions about the future [27]. Introducing automated decision-making to the blockchain can reduce supply chain data problems [28]. Machine learning techniques for blockchain can keep data protected from cybersecurity threats through secure accessibility, malicious data offloading, and detecting anomalies in the provided data [24].

2.4. Blockchain-Based Supply Chain

The blockchain is an excellent choice for addressing the aforementioned supply chain problems. It is a fully decentralized peer-to-peer mechanism that establishes confidence between participants taking part in different activities over time. The blockchain is immutable, tamperproof, decentralized, distributed, and trustworthy. It can support multiple signatures, ensures independent verification, and acts as a ledger of transactions [29]. The main types of blockchain are public, private, and consortium. The blockchain eases the process of managing the supply chain in its functionalities and limitations [30] with the following features:

- Decentralization: Blockchain technology creates a distributed system with no central administrator and establishes its own rules based on a consensus mechanism. In a supply chain based on blockchain, the participants in the blockchain are able to identify any data deterioration [31]. For this reason, blockchain technology solves the issues related to centralization, hacking, data integrity, and corruption and increases data validity [30].
- Trustworthiness: The core feature of the blockchain is a completely unified vision of subscribers' information that is always available. In cryptography systems, the privacy of the user's online accounts, as well as their anonymity, is enabled [32]. Each user in the blockchain sees the same information and cannot modify or remove it. Blockchain's decentralized nature makes trust unavoidable for data records in a decentralized supply chain. One study proposed that supply chain transparency must be a primary feature of blockchain to promote trust among food companies [33].

2.5. Blockchain-Based Supply Chain Challenges

In our situation, blockchain has notable shortcomings due to its inability to satisfy requisites of the supply chain. Blockchain's distributed nature and its structure lead to serious limitations. The main source of concern for blockchain apps is scalability, as the decentralized P2P network structure results in a long response time to multiple requests. The instability of the network further increases the delay and causes scalability issues as the transaction relying on different factors. The fundamental part of blockchain is the consensus mechanism, which links different blocks together and approves transactions in an entirely peer-to-peer environment. While important, the consensus mechanism is the main aspect affecting scalability. Moreover, blockchain slows down apps due to its architecture and reduces transaction speed as a result of its internal cryptographic rules. The best-known consensus protocol, proof of work, has a very low transaction validation rate. The IoT revolution coincided with the proof of stake (POS) algorithm, which confirms transactions with twice the speed of POW. On the other hand, it exhibits significantly lower speed when handling generated data, and it struggles to cope with the throughput of a vast number of IoT peripherals. New protocols are currently being developed to improve transaction effectiveness by using more effective algorithms [34,35].

The second impediment for blockchain scale is the property of being a shared ledger, with blocks containing a set of validated transactions. Block creation and transaction validation require many resources. This hinders the entire blockchain system performance. The number of validator nodes, the block size, and the status of the network are all factors that also change the performance of the network. With the decentralization of blockchain techniques and to keep the distributed ledger up to date, members must perform heavy computational work. IoT devices will challenge supply chain actors in storage and processing capacities. Such devices that track activity struggle to save energy when they are in idle time [36]. That is why they cannot function as a dedicated server-miner in a P2P network. When consensus algorithms and cryptography are applied to limited computational power devices like IoT ones, the security on the Internet of Things is weak. IoT devices are placed for specific activities and widely spread to collect accurate data. Blockchain size, which grows with time, is stored by each participant. The storage capacity of IoT devices is typically restricted [37,38]. Reliance on these devices to store the blockchain is quite a substantial issue that impacts the system. Additionally, the inability to compress or minimize the unwanted ledger data adds to the difficulties.

An effective blockchain requires an ideal network infrastructure, where all nodes involved in each blockchain must be connected and synchronized continuously so that the system can run and the blockchain can function as intended. In general, IoT devices are dispersed across several geographic locations. Providing good throughput requires expensive hardware that is susceptible to hacks and attacks. A lack of hardware security increases the likelihood of hacks and security flaws. Similarly, blockchain fees still pose a substantial challenge in blockchain. Data should also be stored long-term in an extendable form in the cloud to give devices secure access to data with a high throughput. In regard to blockchain fees, the recommended fees for the supply chain should be low. The fees can be made affordable for people of different economic strata and for different currencies. Additionally, we should consider how we could function without the need to connect or how smartphones use peripheral devices that allow payments to be made offline and appear in the blockchain once online. Handling storage, computing, and transaction fees is a tricky task that involves building around the needs and capabilities of each use case of each system. Thus, the previously mentioned terms must be managed in such a way that they do not negatively influence the function of the supply chain. In conclusion, an ideal solution with Internet of Things (IoT) technology should have all the capabilities of the blockchain (e.g., data storage and computational resources) without being involved. At present, new supply chain blockchain solutions have not yet achieved this goal. Most proposed blockchain systems to date do not include the needed features.

2.6. Ideal Supply Chain Requirements

Future supply chains will be based on these main technologies: blockchain, artificial intelligence, and the Internet of Things. Thus, the combination of these items and the supply chain [12] is mandatory given the supply chain issues. Current systems have many flaws and require considerable adjustment to satisfy the needs of enterprises. Blockchain also has its limits and drawbacks. That is why current supply chains based simultaneously on blockchain and the IoT have conspicuous limitations [12,39]. Obviously, there are many differences between the IoT and current supply chains. These technology discrepancies lead to their incompatibility. The alliances between blockchain- and IoT-based supply chains will influence the supply chain's strength. The requirements for an ideal platform system are instant visibility and traceability throughout the chain and high scalability to handle the massive data generated by supply chains.

Current supply chains prove that decentralization is the only viable solution [40]. Decentralization, traceability, immutability, fault tolerance, and data security are all blockchain criteria for a modern supply chain system. Furthermore, smart contract technology can automate processes and boost the integration of IoT systems [13]. Figure 1 below shows the keys to optimizing transaction fees, storage, and computation in relation to the aforementioned blockchain issues.

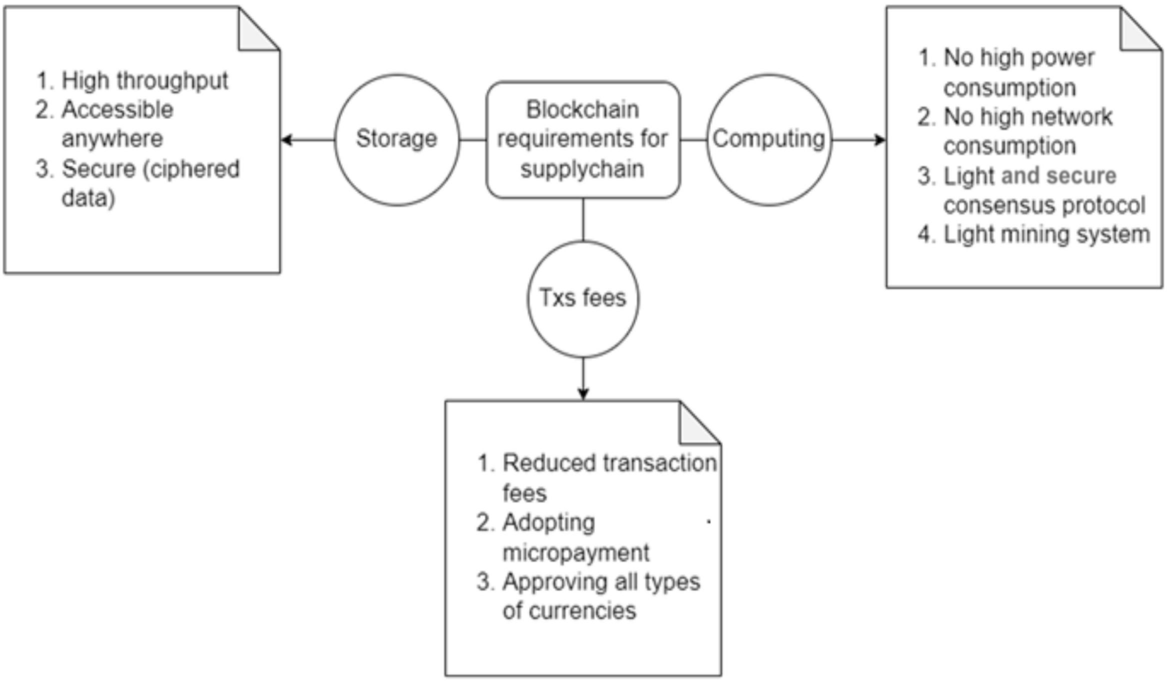

Figure 1. Blockchain requirements for the supply chain.

Furthermore, as supply chain infrastructure is already designed to handle enormous volumes of data and complicated activities, the blockchain consensus algorithm and mining process should have no impact on production progress. High computing can be eliminated but only in certain situations and with significant alterations, such as delving into a permissioned blockchain or using particular consensus methods like proof of authority (POA). Another important aspect of a good blockchain is storage. The blockchain is mostly kept on peripheral devices as it is a P2P system which surcharges these devices as the blockchain grows. In a supply chain system, the appropriate practice is to exclude chain members from difficult tasks.

Automation is a feature that can be incorporated in blockchain based on pre-determined norms and criteria that can represent an AI entity that controls and manages blockchain and progresses over time to maintain the stability of the blockchain, as smart contracts and AI can verify the transactions between parties. A smart contract is a form of software or script that is stored on the blockchain [40] and is activated when certain prerequisites are satisfied. In time, AI entities can redefine the smart contract conditions to keep the blockchain network stable. Once published, the smart contract is transmitted to all network nodes as a traditional transaction. Then, if the fixed conditions are fulfilled, the blockchain state is updated. Current supply chain contracts will no longer be a concern, due to this automated procedure that does not require human participation [41].

2.7. Summary

In this section, we provided an in-depth overview of AI, blockchain, and their roles within IoT-based supply chains to underscore their impact on improving supply chain efficiency and addressing the inherent challenges of traditional systems. We first examined the significant obstacles in supply chain management, including transparency, data integrity, and scalability issues. We then explored the fundamentals of blockchain technology, highlighting its decentralized and immutable nature, which makes it ideal for enhancing supply chain operations. Additionally, we discussed the role of AI in analyzing large volumes of data, enabling real-time decision-making and predictive analytics.

By detailing the integration of AI and blockchain in supply chains, we established a clear understanding of how these technologies can be combined to create a more efficient, transparent, and scalable system. This foundational knowledge is essential for understanding the subsequent analysis in our research and the development of the ABISChain platform, which leverages AI and blockchain to overcome current limitations and meet the ideal requirements of a modern supply chain. This groundwork directly supports the contributions and solutions proposed in our study.

Table 1 clarifies the distinct challenges that the IoT and blockchain technologies face when applied to supply chains. It highlights how the IoT can overload systems with data, face connectivity issues, and struggle with resource efficiency, while blockchain, despite offering enhanced security and transparency, can slow down transactions and impose high resource demands. This comparative analysis sets the stage for understanding how our proposed ABISChain platform could resolve these issues by effectively integrating AI and blockchain technologies.

Table 1. Challenges and impacts in IoT- and blockchain-based supply chains.

Challenge	IoT Impact	Blockchain Impact
Scalability	Overloads systems with vast data.	Slows down transactions with decentralization.
Data Management	Inconsistent databases block data flow.	Slow processing due to consensus validation.
Security	Susceptible to breaches, lacks strong security.	Strong security but high resource demands.
Network Infrastructure	Connectivity issues with dispersed devices.	High costs for continuous synchronization.
Resource Efficiency	Struggles with energy under heavy loads.	Resource-heavy, limiting low-power device use.
Cost and Fees	High costs for servers and infrastructure.	Transaction fees hinder widespread use.
Trust and Transparency	Centralized control, lacking transparency.	Transparent but faces latency and scale issues.

Building on this foundation, the next section critically reviews the existing literature on blockchain-based supply chains, examining how current solutions and techniques align with or fall short of the ideal supply chain requirements identified earlier.

3. Related Work: A Critical Literature Review

This section initially discusses the blockchain-based supply chain projects and the benefits of combining blockchain and supply chains. We also mention their limits and problems. In the second subsection, we present and analyze solutions that can resolve the issues of the existing supply chain projects and satisfy supply chain requirements.

The main component of the supply chain is the IoT layer. That is why the research problem of blockchain on the IoT has been investigated and debated by a number of researchers. According to N. Kshetri [42], there are four types of IoT challenges: Deficient architecture, capacity and costs constraints, cloud server failure or service unavailability, and manipulation susceptibility. Their research examined potential blockchain solutions for each IoT concern as well as the role of blockchain in strengthening overall supply chain security. The research of M. Banerjee et al. [43] looked into IoT security solutions, including the scarcity of freely accessible IoT datasets. Given the potentially sensitive nature of IoT statistics, a protocol allowing scientists to share Internet of Things datasets, professionals, and other interested parties is needed. Reference [44] investigated how blockchain may potentially enhance the IoT, described the link between blockchain and the IoT, provided investigative issues in blockchain IoT apps, and reviewed interesting studies to examine how the IoT can benefit from blockchain. Y. Qian et al. [45] discussed the three levels of the IoT: perception, network, and application layers. They also discussed for each layer the security issues that are faced by high-level blockchain security management systems for various IoT devices and outstanding research questions. Their approach includes aberrant network traffic monitoring and identity verification using machine learning. The advantages of blockchain for AI and societal development were explored in [46]. F. Tian developed an environment-friendly food tracking system based on blockchain and the IoT [30]. It is a dependable, open, self-organized, and eco-friendly system for smart agriculture.

Supply chains are crucial to all enterprises worldwide. Due to blockchain and smart contracts, as well as IoT technology, the integration of blockchain with enterprises and their many partners can remodel the global supply chain. Through research into new blockchain-based platforms, several blockchain-based initiatives have been developed to enhance scalability and save time and money. In addition to the blockchain problems listed above, these projects face several challenges like the kind of supply chain company, each company platform's major objectives, and the type of supply chain business.

Many initiatives involving blockchain and the IoT are included in a report by V. Nikhil and T. Paolo [47] which categorizes them into four categories: supply chain, healthcare, groceries, and fashion. Most of these solutions are built using Ethereum and APIs; however, there are no explicit publications or technical references. In this section, we will present projects integrating blockchain in their supply chain solutions, and we will focus on their contributions and limitations. Also, we will present blockchain solutions that can negate previous blockchain-based supply chain issues.

3.1. Blockchain-Based Supply Chains

This section delves into a range of innovative projects that fuse blockchain and IoT technologies to revolutionize supply chain management. These initiatives harness the power of blockchain to address key challenges such as transparency, traceability, and efficiency. By leveraging decentralized ledgers and smart contracts, these projects offer solutions that enhance data integrity and streamline operations across various supply chain sectors. The following examples illustrate how different blockchain-based systems are applied to real-world supply chains, each with its unique approach to fundamentally transform and enhance traditional supply chain practices:

- Shipchain [48] is an integrated supply chain system that focuses on tracing shipments among their transportation cycle. Shipchain is a smart contract and side-chain platform that runs on the Ethereum public blockchain. For cost-cutting purposes, all records are saved on Ethereum, whereas side chain data are maintained and confirmed on the concerned parties' network. As a result, data are stored either on Ethereum or on side chains without the use of an intermediary. Shipchain also includes a web platform allowing shippers to interact with carriers instead than using traditional brokerage arrangements.

- Devery [49] is an Ethereum verification technology. It is employed to create checking apps in which vendors should provide a unique identifier of their products. The identifiers are kept on Ethereum and are used to validate an item during application searches. This protocol is made up of structures communicating with Ethereum using smart contracts. StructApp, unique identifier, and account are the three types of data structures. Product information, brand accounts, and app accounts are all contained in the Struct product. The unique identification for each product kept on the blockchain is determined via the hash of the product information.
- Cargox [50] is a decentralized system that uses the Ethereum blockchain to handle bill of lading papers. Cargox is a global leader in supply chain logistics trade. Users communicate over the Cargox DApp's API interface and generate their smart bills of lading. Users can consume CXO tokens or exchange them to dollars to make payments.
- CargoCoin [51] is a supply chain platform based on Ethereum that intends to regroup all cargoes in a single platform and connect them to the designated counterparties. Within the blockchain, both the smart contracts and the service's platform are used to achieve this goal. Many communication channels are provided in this platform for CargoCoin actors participating in the supply chain's evolution, including sending/receiving, approving, rejecting, and signing documents.
- WaltonChain [52] is a supply chain blockchain that allows many participants to track RFID-based transactions. It is made up of a main chain and sub-chains, with the mainchain hosting and mining the WTC coin. Following construction and registration within the main chain, a sub-chain runs independently. Significant information about the sub-chains is stored in the main chain. Sub-chains have their own ledgers while still being part of the main chain network. POW, POS, and POL are used to form parent chain consensus. Because the main chain works independently of sub-chains, the size of its ledger is unaffected by the number of sub-chains. As a result, the main chain is scalable and secure.
- OriginTrail [53] combines several partner apps, blockchain, and off-chain solutions. It employs a variety of participants. ODN (OriginTrail Decentralized Network) is the name for the off-chain network. As a result, the solution is made up of blockchain platform apps, the ODN, and concerned parties' apps.
- All manufacturers who utilize the VeChain [54] platform provide unique identifiers to their products. VeChain Identity (VID) technology is used to create these IDs. A SHA256 hash algorithm is used to produce each VID. This VID is saved in the blockchain, while it is embedded in the product through an NFC chip, RFID tag, or QR code. As a result, both retailers and customers may trace the product's journey using this method. It is based on the Ethereum source and has been forked and upgraded. The main improvements of VeChain are as follows: To begin with, the format of the transaction consists of an identifier, Blockref, Expiration, and DependsOn. As every transaction has its unique identifier, the app only needs to deal with a single transaction. Blockref in VeChain provides further data about the current, previous, and future blocks and information about transaction creation. The expiration feature is utilized to avoid stacking over an extended period. VeChain supports the multi-task transaction concept to handle complicated business payments, and each transaction is made up of numerous small transactions. Proof of authority (POA) is the consensus mechanism used by VeChain. This mechanism incorporates both stake and reputation.
- Modum [55] is a supply chain management system which manages the delivery of large quantities of fragile items, particularly pharmaceuticals. It consists of a Modum temperature logger sensor, Ethereum, and API apps. The frontend and backend parts of the Modum architecture are separated. Ethereum smart contracts and a dedicated server connecting external users constitute the backend. The frontend consists of mobile apps and sensors that communicate with backend server through the REST API and JSON. Tags are the most valuable added value, as they are used to assess the environmental conditions of shipments.

- The Bext360 [56] technology employs a blockchain-based system to track agricultural goods at any level of the supply chain. Bext360 offers traceability as well as payment and smart contract management. It is built on a RESTful API that supply chain actors can use to integrate the solution to their apps and websites.
- The decentralized application WaBI [57] establishes a safe interface between participants. It is a standalone blockchain that is placed on a user's smartphone and used to verify their merchandise via a phone app. WaBI offers a mining mechanism which rewards users for their participation. The incentive procedure takes place during the scanning process, in which each scan is completed with a proof of purchase. Tokens in this solution are used to safeguard the registered goods.
- To achieve successful farm-to-table food traceability, the TE-FOOD [58] solution proposes a single ecosystem which includes all manufacturing parties (production, transportation, and so on). Food corruption and untrustworthy supply networks are combated by TE-FOOD. It includes the TFD utility token as well as blockchain technology, smart contracts, and RFID identification technologies. The procedure involves two types of blockchain: Ethereum (public blockchain), which was adopted for the payment procedure using TE-FOOD tokens, and a private blockchain for recording these transactions.
- FarmaTrust [59] is a reliable cloud-based technology that offers a means of tracing pharmaceutical items via a supply chain. To improve scalability, it is built on Ethereum and uses proof of authority as a consensus mechanism. Both Cassandra and MongoDB represent the database layer. In this solution, the API and blockchain layers are separated.
- Agrichain [60] is a decentralized network for the agriculture supply chain that uses the Ethereum blockchain. The three major levels of Agrichain are private, public blockchains, and apps. The public blockchain stores the basic Agrichain data, transactions, and smart contracts. Shoppers use a private Agrichain to minimize fees and waiting periods. The Agrichain platform's application layer controls the blockchains.
- Blockverify [31] is a blockchain-based anti-counterfeiting solution for premium supply chain products. Blockverify is a hybrid of blockchain that sequentially stores information in public (Bitcoin) and permissioned blockchains. In this approach, a product is supervised and has its own specific tag; with this tag, clients can determine the transparency level of the product since its creation.
- Chronicled [61] uses "tamper-proof cryptographic stamp" identification to trace tangible objects and record them on the blockchain using smart tags and the Chronicledapplication. A Smart Tag is a cryptographically secure chip containing information on a physical product and is connected to a private key.
- Everledger [62] is a company that uses two blockchain systems to preserve the quality of diamond articles. Rather of scaling up the system, it employs Hyperledger (private) and Ethereum (public) blockchains to assure the immutability of the transaction history.
- Leteane et al. [63] proposed a framework solution combining blockchain technology with a multi-trust, package-based trust model to address the trustworthiness issues in food supply chain traceability. This solution leverages the immutable and transparent nature of blockchain to ensure data integrity, preventing any actor in the supply chain from tampering with records. The integration of the trust model enhances the system by identifying specific areas in the supply chain where quality and safety issues arise. This combination of blockchain for data security and the trust model for transparency and accountability results in a more reliable and adaptable system that strengthens trust among supply chain actors and end consumers.
- The Agri-4-All [64] framework integrates blockchain, smart contracts, and the IoT to transform agricultural food supply chains by automating and digitizing both intra-organizational and inter-organizational processes. By utilizing business process modeling and the Reference Architecture for Modeling Industry 4.0, this framework monitors the health and environment of agricultural products in real time throughout the supply

chain. The implementation of hybrid smart contracts using Ganache and Truffle suite significantly reduces gas costs, improving transaction efficiency. While the framework provides transparency and security, future work will focus on addressing interoperability challenges between different blockchains and improving privacy protection for stakeholders.

- A proposed distributed application [65] for the traceability of table olives on the Ethereum blockchain demonstrates the potential of blockchain technology in enhancing traceability, transparency, and food safety. By providing a secure, transparent, and efficient solution for tracking table olives from producer to consumer, the application improves the reliability of supply chain data, reduces processing time, and helps producers comply with international standards. The study also highlights the importance of integrating disruptive technologies like the IoT for real-time monitoring and suggests future research to address scalability, interoperability, and cost challenges.
- Petratos et al. [66] explore the impact of fake news, misinformation, and disinformation on supply chain disruptions and propose blockchain as a solution to manage information risks. They developed a theoretical framework that considers these types of misleading information in supply chain risk management and supply chain resilience. Their paper suggests strategies to mitigate disruptions caused by low-quality information by leveraging blockchain, such as using blockchain's transparency and immutability to enhance risk management and resilience. Blockchain also promotes cooperation and information sharing among supply chain participants, improving overall risk management. While the framework presents a theoretical solution, future research is needed to empirically validate blockchain's effectiveness and explore its integration with other Industry 4.0 technologies for more robust supply chain risk management.
- A blockchain-enabled healthcare supply chain management [67] approach was proposed to enhance the efficiency and performance of healthcare supply chains, especially in the wake of the COVID-19 pandemic. The solution integrates blockchain technology to create a more sustainable healthcare supply chain, focusing on improving stakeholder involvement and sustainable healthcare supply chain practices. By utilizing blockchain's secure, transparent, and immutable data recording capabilities, the system enhances trust among stakeholders while optimizing the flow of medical supplies and services. This approach also facilitates real-time tracking of healthcare goods, ensuring the quality and timely delivery of medical supplies. Through the adoption of blockchain, the healthcare supply chain becomes more resilient, helping to combat the challenges posed by the pandemic. The data analysis performed in this study shows that blockchain adoption positively affects the overall performance of healthcare supply chain practices, providing a robust framework for future implementations in healthcare logistics.

In Table 2, we present a multitude of options developed with the aim of improving IoT-based supply chains using blockchain, which provides trustworthiness, traceability, and complete visibility. All these initiatives have restrictions, despite the fact that their technologies and requirements differ significantly. These initiatives integrate blockchain technology into their platforms in different ways to overcome drawbacks and provide value to existing blockchain systems. The most important supply chain parameter that substantially influences the quality of user experience is scalability. Maximum throughput, data size, and transaction cost are parameters that have an impact on scalability. As a result, each metric's failures have different causes and consequences that affect performance. Most of the technologies are grouped together to improve the scalability of blockchain's supply chain integration. Each solution focuses on one of the three scalability parameters.

Table 2. Blockchain-based supply chain solutions.

Work/Tool or Technique	Sharding	Side-Chain	Core Improvement	Transaction Format	Cloud-Based	Multiple Blockchains Public/Private	Based on Existing Blockchain Solutions (Ethereum, Hyperledger)	Web App
Shipchain [48]		+				+	+	
Devery [49]						+	+	
Cargox [50]						+	+	
CargoCoin [51]						+	+	
WaltonChain [52]		+	+			+		
OriginTrail [53]			+		+			
VeChain [54]	+		+	+	+	+	+	+
Ambrosus [68]						+	+	
Modum [55]						+	+	
Bext360 [56]							+	
Tael (WaBI) [57]			+				+	
TE-FOOD [58]						+	+	
FarmaTrust [59]					+	+		
Agrichain [60]						+	+	
Blockverify [31]						+		
Chronicled [61]							+	+
Everledger [62]						+	+	+
Leteane et al. [63]			+			+	+	
Agri-4-All [64]			+				+	+
Table Olives [65]							+	+

+: Used Tool or Technique.

Several approaches address the system's flaws by changing properties or adding additional blockchains to disperse data loads. As consensus influences scalability the most, it is regarded as the most important factor in advancing supply chain integration with blockchain. For example, Ambrosus [68] solves the scalability problem by minimizing the list of the confirmed nodes. This is achieved through the use of Apollo nodes to ensure that transitions are validated only by nodes with the appropriate authority. Indeed, rather than specializing separate servers for validation, numerous alternative algorithms [69] are used to increase performance, like POA and PBFT. VeChain [54] makes use of the POA consensus mechanism to boost network data circulation. POA is built on blockchain's concept of restricting the number of validating nodes. POA is faster than PBFT as it requires fewer message exchanges. Unfortunately, these approaches can still only be applied in a permissioned blockchain. WaltonChain [52] presents a new consensus method by integrating POW, POS, and POL into a single consensus algorithm termed POST. This method significantly simplifies the mining process, saves critical processing resources, and offers a mechanism for picking the best mining strategy at the same time. This technique greatly accelerates the mining process, saves significant computer resources, and offers a method for selecting the appropriate nodes to increase the platform's security. The WaltonChain system also permits a connection with any other sub-chain consensus, which enables interoperability among supply chain systems. As a result, it is appropriate for supply chains with a unique main blockchain, and its job is restricted to the administration of the blockchain. It is not built to handle high throughput with a large number of transactions, and it takes one minute to confirm a block. The scale of the blockchain represents a significant barrier for any supply chain, as devices used in the IoT are incapable of handling such a large amount of data due to their limited resources. Furthermore, the data size of the blockchain should be tightly regulated to avoid exceeding the limit. The Sharding approach is used in VeChain to divide the blockchain volume over many locations. Sharding partially solves size concerns since all data are stored on the blockchain. Sharding does not directly address the problem of data volume; instead, it distributes the data. Furthermore, running a cloud-based blockchain or using blockchain as a service is another alternative used by OriginTrail [53] for scalability and blockchain volume. When running blockchain in the cloud, there is no requirement to use the nodes' capacity or to be perfectly synchronized. BaaS's cloud computing approach improves scalability [19]. As a result, the cloud enhances real-time applications and saves time, but the intensive use of this service is very expensive, even potentially exceeding the cost of confirming transactions.

Despite the advancements made by blockchain-based supply chain solutions, recent research continues to prioritize traceability and trust rather than scalability. Refs. [63–65] focus on improving trust and transparency in supply chains through blockchain integration but have yet to address the critical scalability issue. While these systems enhance traceability, security, and transparency, they do not significantly improve scalability, which remains a key barrier to widespread adoption in large-scale supply chain networks.

For instance, Leteane et al.'s framework [63] uses blockchain and a multi-trust model to ensure the integrity and trustworthiness of data in the food supply chain. Similarly, the Agri-4-All [64] framework utilizes blockchain and the IoT to automate agricultural supply chains but focuses on efficiency and security rather than scaling capabilities. The table olives application [65] showcases blockchain's potential for traceability but leaves scalability, interoperability, and cost as areas for future research. Thus, the prevailing focus of recent research remains on enhancing trust and traceability, with limited attention to scalability solutions.

According to the foregoing solutions, multiple scenarios can be used to achieve an ideal supply chain environment if these solutions are merged, for example, sharding, private/hybrid blockchain, and off-chain solutions that address a particular scalability problem, such as the storage issue. The core improvement of blockchain, editable blockchain, and blockchain as a service are used as solutions for the supply chain to enhance the performance of the entire blockchain. We may conclude that significant attempts were made to overcome the blockchain's drawbacks. Nonetheless, blockchain is not yet ready to scale to the point where it can completely replace centralized and conventional supply chains. In addition to the benefits of the aforementioned blockchain-based initiatives, multiple solutions can assist the typical modern supply chain. In the following subsection, we will focus on the approaches that can be applied to the public blockchain, which is the most suitable type for supply chain applications.

3.2. Existing Blockchain Solutions and Techniques That Can Satisfy Supply Chain Requirements

3.2.1. AI-Based Blockchain "NeuroChain"

Within the domain of inclusive governance and decreased reliance, solutions such as NeuroChain strive to actualize the notion of a self-governing blockchain. This entails employing artificial intelligence as the governing mechanism, which can minimize the reliance on powerful nodes as the necessity for intricate hash puzzles to verify blocks becomes outdated. NeuroChain [70] utilizes software agents known as bots, which are distributed across the blockchains of each participant, enabling streamlined decision-making and communication within the ecosystem. The groundbreaking technological advancement of NeuroChain revolves around the introduction of a new consensus protocol known as "Proof of Involvement and Integrity." This consensus mechanism acts as the central engine of the blockchain, overseen by intelligent bots that improve their actions' logic as they accumulate data. The algorithms employed by the bots establish an innovative consensus process which assesses the interactions of each member with the network and the caliber of their exchanges. By sharing and appreciating this evaluation information, the network can swiftly and efficiently select the member that will validate a block while also performing a valuable job.

The mechanism of creating a fresh block in NeuroChain involves several steps: First, the generation of new transactions is conveyed to all bots for verification. Second, once a specific number of block validations occurs, the assembly of participants is initiated through the Proof of Involvement and Integrity mechanism. Third, the leader in charge of the gathered group is chosen in a decentralized manner using a random selection process involving specific electors assigned to each bot. Additionally, the entire group will only approve the block if every transaction is valid and authorized. Finally, the group works together to create a fresh block by utilizing the ID or hash of the approved block, which acts as evidence of acknowledging the previous block. Table 3 gives a summary of the NeuroChain solution, highlighting the key aspects of its consensus mechanism, network structure, advantages, and limitations.

Table 3. Summary of NeuroChain solution.

Consensus	Network	Pros	Cons
Bots now fulfill the duties of miners, with their performance assessed according to their ability to engage effectively with their environment. Involvement = quality of information provided Integrity = The accuracy of the information provided is ensured by randomly selecting highly ranked bots to validate a block.	Machine learning and AI algorithms will allow bots to interact with each other. Bots will adapt to their surroundings on their own.	The consensus mechanism is characterized by its intelligence, adaptability, and dynamic nature. Bots can be hosted on various devices, including desktops, laptops, and smartphones. The scoring process of the bots establishes the trustworthiness of the network and smart applications.	Fails to offer a solution to address the issue of increasing blockchain volume.

Despite the innovative advancements introduced by NeuroChain, particularly through its intelligent and adaptive consensus mechanism, the solution still faces challenges that require further exploration. While the use of AI-driven bots and the Proof of Involvement and Integrity protocol significantly enhance the network's efficiency and reliability, the issue of blockchain volume management remains unresolved. Addressing this limitation is crucial for the broader application of NeuroChain in scalable, real-world environments. This highlights the need for ongoing research and development in optimizing blockchain technologies to balance security, efficiency, and scalability.

3.2.2. Pruning

The ever-growing size and complexity of blockchains, due to storing every transaction, pose a challenge in terms of storage requirements and verification processes. Blockchain pruning addresses this challenge by strategically removing/archiving unnecessary data from the blockchain while preserving the crucial information needed for security and verification [71]. This allows blockchain nodes to operate with reduced storage requirements and improved processing power, ultimately leading to a more scalable blockchain with higher performance that is capable of handling a higher volume of transactions. The following presents the main potential benefits of pruning blockchain:

- Reduced storage requirements: Pruning the state, meaning removing unnecessary data from the blockchain, significantly reduces storage requirements for nodes, enabling a broader spectrum of devices to participate in the network.
- High performance: Through strategically removing unnecessary data from the blockchain, the network can operate faster and with lower resource requirements, leading to improved overall performance.
- Reduced synchronization time: Reducing the blockchain state size allows new nodes to synchronize with the latest state much faster, lowering the barrier to entry for joining the network and contributing to the consensus process.
- Reduced transaction fees: As the blockchain state grows, verifying transactions requires more computational power and storage space. This strain on the network can lead to congestion, slowing down processing times and driving up transaction fees. Pruning can dramatically speed up transactions, potentially leading to very low fees.

As presented by Matzutt et al. [72], there are three primary classifications for blockchain pruning: simple block pruning, state-based synchronization, and balance-based synchronization.

Simple block pruning involves selectively keeping only the Unspent Transaction Outputs (UTXOs) in the blocks while making certain modifications to ensure a significant blockchain. In Bitcoin [73], once nodes have completed the initial synchronization, nodes can discard old data and retrieve it through queries when needed.

State-based synchronization focuses on utilizing snapshots, which are temporary data repositories that store the UTXOs of the blockchain. Rather than depending on the blockchain blocks directly, nodes leverage the information contained within these snapshots. Similar solutions include Ethereum's Fast Sync [74], Marsalek's approach [75], and Rollerchain [76], all of which emphasize efficient initial synchronization.

Balance-based synchronization can be seen as a specific type of state-based block pruning. The key difference is that it does not track all UTXOs in the blockchain but rather focuses on monitoring existing accounts and their respective balances. Approaches such as Mini-Blockchain [77], Mimblewimble [78], and Pascal [79] primarily concentrate on tracking account balances, with Mini-Blockchain and Mimblewimble replacing Bitcoin's UTXO set with an account tree linked to each mined block, while Pascal introduces safe boxes as an alternative to account trees.

All the aforementioned studies introduce certain features that have the potential to significantly enhance blockchain performance. However, they also come with drawbacks that discourage their immediate adoption by existing platforms. Initially, in the cases of [75,78], there is a reduction in blockchain size, but this comes at the expense of increased processing workload for the nodes, such as generating blockchain snapshots. Additionally, some solutions involve broadcasting empty pruned blocks, which is an unnecessary task that consumes bandwidth and computing resources to distribute redundant data. Also, due to security considerations, solutions like the approach of [71] are not applicable to public scenarios where unidentified or anonymous individuals can participate.

3.3. Summary

In this section, we critically reviewed the existing literature on blockchain-based supply chains, with a focus on evaluating how current solutions and techniques address the challenges and requirements of modern supply chains. We began by exploring the foundational concepts of blockchain in supply chains, identifying both the strengths and limitations of various approaches.

We then examined advanced blockchain solutions, such as AI-based blockchains and pruning techniques, which offer potential improvements in scalability, efficiency, and data management. However, despite their advancements, these solutions often fall short in fully addressing the scalability needs of IoT-enabled supply chains, particularly concerning real-time data integration and secure identification during transportation processes.

This review not only reinforces the importance of traceability, security, and scalability, but also reveals significant gaps in meeting the scalability demands of IoT-based supply chains. Our evaluation lays the groundwork for introducing our proposed solution, ABISChain, which we detail in the following section. ABISChain is specifically designed to overcome the limitations identified in the literature through incorporating novel approaches to scalability, secure identification, traceability, and real-time tracking using IoT and blockchain technology.

4. ABISChain: System Model, Design, and Implementation

A blockchain system with a smart pruning mechanism can be a game-changer for users who need constant access to up-to-date and frequently used information. Our approach prioritizes storing the most relevant data, maximizing accessibility while optimizing storage efficiency. Let us explore the power of this solution through the lens of a supply chain where only critical shipment details and current locations are readily available on the blockchain. This eliminates the need to store every historical record, saving valuable resources without sacrificing access to the most crucial data. This exemplifies the power of such a system, providing a balance between data availability and storage optimization across various domains.

4.1. System Model

ABISChain: A pruned public blockchain based on intelligent agents utilizing the Belief–Desire–Intention (BDI) algorithm is an innovative approach to blockchain technology. This system combines the principles of multi-agent systems with the power of blockchain to create a decentralized and efficient network as shown in Figure 2.

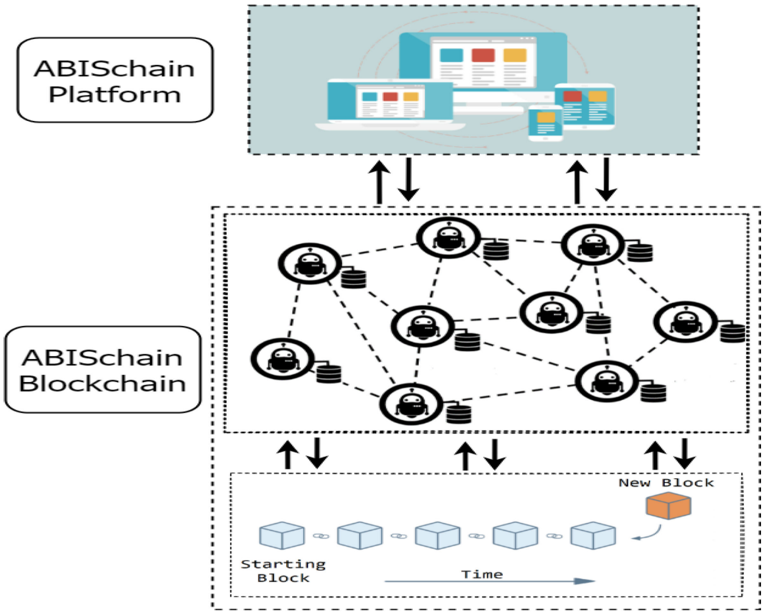

Figure 2. ABISChain architecture.

In traditional blockchain systems, every transaction is recorded and stored on every participating node [7], leading to scalability issues as the network grows. However, in our pruned blockchain, not all nodes store all data. Instead, the system intelligently selects a subset of nodes to maintain the entire blockchain history, while other nodes store only frequently used data. Therefore, our pruning is based on the data usage. This pruning technique reduces storage requirements, enhances scalability, and improves overall network performance.

ABISChain Blockchain Concepts

The ABISChain blockchain is based on many concepts that maintain its proper function to provide data availability while optimizing storage resources. The following is an overview of all of them:

- **Agents**: An agent refers to a software entity capable of autonomous decision-making and interaction within the network. Agents operate independently, making their own decisions based on their beliefs, desires, and intentions [80]. The BDI algorithm is a well-established framework used in multi-agent systems [81]. It models an agent's decision-making process by considering its beliefs (the agent itself, other agents (data), and its environment like the blockchain, pruned blockchain, and blockchain network), desires (the agent's goals like generating blocks and pruning the blockchain), and intentions (the chosen desires and its impact on ABISChain). After the BDI algorithm is integrated into the pruned blockchain architecture, each agent can analyze its beliefs about the state of the blockchain network, evaluate its desires and goals, and form intentions to participate in specific blockchain activities such as creating or proposing new blocks. There are two different agent types (light agent and full agent):
    1. Light agent: The light agent holds only the pruned blockchain and considers it as its current belief according to the environment state to decide which action to perform.

2. Full agent: In contrast to light agents, full agents consider the entire blockchain as their belief according to the environment state.

- **Consensus and Validation**: As highlighted by Baliga [82], a blockchain-based system is as secure and robust as its consensus model. The consensus mechanism not only ensures that all participants in the network agree on the validity of transactions but also plays a critical role in securing the blockchain against malicious attacks and ensuring its scalability. In our ABISChain blockchain, the consensus is achieved through a voting process where agents participate in electing a representative agent responsible for creating the new block. This approach not only decentralizes decision-making but also allows for pruning the blockchain when necessary, which optimizes storage and enhances the overall efficiency of the system. The combination of a robust voting-based consensus mechanism and strategic pruning ensures that ABISChain remains both secure and scalable, adapting dynamically to the needs of the network.
- **Data Pruning Mechanism**: The mechanism analyzes the usage of data and determines which information is frequently accessed or modified. By considering the relevance and frequency of data usage, the system prioritizes the availability of such data by providing it to all agents.
- **Usage Tracking**: Data usage is tracked within the blockchain network via the agent caching system. Tracking the usage helps to identify the most frequently accessed or modified data.
- **Pruning Algorithm**: The algorithm analyzes the usage data and determines which information should be pruned. This algorithm should consider factors like recency, frequency, and relevance of data usage. Based on these parameters, the algorithm can determine which data should be retained and which can be pruned from the blockchain.
- **Data Retrieval**: Users can easily retrieve pruned data if needed. A light node is allowed to retrieve the required pruned data from a full agent. Zheng et al. [83] discuss the importance of efficient data retrieval mechanisms to ensure that data remain accessible when required.
- **APIs**: APIs allow supply chain users to interact with the ABISChain blockchain system, retrieve relevant data, and access the most recent information. Prusty [84] highlights the role of APIs in facilitating user interaction with blockchain systems, ensuring seamless data access and retrieval.

4.2. Design and Implementation

Below in Figure 3, we will provide a general overview of the ABISChain design.

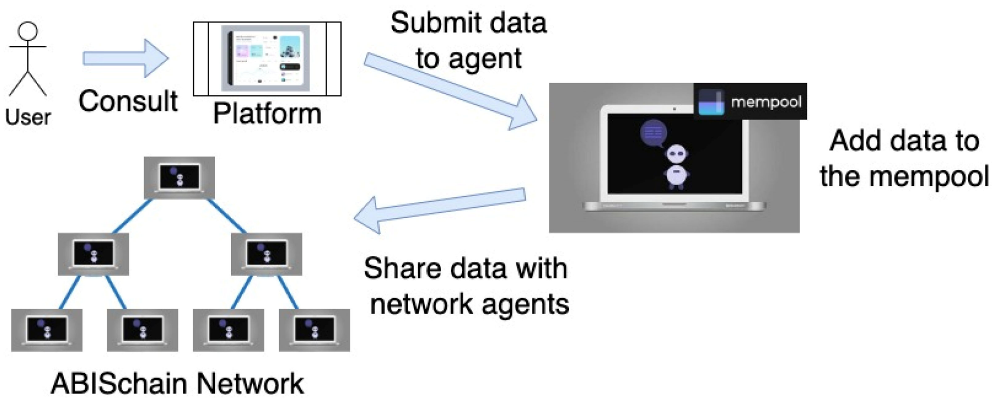

Figure 3. Adding new data to ABISChain.

To add data to the ABISChain blockchain mempool, a few steps must be followed:

1. User submits data: The user provides the data that they want to add to the ABISChain blockchain. These data can be in any format or structure depending on the requirements of the blockchain; in our platform, we use JSON objects Figure 4.

2. Connection to an ABISChain agent: The user's data needs to be submitted to an agent that is connected to the ABISChain network. An agent is a software component responsible for interacting with the blockchain network. The agent can be a node, a specialized application, or a service provided by a third party.
3. Agent adds data to the mempool: The ABISChain agent receives the data from the user and adds the data to its mempool. The mempool, short for memory pool, is a storage area where pending transactions or data are temporarily held before they are included in a block and added to the blockchain.
4. Broadcasting to other network agents as shown in Figure 5: After adding the data to its mempool, the ABISChain agent broadcasts this information to other agents in the ABISChain network. Broadcasting means sending the data to all the connected agents in a peer-to-peer manner so that they are aware of the pending data.

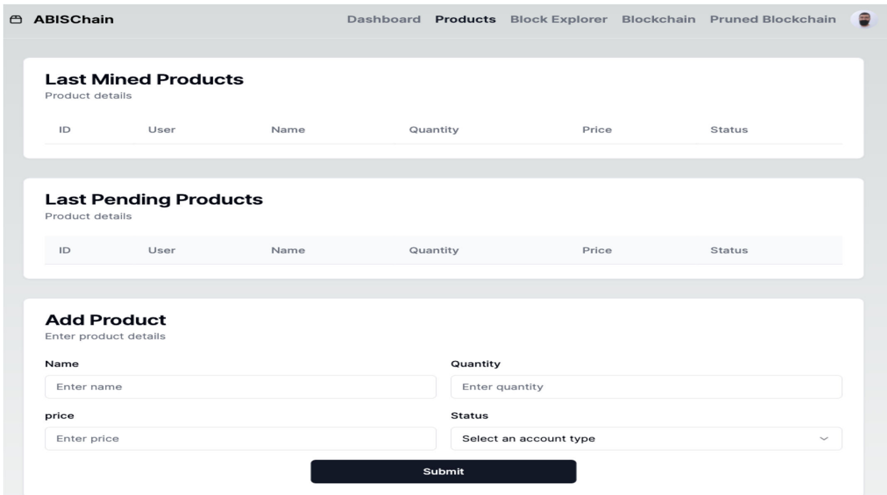

Figure 4. ABISChain form for adding data.

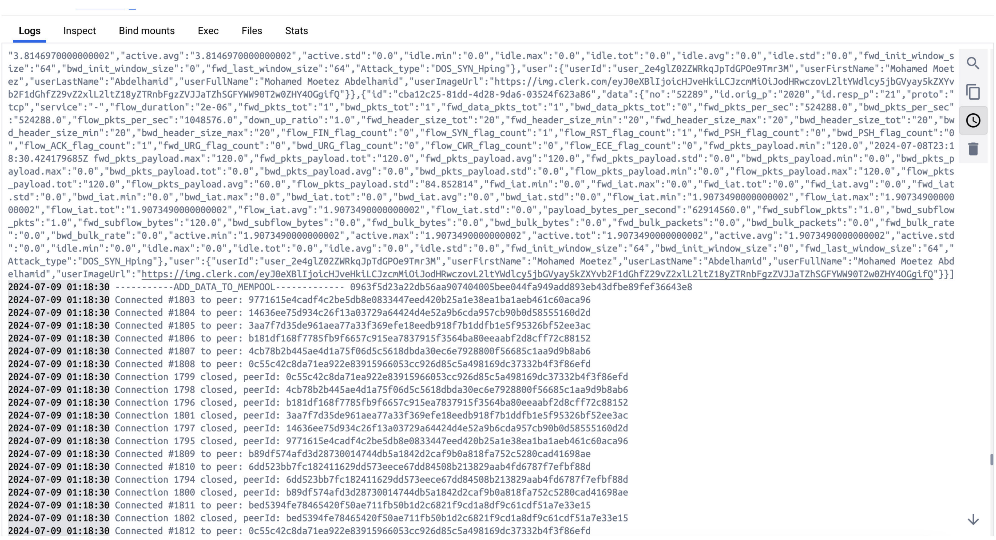

Figure 5. Broadcasting new data to ABISChain agents.

The ABISChain blockchain agent voting system is a mechanism for selecting an elected agent that will generate the new block in the ABISChain blockchain network and potentially prune the ABISChain blockchain. The following is a summary of the steps presented in Figure 6:

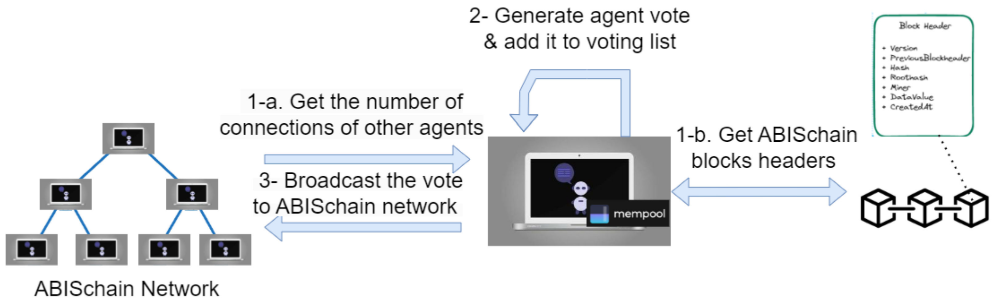

Figure 6. ABISChain voting process.

1. Each agent obtains the number of connections of other agents. This represents the number of agents that an agent is connected to in the ABISChain network.
2. The agent obtains the ABISChain block headers. Block headers typically contain metadata about the blocks in the blockchain, such as the previous block hash, timestamp, and other relevant information like the block value.
3. The agent generates its vote of other agents using the formula: *ABV(AgentBlocksValue)

$$AgentValue = ABV + agentConnections + 1 \tag{1}$$

$$ABV = \sum_{i=1}^{n} \sum_{j=1}^{3} BlockValue_{ij} * DataWeight_j \tag{2}$$

   This formula takes into account the block value, the number of connections the agent has, and adds 1 to the total. The block value is calculated based on the type of data associated with the block. In our system, we use three types of data: health, finance, and information technology. These types have different weights: 3 for health, 2 for finance, and 1 for information technology. The block value is calculated based on the type of data that will be added to the block.
4. The agent adds its vote to the voting list, which likely consists of the votes from other agents participating in the election process.
5. The agent broadcasts its vote to the ABISChain blockchain network, allowing other agents in the network to receive and process the vote.

In the ABISChain blockchain, the agents have a caching system that aids in generating the pruning list. The following is an overview of the process presented in Figure 7:

1. The agent begins by pulling the cached data from its caching system. This cached data are typically the information that was previously provided to ABISChain users through ABISChain APIs by the current agent. The caching system stores these data for the pruning list generation phase.
2. The agent runs a script that applies Dice's coefficient to identify the active data. Dice's coefficient is a similarity measure used to compare two sets of data. By employing this coefficient, the agent can determine which data are considered active or relevant.
3. Once the agent generates the list of active data, it adds this list to its pruning lists' mempool. The pruning list's mempool serves as a temporary storage location where pending pruning lists are stored before they are used to generate the pruned ABISChain blockchain.
4. The agent broadcasts its pruning list to the other agents in the ABISChain network. Through this broadcast, the agent enables other agents to receive and process the shared pruning list.

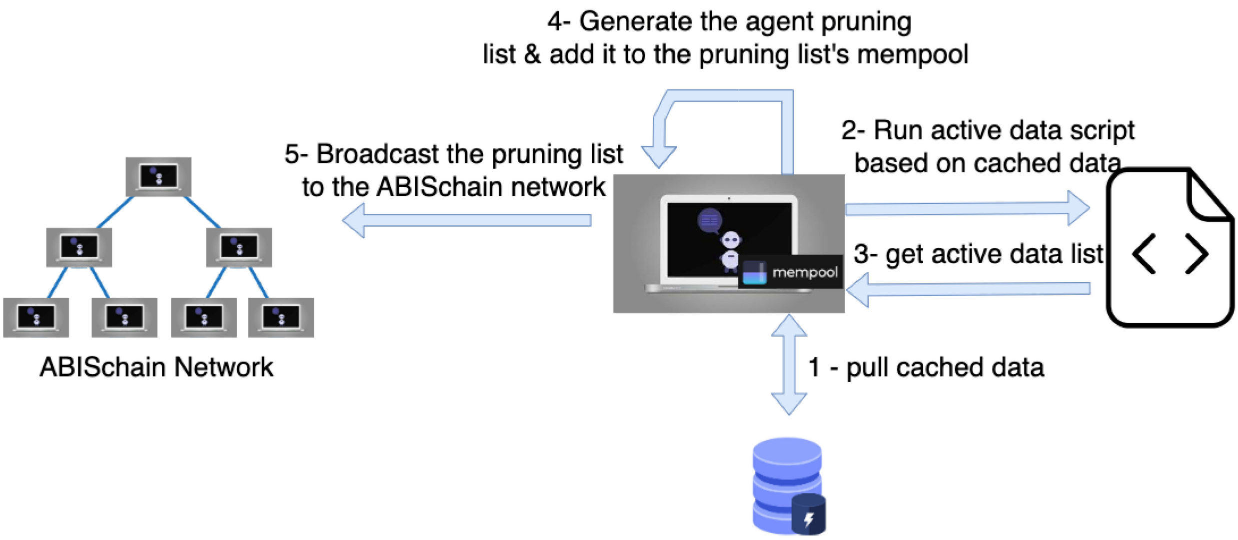

Figure 7. The process of generating and sharing a pruning list.

In ABISChain, the process of requesting data presented in Figure 8 follows the following steps:

1. A user requests data from an agent through an API. Our platform offers two interfaces for retrieving data from the blockchain: Block Explorer and Blockchain Explorer, as shown in Figure 9. The user specifies the data they require from the ABISChain network.
2. The agent receiving the request first checks its cache for the requested data. The cache stores previously retrieved data for faster access.
3. If the agent finds the requested data in its cache, it can directly provide the data to the user.
4. If the agent does not find the requested data in its cache, its actions depend on whether it is a light node or a full node:
    - Light Node: A light node, which typically maintains a pruned version of the blockchain, will search for the requested data in its pruned blockchain. If the data are found, they can be provided to the user. However, if the data are not available in the pruned blockchain, the light node needs to request the data from a full node.
    - Full Node: A full node maintains the entire blockchain and has a complete copy of all the data. If the agent is a full node, it will search for the requested data in the entire blockchain.
5. In case the agent does not the requested data in its cache, the agent adds the requested data to its cache before providing the data to the user.

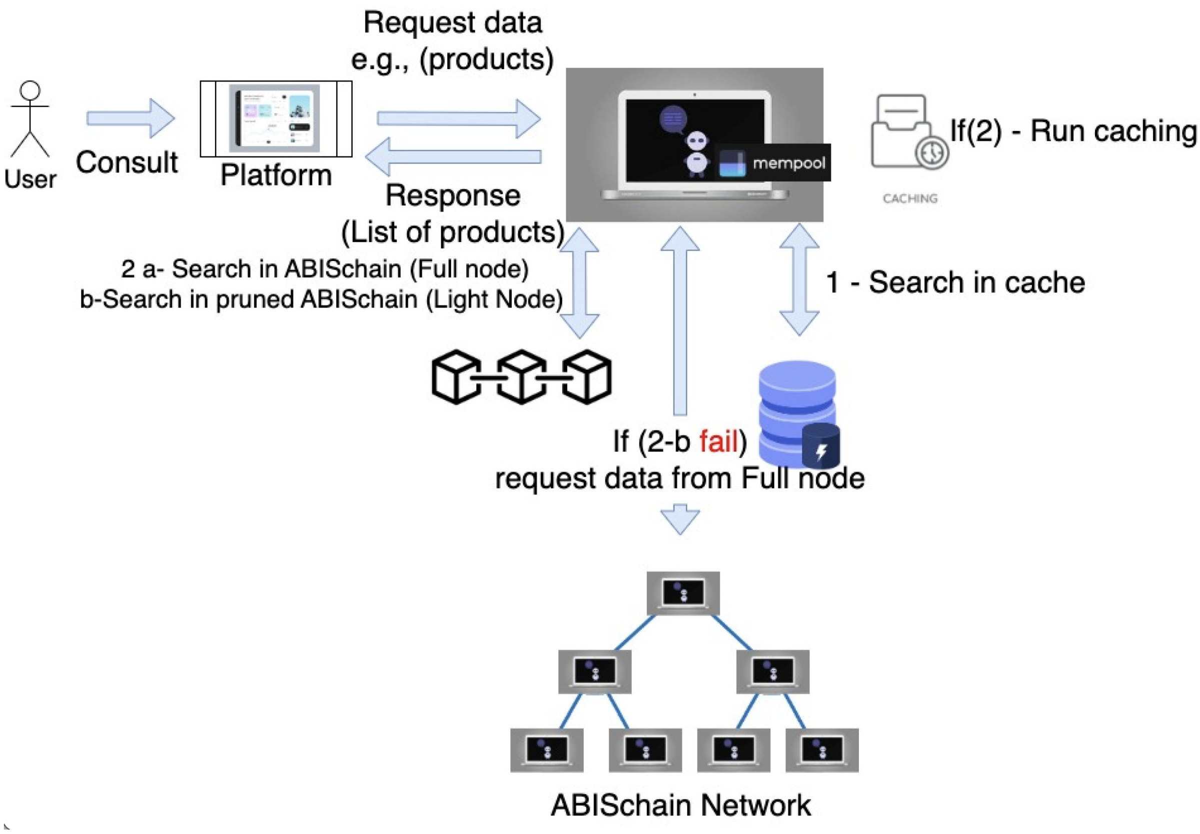

Figure 8. The process of requesting data from the ABISChain blockchain.

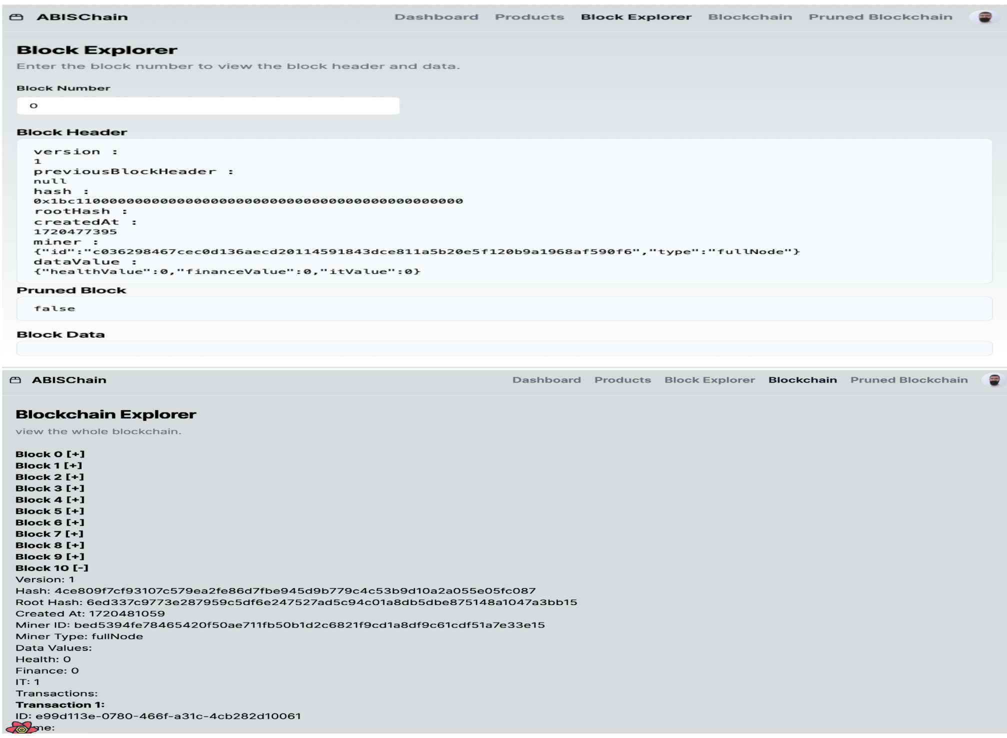

Figure 9. Block and Blockchain Explorer.

By utilizing caching mechanisms and checking the appropriate sources, ABISChain agents efficiently handle data requests, ensuring that data are readily available and minimizing the need for unnecessary data retrieval.

In ABISChain, once an agent is elected as the block miner, they are responsible for performing two main tasks presented in Figure 10. In what follows, we will explain each task in detail:

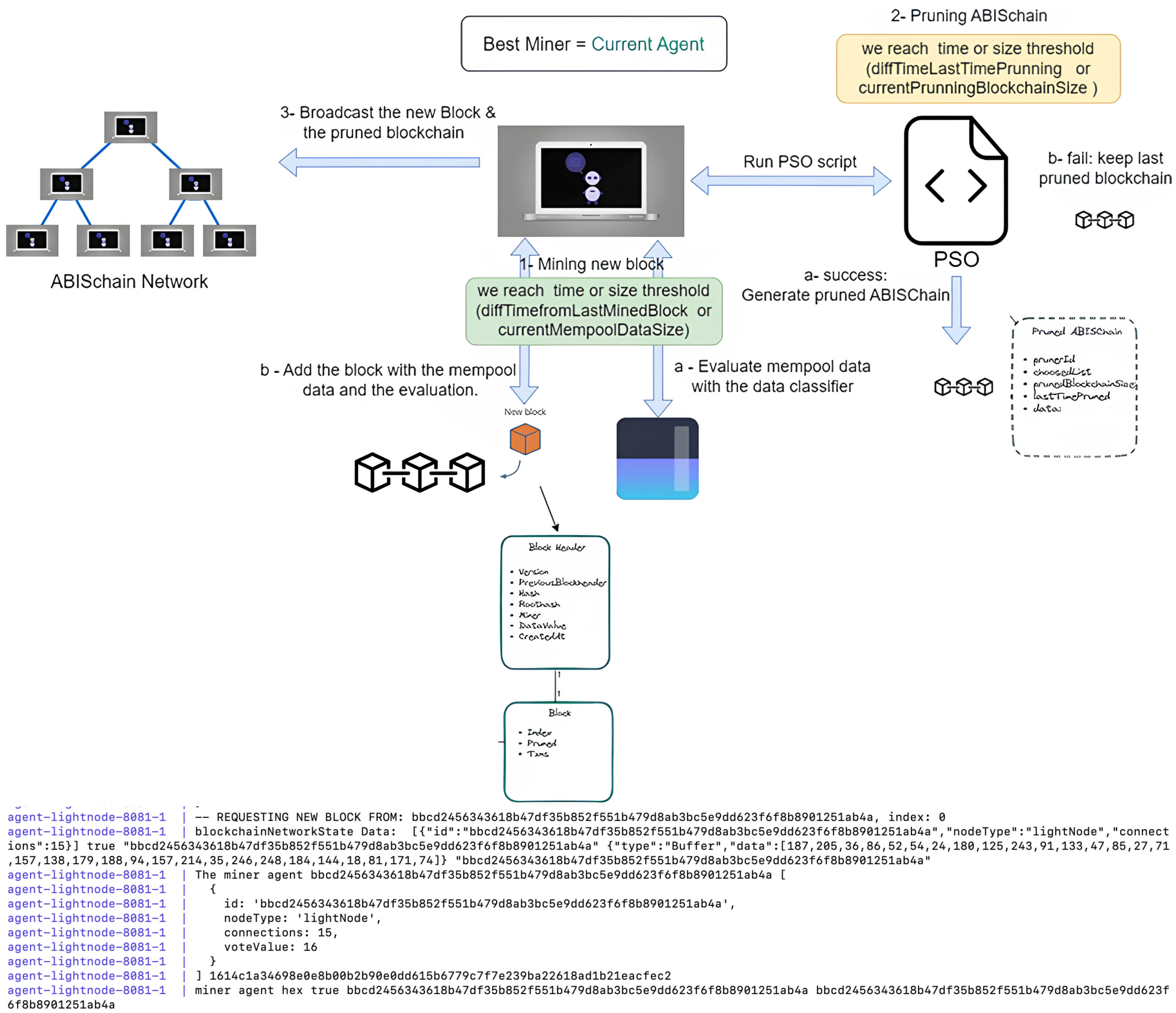

Figure 10. ABISChain block mining and pruning process.

- Block Mining Process:
    1. Triggering the Process: The elected miner initiates the block mining process after a specific time has elapsed since the last mined block or when the size of the mempool data reaches a certain threshold.
    2. Data Classification: The miner evaluates the data in the mempool using a data classifier. The data classifier employs techniques like n-grams and cosine similarity to classify and categorize the data.
    3. Block Creation: Based on the evaluation and classification, the miner creates a new block. The block includes a body containing the selected data and a header that comprises information such as the previous block header hash, block hash, creation date, miner's identity, and data value.
    4. Broadcasting: Once the new block is created, the miner broadcasts it to the ABISChain network, allowing other agents to receive the block.
- Pruning Process:

1. Triggering the Process: The agent launches the pruning process when a certain time has elapsed since the last pruning process or when the current size of the blockchain reaches a specific threshold, as shown in Figure 11.
2. Pruning Execution: During the pruning process, the agent selects the best pruning list to optimize the ABISChain blockchain. The pruning list selector is based on the particle swarm optimization algorithm that allows us to obtain the finest pruning list. The specific details of the pruning based on the particle swarm optimization process are explained in detail in our article [85].
3. Result Handling: If the pruning process succeeds, a new pruned blockchain is generated. However, if the process fails, indicating unsuccessful pruning by the agent, the previous pruned blockchain is retained.
4. Broadcasting: If a new pruned blockchain is generated, the agent broadcasts it to the ABISChain network, enabling other agents to receive and adopt the updated pruned blockchain.

Figure 11. Triggering the pruning process.

4.3. Summary

In this section, we explored the core concepts and design of ABISChain, a pruned blockchain system enhanced by intelligent agents and the Belief–Desire–Intention (BDI) algorithm. Through integrating a robust consensus mechanism, strategic data pruning, and efficient data retrieval processes, ABISChain offers a scalable and optimized solution for managing critical supply chain information. The detailed design and implementation showcase the potential of ABISChain to maintain data availability while reducing storage overhead, ultimately achieving a balance between performance and resource efficiency.

With the system model and design now established, the following section delves into the experiment and analysis, and we outline the performance and effectiveness of ABISChain in real-world scenarios.

5. Experiment and Analysis

In this study, we analyzed the performance of ABISChain and benchmarked it with some existing work. To verify the validity of the proposed solution, it was essential to conduct an analysis of its storage complexity, processing time, and other relevant factors. To streamline the simulation of agents, we developed a Docker Compose configuration that defines containers representing each agent. This setup enables us to specify the number and type of agents easily. Each agent container was paired with a Redis service acting as its cache, ensuring efficient data management. Figure 12 illustrates this configuration. The work by Boettiger [86] demonstrates the effectiveness of Docker in creating reproducible and scalable research environments, which supports our approach to using Docker Compose for agent simulation. Abu Kausar et al. [87] further confirm that Redis is an effective caching solution in distributed environments, aligning with our use of Redis for efficient data management in agent containers.

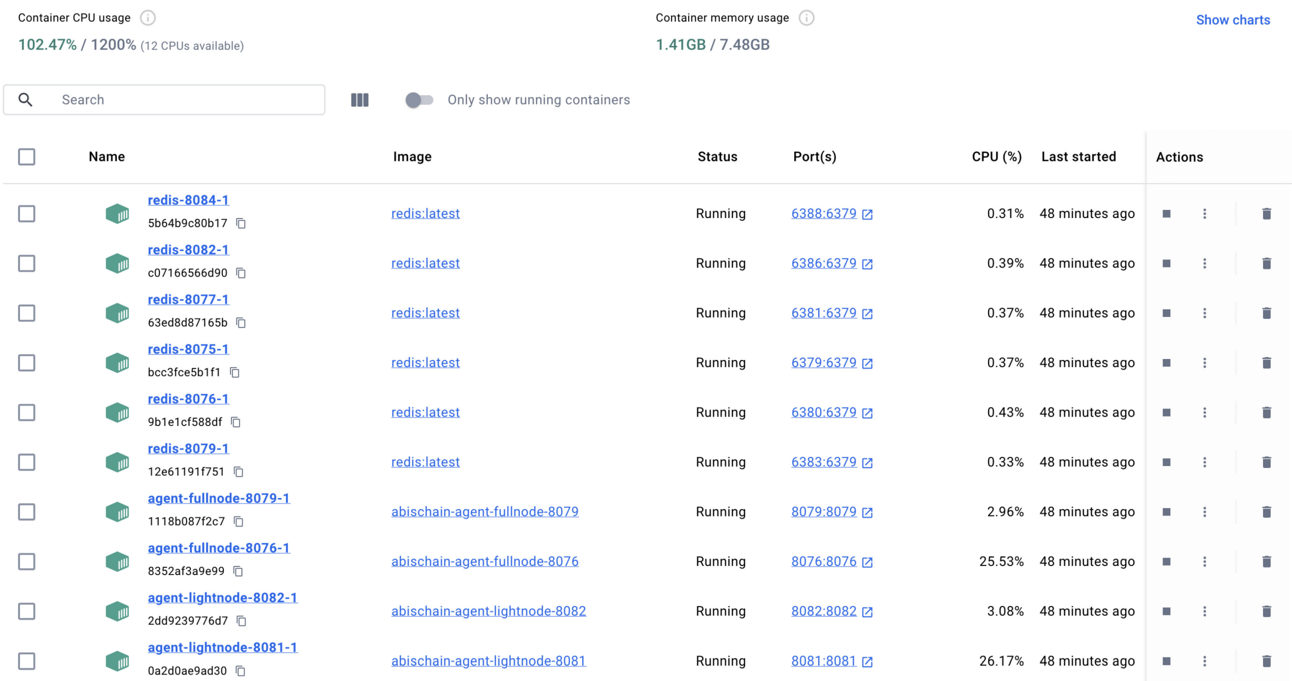

Figure 12. ABISChain agents.

Additionally, we utilized 1 MB data chunks, each representing 500 objects from the RT-IoT2022 dataset (https://archive.ics.uci.edu/dataset/942/rt-iot2022, accessed on 1 May 2024), as transactions within our blockchain blocks. This approach facilitates realistic and scalable simulations. Almutairi et al. [88] have discussed the importance of using realistic datasets in IoT research, as simulator data may not fully replicate that of real devices, which validates our use of the RT-IoT2022 dataset. Throughout the simulations, we consistently called the last 3 to 5 blocks, as these generally represent the most recent data that users would consult. In practical use, even if users were to consult earlier blocks, it would not significantly affect the results obtained. In Figure 13, we present our dashboard stats page that offers a detailed overview of the ABISChain blockchain's status during the simulations. These visuals provide extensive statistics, including the number and types of nodes, the nature of the stored data, the count of pending and mined transactions, and the total number of mined blocks along with the transactions contained within each block. Moreover, we have the most recent instance of the pruning process, offering a comprehensive insight into the blockchain's composition and operational dynamics. This detailed visualization underscores the robustness and efficiency of the ABISChain platform. We derived our performance metrics by drawing inspiration from comparative studies on general blockchain technologies and, more specifically, blockchain-based supply chain solutions, such as the foundational work by Arslan et al. [89] and the analysis by Litke et al. [90]. These studies provided a robust combination of metrics that were instrumental in demonstrating the effectiveness of our solution.

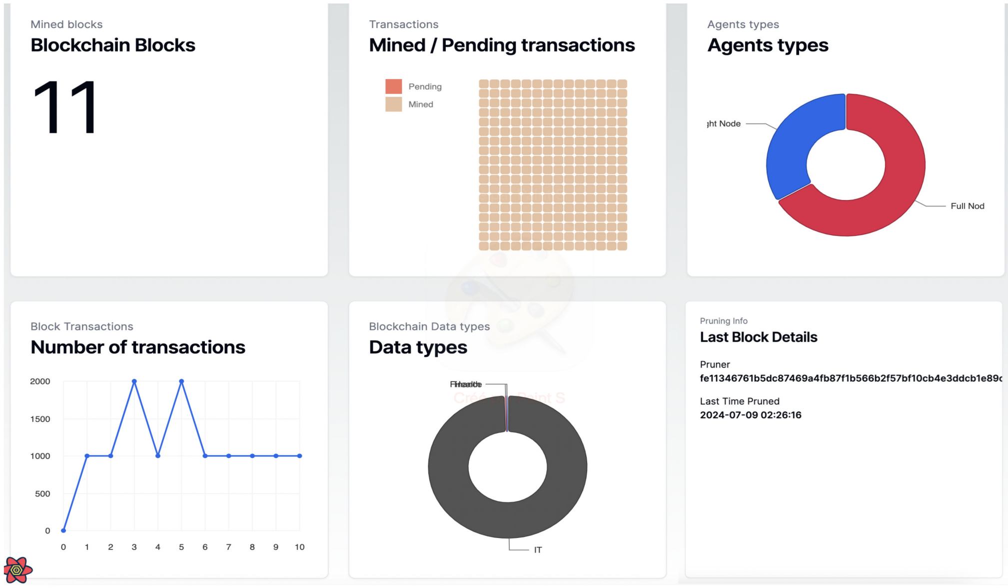

Figure 13. ABISChain platform stats.

5.1. Storage Complexity

Inspired by the work of Du et al. [91], we conducted a comparative analysis to evaluate the storage complexity of our blockchain system. In the context of blockchain systems, the storage complexity is typically measured in terms of the size of the blockchain, denoted as $|B|$. The complexity $O\ (|B|)$ means that the storage requirements grow linearly with the size of the blockchain. This implies that as the blockchain grows, more storage space is needed to store the entire blockchain history. Bitcoin and Ethereum are examples of blockchain systems where the storage complexity is $O(|B|)$. This means that to store the entire blockchain history, storage space proportional to the size of the blockchain is required. Sharded blockchains, such as Elastico and Omniledger, use a technique called sharding to divide the blockchain into smaller parts called shards. Each shard contains a subset of the total blockchain. In these sharded systems, the storage complexity is given by $O(|B|/C)$, where C represents the number of nodes per committee. ABISChain storage complexity (ASC) can be calculated as follows:

- Let $|B|$ represent the size of the entire blockchain.
- Let $|PB|$ represent the size of the pruned blockchain.
- Let F denote the number of full nodes.
- Let L denote the number of light nodes.

Considering these variables, the storage complexity of ABISChain can be expressed as:

$$ASC = O(F{*}|B|{+}L{*}|PB|/(F+L)) \tag{3}$$

In summary, this inequality $F|B|{+}L|PB|/(F+L){<}|B|/C<|B|$ implies that ABISChain achieves a storage advantage compared to sharded blockchains and traditional blockchains since $F|B|{+}L|PB|/(F+L)$ is less than $|B|/C$ and $|B|$.

5.2. Processing Time to Generate Blocks

The processing time required to generate blocks is a critical metric in assessing the efficiency of blockchain networks. This section examines the resilience of ABISChain's performance, particularly in scenarios involving different types of nodes.

The ABISChain blockchain remains unaffected by the type of nodes present in the blockchain network. As presented in Figure 14, whether the network consists of 10 full nodes, 5 full nodes and 5 light nodes, or even 1 full node and 9 light nodes, the processing time remains consistent. This characteristic indicates that a network with a majority of light nodes can perform on par with a network composed solely of full nodes. In other words, the presence of light nodes does not hinder the efficiency and effectiveness of the network, allowing it to operate with comparable performance to networks predominantly comprising full nodes.

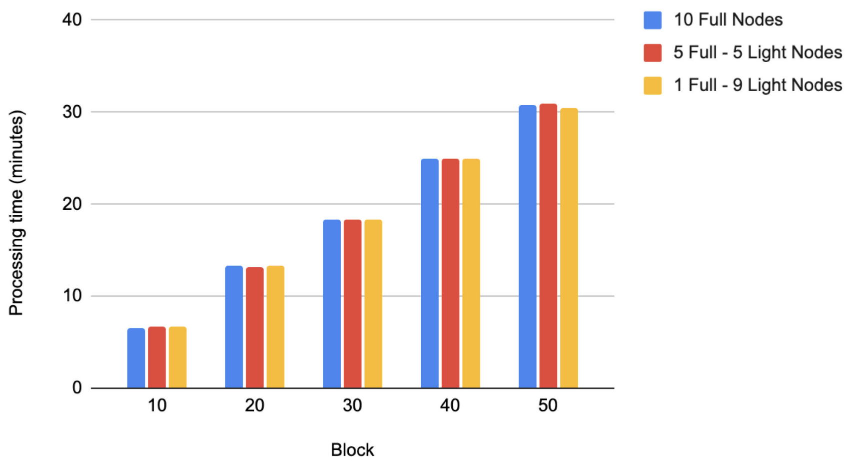

Figure 14. Processing time analysis in terms of block count.

5.3. Reading Data Time

When it comes to reading data from the ABISChain blockchain, the required time does not vary significantly depending on the types and distribution of network nodes. In the three scenarios presented in Figure 15, involving networks with 10 full nodes, 5 full nodes and 5 light nodes, and 1 full node and 9 light nodes, there are no noticeable differences in the reading time. In the scenario where the majority of nodes are light nodes, the reading times remain consistent because the pruning process ensures that the pruned ABISChain blockchain, maintained by all light nodes, contains the data that users are most likely to request. Consequently, a network consisting of 1 full node and 9 light nodes can be practically as efficient, reliable, and consistent for data retrieval as a network solely comprising full nodes.

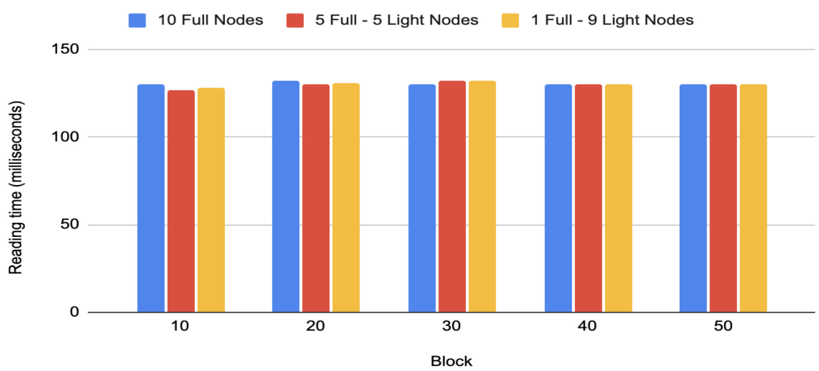

Figure 15. Reading data time according to node type.

5.4. Pruning Time

Figure 16 shows that in the ABISChain blockchain, the duration of the pruning process remains consistent across the three scenarios involving different node compositions. Whether the network consists of 10 full nodes, 5 full nodes and 5 light nodes, or 1 full node and 9 light nodes, the pruning duration does not vary significantly. This is because the pruning process utilizes the cache system of the nodes, which remains the same regardless of the node type. Instead, the pruning process is primarily affected by the influx of requests from ABISChain blockchain users. As user requests increase, the pruning process is directly impacted, potentially leading to longer durations.

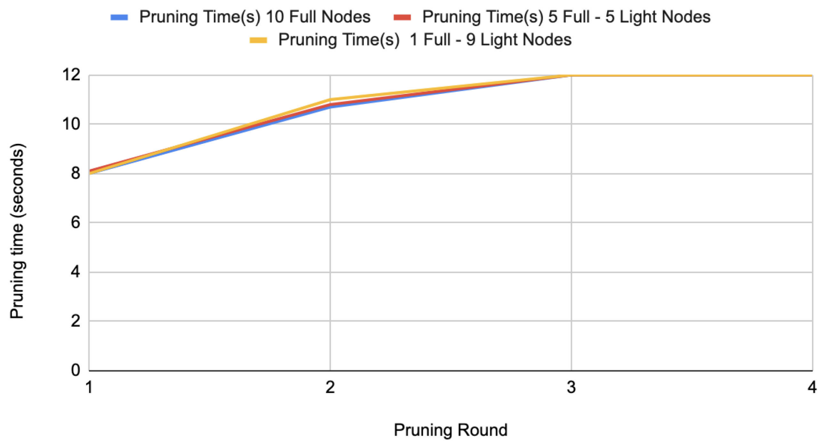

Figure 16. The pruning duration according to node type.

5.5. Pruned ABISChain Evolution over Time

Figure 17 illustrates the sizes of the ABISChain and the pruned ABISChain following each pruning round. The ABISChain displays a distinct upward trajectory in size as the number of pruning rounds increases. In contrast, the pruned ABISChain maintains a stable size throughout these rounds, fluctuating only slightly around a consistent value. This stability suggests that the pruned ABISChain effectively minimizes its size over time by eliminating redundant or unnecessary data—those that users did not request in previous rounds—ensuring that the blockchain does not experience significant growth.

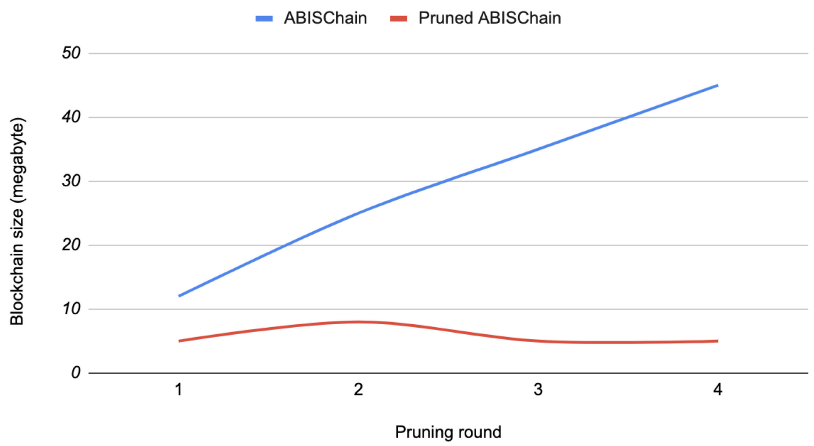

Figure 17. ABISChain and pruned ABISChain sizes after each pruning round.

The data presented clearly indicate that as the pruning rounds progress, the disparity in sizes between the two blockchains becomes increasingly evident. While the ABISChain continues to expand linearly, the pruned ABISChain remains nearly constant, underscoring the efficacy of the pruning process in maintaining an optimized blockchain structure.

5.6. Comparing ABISChain to Other Blockchains

In this section, we provide a comprehensive analysis of ABISChain by comparing its performance against both general-purpose blockchains and blockchain-based supply chain solutions. This comparison aims to highlight ABISChain's advantages in key areas such as block size, block time, throughput, and storage efficiency, all of which are critical for applications requiring high-volume data processing and scalability, such as supply chain management.

The comparison is divided into two parts:

1. **Comparison of ABISChain with general blockchains:** This includes well-known blockchains like Bitcoin, Litecoin, and Solana, which serve a variety of use cases but are not specifically tailored for supply chain management.
2. **Comparison of ABISChain with blockchain-based supply chain solutions:** This focuses on blockchain platforms developed explicitly for supply chain management, such as VeChain, Devery, and Shipchain, which ABISChain surpasses in terms of data throughput and storage optimization.

By contrasting ABISChain with these platforms, we aim to demonstrate the superiority of its architecture, particularly in terms of its pruned blockchain model, which enhances both scalability and efficiency without sacrificing performance, even in high-demand environments.

5.6.1. Comparison of ABISChain with General Blockchains

In this subsection, we present a comparison of ABISChain with the different blockchains outlined in Table 4. However, it is important to note that we exclude well-known blockchains such as Ethereum due to their reliance on the gas limit per block to determine block size.

Table 4. Blockchain block time and size.

Blockchain	Bitcoin	Litecoin	Solana	Dogecoin	Monero	ABISChain
Block Size (KB)	1024	1024	15–20	1024	2048	1024–2048
Block Time (S)	600	150	3	60	120	60–30

Block time is a critical determinant of blockchain performance, and ABISChain demonstrates a commendable average block generation time ranging from 30 to 60 s. This performance metric situates ABISChain between Bitcoin, which has a notably longer block time of 600 s, and Solana, which achieves near-instantaneous block times. The intermediate block time of ABISChain facilitates a balance between rapid transaction processing and system stability. Furthermore, with its block size capacity ranging from 1024 to 2048 KB, ABISChain is well-suited to manage large transaction volumes, making it an efficient and flexible blockchain solution.

As seen in Figure 18, ABISChain can add up to 68 KB of data per second, far surpassing the 17 KB per second throughput seen in Bitcoin, Dogecoin, and Monero. Although Solana's architecture allows for higher throughput, its block size and configuration are not designed for the types of large, complex transactions typically required in supply chain systems.

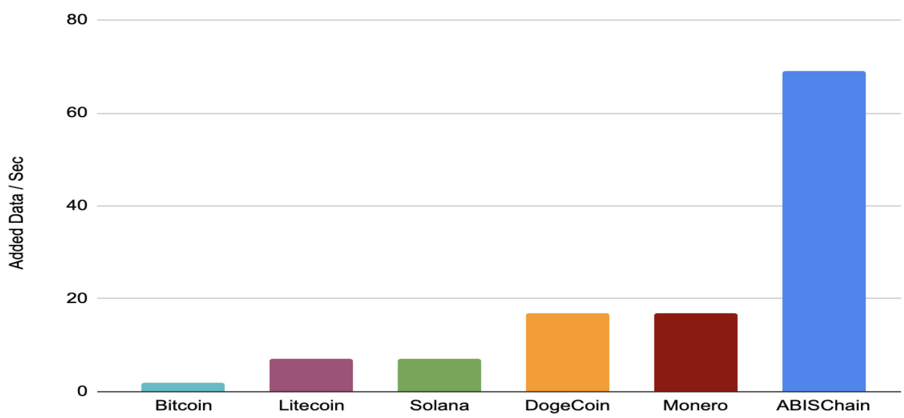

Figure 18. Comparison of data size (KB) added by blockchains.

5.6.2. Comparison of ABISChain with Blockchain-Based Supply Chain Solutions

In this subsection, we focus on blockchain-based platforms designed specifically for supply chain management, such as ShipChain citeShipChain, Devery [49], CargoX [50], and OriginTrail [53]. These projects rely on Ethereum, so the values are approximations based on Ethereum's specifications. By comparing the block size, block time, and data throughput of ABISChain with these solutions, we can demonstrate its advantages in scalability and efficiency.

Table 5 outlines how ABISChain outperforms other systems in terms of block size and data handling capacity. With block sizes ranging from 1024 to 2048 KB, it accommodates larger transaction volumes per block, supporting more complex operations compared to Shipchain and Cargox, which are constrained by Ethereum's gas limit.

Table 5. ABISChain and supply chain blockchain characteristics.

Blockchain	Block Size (KB)	Block Time (s)	Data Throughput (KB/sec)	Storage Optimization Technique
ABISChain	1024–2048	30–60	68	Pruning
Shipchain [48]	60–100	15	4.5	N/A
Devery [49]	60–100	15	4.5	N/A
CargoX [50]	60–100	15	4.5	N/A
OriginTrail [53]	60–100	15	4.5	N/A
WaltonChain [52]	562	60	9.3	Sharding
VeChain [54]	50	10	5	N/A

ABISChain's pruned blockchain architecture presents a significant advantage over traditional full-chain storage solutions seen in VeChain, Shipchain, and Cargox. By selectively storing only the most relevant and recent data on light nodes, ABISChain reduces storage complexity, as indicated by the Formula (3), while ensuring that the blockchain remains lean and efficient. This contrasts with VeChain, where all nodes must store the entire blockchain, resulting in higher storage costs and inefficiencies over time.

Additionally, ABISChain's approach outperforms sharding solutions such as those provided by WaltonChain. While WaltonChain's sharding aims to manage storage by dividing the blockchain into smaller, independent shards, this method introduces complexities related to inter-shard communication and synchronization. Shards must coordinate with each other to maintain consistency and security, which can lead to potential inefficiencies and increased overhead. In contrast, ABISChain's pruned architecture avoids these complications by maintaining a simpler, more streamlined system that focuses solely on essential data. This not only reduces storage requirements but also minimizes the need for complex coordination mechanisms, resulting in a more efficient and less cumbersome blockchain infrastructure.

We demonstrate ABISChain's superior throughput, scalability, and storage efficiency by systematically comparing it with both general-purpose blockchains and blockchain-based supply chain solutions. The incorporation of pruning and light node support ensures that ABISChain can meet the demands of high-volume, high-complexity use cases, further enhancing its utility for industries such as supply chain management. As mentioned in the previous section, we can further enhance ABISChain performance by adding an AI implementation to optimize key parameters like block size and block generation time based on the specific needs of the network users.

6. Conclusions

This paper introduced ABISChain, a dedicated blockchain solution for the supply chain. A comprehensive review of the existing literature on blockchain evaluation approaches for supply chains was conducted, along with an analysis of the current challenges and requirements in the field.

The paper began by providing an overview and background of the key concepts. Subsequently, it critically reviewed the existing solutions and presented various blockchain techniques that can meet the requirements of the supply chain. Specifically, two approaches were proposed: AI-based blockchain and pruning blockchain solutions.

ABISChain, the proposed blockchain, was then introduced. It is built upon a BDI (Belief–Desire–Intention) agent framework and incorporates an intelligent pruning process to address the scalability issue commonly associated with blockchains. The ABISChain system utilizes a multi-agent system, consisting of full nodes that store the entire blockchain and light nodes that store the pruned blockchain. These nodes collaborate to ensure the proper function of ABISChain.

For future research endeavors, we suggest the introduction of a mechanism based on artificial intelligence to update crucial values in the ABISChain blockchain. These values include the time difference since the last mined block, the size of the mempool data, the time difference since the last pruning, and the size of the pruned blockchain. The aim of this mechanism is to promote the adaptive blockchain performance of ABISChain.

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