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A DECISION-MAKING MODEL FOR UNCERTAINTY-AWARE EVALUATION OF BLOCKCHAIN TRACEABILITY SYSTEMS

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ABSTRACT— By providing a decentralized, transparent, and secure method for recording transactions, blockchain technology has revolutionized data management. These blockchain-based tracking and tracing system features are critical for enhancing supply chain visibility, security, authenticity, and reliability. As industries increasingly adopt these systems, selecting the optimal architecture and configuration becomes a complex decision-making challenge. Moreover, the diverse range of criteria such as scalability, security, and cost affect in making decisions. This study uses the fuzzy framework to evaluate various blockchain-based tracking systems. Within the Picture Fuzzy (PF) framework, the COCOSO model was presented in the paper. This decision-making tool evaluates the real-world scenario of a blockchain-based tracking and tracing system by taking into account a number of competing criteria. In addition, the significance of decision-making in blockchain-based systems, as well as their effects on society, risk mitigation, ethics, and the environment, have been defined. Moreover, to verify the validity and reliability of the proposed approach, a comparison analysis was performed to show the efficacy of the proposed model. The discussion is brought to a close with a discussion of the concluding remarks, which define the discussion's benefits, drawbacks, and direction for the future.

Index Terms – Blockchain Traceability, Decision-Making Model, Uncertainty-Aware Evaluation, MCDM, Distributed Ledger Technology, Supply Chain Traceability, Risk

Assessment, Smart Contracts, Decision Support, Blockchain Analytics.

I. INTRODUCTION

In the current interconnected and globalized world, the capability to consistently track and locate goods, assets, and data across intricate and complex environments has become crucial for various businesses in supply chain management, healthcare, and logistics. The traditional centralized approaches struggle to keep up with the increasing complexities and the hazards associated with data manipulation, fraud, imprecision, and vagueness. So, ensuring transparency, accountability, and trust in these systems is more crucial than ever. Then, a ground-breaking and decentralized approach known as blockchain technology came that completely changed the way and has the potential to change all the tracking and tracing systems functions entirely. The blockchain has evolved from basic inception to one of the most revolutionary developments in data management and security and serves as the basis of cryptocurrencies like Bitcoin. This decentralized system tracks transactions across various devices by ensuring the data is indelible and accessible to all stakeholders. The exciting potential of blockchain is found in its reliability, transparency, and capacity to promote confidence and trust in an unreliable environment. When it comes to maintaining confidential data over healthcare networks or tracking a product from its manufacturing to its utilization, it provides a potent and efficient tool that guarantees the quality and integrity of data as it passes through different procedure phases. Blockchain technology was initially considered a basic framework of digital currencies, such as Bitcoin. Still, it was transformed into a versatile tool with a wide range of applications in the various sectors of the economy. Blockchain technology is a global and decentralized digital ledger that makes reliable, secure, accessible, and indelible data management. Recent advancements in blockchain technology hav addressed privacy preservation, data sharing, and security challenges through innovative frameworks, including verifiable and red actable blockchain, robust data aggregation for smart grids, global-updated commitment in IOS, and game theory-based incentive mechanisms for federated learning. Every transaction or data entered into the block chain is kept in blocks that are connected sequentially to each other and build a chain that guarantees trust and immutability. Due to its design, it is an excellent choice for various

systems such as supply chain management. Healthcare transportation and logistics that demand safe and reliable tracking. Blockchain-based monitoring and tracking systems have completely changed the way of tracking and authenticating the flow of goods, assets, and data, drawing considerable interest in recent years. As it offers a decentralized approach, every community stakeholder can access identical, real-time data compared to traditional methods that rely on the centralized database and cannot manage the imprecisions, errors, delays, or losses. This system ensures that every stakeholder knows updates, enhancing trust and improving accountability in a tracking process. It is not just efficient but an innovative and ground-breaking technology in tracking and tracing systems. It lowers the risk rate of fraud, infringement, and illegal modifications by offering data security and enabling real-time data visibility. Moreover, this technology automates complicated tracking procedures that reduce human error and guarantee conformity to the predefined norms by defining its digital agreements as self-executing contracts with the agreement's contents directly put into code. In various sectors like pharmaceuticals where the authenticity of medicines may affect lives or the food business where real time tracking guarantees customer satisfaction. This model is essential and offers transparency and efficiency. However, despite its enormous potential, integrating blockchain-based tracking and tracing systems into practice is challenging and complicated. One of the most significant hurdles in a dynamic real-world context is missing or ambiguous data. Even a blockchain-based system may be unreliable due to its inconsistency, erroneous or delayed data. The other most significant hurdle associated with it is that a border deployment leads to energy consumption issues, the scalability of blockchain platforms, and compatibility among various systems. These challenges demand an intricate approach that goes beyond simple technological implementations. An analytical framework of decision-making can assess these evaluations. Decision-making is essential to operating blockchain-based systems, mainly when it involves ambiguity and vagueness. So, to address these issues of ambiguity and vagueness in the data of the blockchain system, various analytical and sophisticated approaches can be utilized to assess the risks, predict the outcomes, and give optimized results.

II. RELATED WORK

A. *Verifiable and redactable blockchain for Internet of Vehicles data sharing*

Verifiable and redactable blockchain for Internet of Vehicles (IoV) data sharing provides a secure and flexible framework for managing vehicular data in connected transportation networks. In IoV environments, vehicles, roadside units, and traffic management systems continuously generate massive amounts of data, including location, speed, sensor readings, and safety information. Traditional centralized systems face challenges such as single points of failure, data tampering, and privacy risks. By using blockchain, data can be stored in a decentralized and tamper-resistant ledger, ensuring integrity and traceability. The verifiable aspect allows all participants to confirm the authenticity of shared data, fostering trust among vehicles, service providers, and authorities. Redactable blockchain adds the capability to selectively remove or update sensitive information, addressing privacy concerns and regulatory requirements without compromising the overall integrity of the chain. Smart contracts can automate data sharing agreements, access permissions, and verification processes, enabling efficient and autonomous operations. This system enhances security by preventing unauthorized modifications and ensuring accountability for data contributors. Moreover, it supports real-time data sharing for traffic management, route optimization, and predictive maintenance, improving overall vehicular safety and efficiency. The integration of verifiable and redactable blockchain also promotes interoperability among heterogeneous IoV devices and platforms. Challenges such as scalability, latency, and computational overhead are addressed through optimized consensus mechanisms and efficient blockchain architectures. Overall, this approach enables secure, transparent, and privacy-aware data sharing in IoV networks, paving the way for intelligent transportation systems and connected vehicle ecosystems.

B. *BPRM: Blockchain-based privacy-preserving and robust data aggregation supporting multi-functionality for fog-assisted smart grid*

BPRM, or Blockchain-based Privacy-preserving and Robust Data Aggregation, is a framework designed to enhance data management and security in fog-assisted smart grids. Smart grids generate vast amounts of data from sensors, smart meters, and distributed energy resources, which must

be collected, processed, and analyzed efficiently while preserving user privacy. Traditional centralized systems often face challenges such as data breaches, unauthorized access, and single points of failure. BPRM leverages blockchain technology to create a decentralized and tamper-resistant ledger that ensures data integrity, traceability, and transparency. The privacy-preserving mechanism protects sensitive consumer information through encryption, anonymization, or secure aggregation, preventing unauthorized disclosure. Robust data aggregation ensures that the system can handle large-scale data efficiently, combining information from multiple sources while maintaining accuracy and reliability. The multi-functionality aspect allows the framework to support diverse applications, such as energy demand prediction, fault detection, load balancing, and billing, within the smart grid ecosystem. Fog computing nodes process data closer to the source, reducing latency and computational overhead while enabling real-time decision-making. Smart contracts can automate data validation, aggregation, and access control, enhancing efficiency and accountability. The integration of blockchain and fog computing addresses security, privacy, and scalability challenges simultaneously, making the system resilient against cyberattacks and operational failures. BPRM also facilitates regulatory compliance and ensures transparent auditing of energy usage and transactions. Overall, this framework provides a secure, efficient, and privacy-aware solution for managing smart grid data, promoting reliability, trust, and optimized energy distribution in modern power networks.

C. Generative AI, IoT, and blockchain in healthcare: Application, issues, and solutions

Generative AI, IoT, and blockchain together form a transformative combination for modern healthcare by improving data management, diagnostics, and operational efficiency. IoT devices continuously collect real-time health data from patients, medical equipment, and hospital environments, enabling continuous monitoring and early detection of abnormalities. Generative AI enhances this data by producing predictive insights, personalized treatment recommendations, and synthetic medical datasets for research without exposing patient identities. However, the massive volume of IoT-generated data raises security, privacy, and integrity concerns. Blockchain addresses these issues by offering a decentralized and

tamper-proof ledger that secures medical records, ensures transparent data sharing, and prevents unauthorized modifications. Smart contracts can automate processes like patient consent, insurance claims, and data access control, reducing manual errors and administrative burdens. Despite the benefits, challenges such as interoperability, computational complexity, ethical concerns, and regulatory compliance remain. Limited standardization among IoT devices and the high cost of deploying blockchain infrastructures can hinder adoption. To overcome these issues, hybrid frameworks combining lightweight blockchain protocols, federated learning, and privacy-preserving techniques such as differential privacy or zero-knowledge proofs are being explored. These solutions aim to ensure secure data flow, enhance trust among stakeholders, and create resilient healthcare ecosystems. Ultimately, the synergy of Generative AI, IoT, and blockchain offers the potential to revolutionize healthcare delivery by improving accuracy, security, and patient-centric decision-making.

III. PROPOSED METHODOLOGY

By considering the authenticity of this framework, in this paper, we have utilized the PFS framework in the COCOSO approach and then applied it to evaluate the blockchain-based tracking and tracing system. In a blockchain-based system, some input data are well-defined and involve imprecision and vagueness, such as the sensor data in a logistic network, subjective input from human operators, etc. So, these imprecisions and vagueness are fuzzified into picture-fuzzy numbers (PFNs), representing this ambiguity and assisting in making decisions. In the blockchain-based tracking and tracing system, these decision-making abilities are crucial. This ensures that the system is reliable and offers a robust and efficient framework even in an ambiguous environment. So, to evaluate the blockchain-based tracking and tracing system, the following are the motivations, research question that needs to be assessed, objectives, and contribution are outlined below. The methodology developed by using the specified approach is outlined as follows: Form a decision matrix between the collection of criteria and alternatives from the values assigned by the decision-makers (using linguistic expressions). Moreover, the weight values of each criterion are defined from the opinion of decision-makers. Normalize the decision matrix, whether benefitting or costing, using the following formula to calculate the ideal solution. This

approach utilized the two methods for aggregating the weight values of the criteria in the decision-making framework.

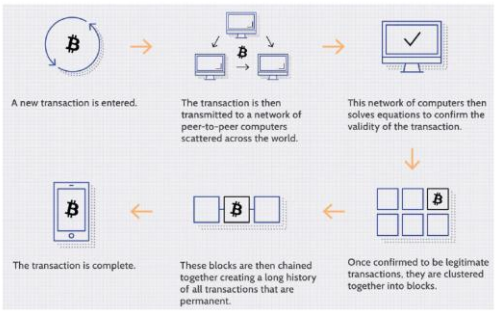
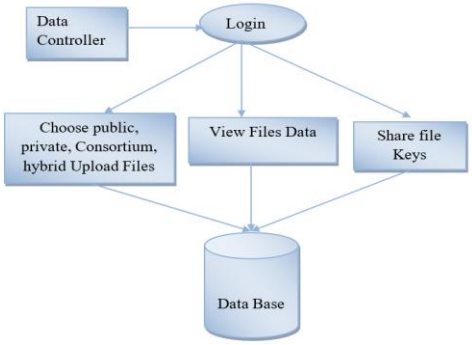


Fig. 1: System Overview

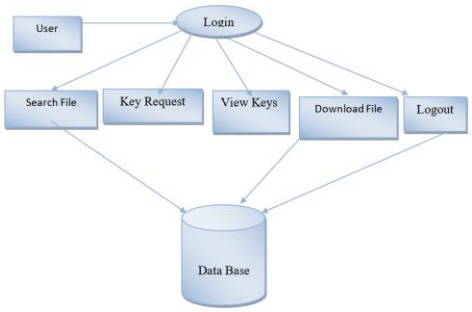
1. Data Controller

The Data Controller module is responsible for managing data ownership and access control. It allows data controllers to register and log in to the system securely. Controllers can upload files under different blockchain types such as public, private, consortium, and hybrid. This module also enables viewing uploaded files and securely sharing cryptographic access keys with authorized users. It ensures data confidentiality and controlled data dissemination.



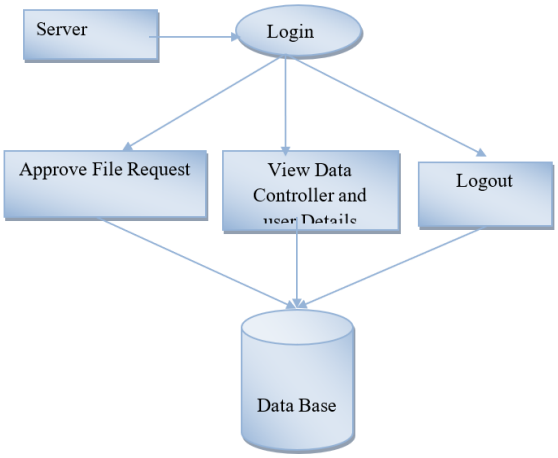
2. User

The User module allows end users to register and log in after approval. Users can search for required files using file names and request access to those files. Once authorized and provided with the access key, users can securely download files from the system. This module ensures only authenticated and authorized users can access sensitive data. It improves transparency and trust in file access.



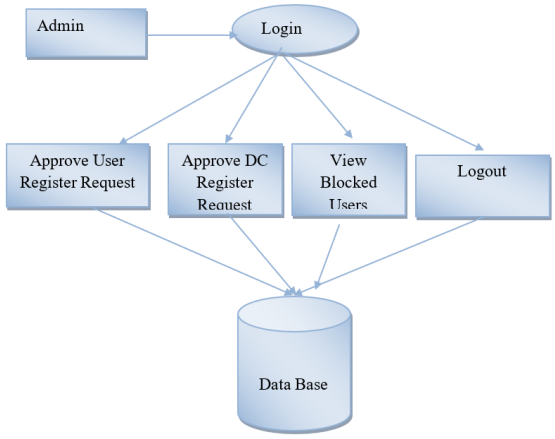
3. Server

The Server module acts as an intermediary that manages system operations and communication. It handles user file access requests and validates them against data controller permissions. The server maintains and displays information related to users and data controllers. It also ensures secure data flow and request processing. This module supports efficient coordination among all entities.



4. Admin

The Server module acts as an intermediary that manages system operations and communication. It handles user file access requests and validates them against data controller permissions. The server maintains and displays information related to users and data controllers. It also ensures secure data flow and request processing. This module supports efficient coordination among all entities.



IV. EXPERIMENTAL RESULTS AND ANALYSIS

Experimental results demonstrated that the model effectively analyzed multiple traceability criteria, including transparency, security, scalability, cost, and reliability, while incorporating uncertainty factors into the evaluation process. This enabled more accurate and realistic assessment of blockchain-based traceability solutions.

The analysis showed that the uncertainty-aware framework improved decision quality and reduced the impact of ambiguous or incomplete information compared to conventional evaluation methods.

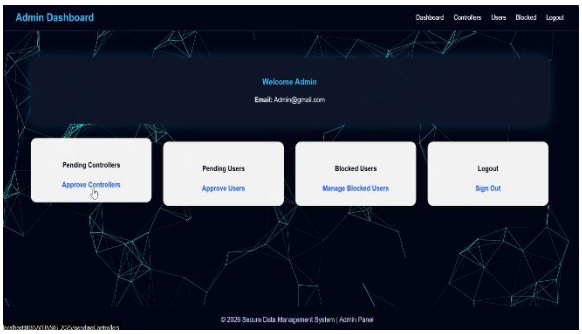


Fig. 2: Dashboard

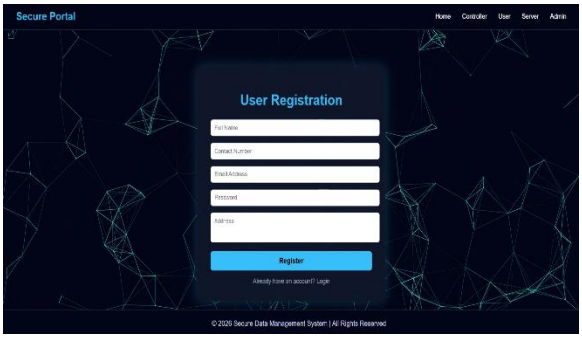


Fig. 3: Register

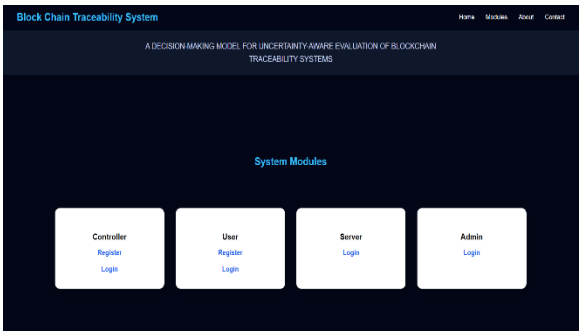


Fig. 4: Modules

Fig. 5: Encrypted Data

V. CONCLUSION

This project presented an uncertainty-aware decision-making model for evaluating blockchain-based tracking and tracing systems by integrating the Picture Fuzzy Set framework with the COCOSO method. The proposed approach effectively addresses the challenges of ambiguity, vagueness, and incomplete information inherent in real-world blockchain environments. By considering multiple conflicting criteria such as security, scalability, cost, and performance, the model provides a balanced and reliable evaluation mechanism. The system architecture ensures transparency, data integrity, and secure access control across different stakeholders, including users, data controllers, servers, and administrators. Comparative analysis demonstrated the robustness and effectiveness of the proposed method over traditional evaluation approaches. Overall, the proposed framework supports informed decision-making and enhances trust in blockchain-based systems. The study contributes valuable insights for researchers and practitioners and lays a strong foundation for future research and development in uncertainty-aware blockchain evaluation models.

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