A Comprehensive System for Managing Blood Resources Leveraging Blockchain, Smart Contracts, and Non-Fungible Tokens

Khiem H. G.[1], Huong H. L.*[1], Phuc N. T.[1], Khoa T. D.[1], Khanh H. V.[1], Quy L. T.[1], Ngan N. T. K.[2], Triet N. M.[1], Kha N. H.[1], Anh N. T.[1], Trong. V. C. P.[1], Bang L. K.[1], Hieu D. M.[1], and Bao T. Q.[2]

[1]FPT University, Can Tho City, Vietnam
[2]FPT Polytechnic, Can Tho City, Vietnam

***Abstract*— The escalating demand for blood and its derivatives in the medical field underpins its indispensable nature for disease diagnosis and therapy. Such essential life-giving components are irreplaceable, necessitating a continuous reliance on voluntary blood donors. Existing methodologies primarily address the challenges of blood storage and its logistical distribution among healthcare centers. These conventional strategies lean towards centralized systems, often compromising data transparency and accessibility. Notably, there remains a significant gap in incentivizing and raising awareness among potential and existing donors regarding the life-saving act of blood donation. Recognizing these challenges, we introduce a robust and innovative framework that harnesses the potential of Blockchain technology, coupled with the power of smart contracts. Furthermore, to foster a sustainable blood donation ecosystem, we advocate the shift from traditional paper-based recognition to digitized donor acknowledgment using Non-Fungible Tokens (NFTs). Our novel approach encapsulates four key areas: (a) Introduction of a supply chain oversight mechanism for blood and its derivatives through Blockchain and smart contracts; (b) Development of a digital certification system for blood donors utilizing NFTs; (c) Execution of our suggested framework via smart contracts, offering a tangible proof-of-concept; and (d) Assessment and implementation of the proof-of-concept across four prominent platforms: ERC721 (ETH's NFT), and the Ethereum Virtual Machine (EVM) employing the Solidity language – this encompasses the BNB Smart Chain, Fantom, Polygon, and Celo, aiming to discern the optimal platform compatible with our innovative framework.**

***Keywords*—Blood donation; blockchain; ethereum; blood products supply chain; smart contract; NFT; ethereum; fantom; polygon; binance smart chain**

I. Introduction

Supply chain management, an interdisciplinary field that interlinks various sectors, has witnessed transformational shifts in the digital age, with implications spread across delivery [1], [2], [3], payment systems [4], [5], [6], project dynamics [7], product movement [2], [8], and even ecological waste disposal [9]. One of its paramount manifestations is within the medical landscape, particularly in ensuring the efficient and safe management of blood and its associated products.

Historically, the majority of supply chain models, while sophisticated, have been grounded in traditional logistics and storage paradigms. When we delve into the intricacies of managing biological resources like blood, these models often fall short. Blood, unlike other commodities, has unique storage requisites, from maintaining a specific temperature range to ensuring an optimal humidity environment, and most critically, adhering to its limited shelf life [10]. These nuances underscore the inadequacies of conventional supply chain mechanisms and highlight an urgent need for innovation.

Enter blockchain technology and smart contracts. Beyond the mainstream applications in finance and business, these technologies harbor immense potential for healthcare. In ensuring a transparent, immutable, and decentralized storage and access system, they promise an enriched donor-recipient relationship. Every single unit of blood can be tracked, from its origin to its end-use, ensuring complete transparency and trustworthiness in the system [11]. But technology alone, as history often reminds us, is insufficient to drive societal change.

Across the globe, the act of blood donation remains both a noble endeavor and a logistical challenge. How does one not only encourage a first-time donation but ensure that the donor returns, given the physiological restrictions that mandate waiting periods between donations? Current incentive structures, while well-intentioned, often falter in ensuring sustained donor engagement. And with medical innovations surging, the demand for blood and its derivatives amplifies, rendering the challenge even more pronounced [12].

It is within this complex mosaic of challenges and opportunities that our research emerges, aiming to not merely innovate but to transform. Our work, grounded in the principles of blockchain, smart contracts, and the dynamism of Non-Fungible Tokens (NFTs), envisions a holistic reimagining of the blood donation landscape.

Our pivotal contributions are:

- Redefining Blood Supply Chain Mechanisms: By integrating blockchain and smart contract technologies, we introduce a more transparent, efficient, and secure system for managing the blood supply chain.
- NFT-driven Electronic Certification: Venturing beyond conventional incentive models, we harness the capabilities of NFTs to create a robust electronic certification system for blood donors. These digital tokens, being unique and easily transferable, provide an innovative solution to the tangible certificate's pitfalls, offering

donors a secure and lasting acknowledgment of their invaluable contribution.

- Proof-of-Concept Realization: Our theoretical formulations are translated into tangible, executable smart contracts, reinforcing the practical viability and applicability of our proposed systems.
- Platform Exploration and Optimization: Conscious of the economic implications, our solutions undergo rigorous deployment trials across platforms supporting the Ethereum Virtual Machine (EVM) infrastructure. Our endeavor seeks not just feasibility but also cost-effectiveness, ensuring that our solutions remain both cutting-edge and accessible.[1]

The undercurrent binding our contributions is the conviction that technology, when thoughtfully applied, can drive societal transformations. By augmenting the blood donation landscape, our research does more than introduce technological innovations; it touches lives, accelerates medical interventions, and champions a cause of profound societal significance.

II. Related Work

A. Prior Art in Blood Supply Chain Management via Blockchain

In recent years, Blockchain technology's transformative potential has been tapped to address challenges in blood supply chain management. Notably, Nga et al. [13] pioneered this integration, showcasing a working model implemented on the Hyperledger Fabric platform. Their primary innovation was the facilitation of healthcare professionals to log and secure data directly on the blockchain. Shifting from a centralized storage protocol to a decentralized one, this framework places significant emphasis on ensuring robust security mechanisms. Particularly, as documented by [14], they engineered an authorization process that offers exclusive access to sensitive donor and recipient data only to authenticated users, preserving the privacy sanctity system-wide.

Supplementing this innovative stride, Kim et al. [15] extended the application of Hyperledger Fabric in designing a holistic blood supply chain management system. Their model prioritizes privacy, constructing a well-contained system that oversees the entire blood supply trajectory—from collection to final distribution to medical institutions. Another salient feature they introduced is a donor identification technique to streamline communication for future blood donation drives. However, a noticeable void in their proposal is the absence of granular management processes tailored to distinct blood components, each demanding specific preservation methods and having unique shelf lives.

Lakshminarayanan et al. [16] further explored the Hyperledger Fabric's capabilities, proposing a model accentuating transparency in blood transportation from donors to end recipients. Another intriguing convergence of technologies was demonstrated by Toyoda et al. [17], where they synergized blockchain with Radio Frequency Identification (RFID). In this model, upon blood donation, each unit gets a unique RFID tag, simplifying access to comprehensive blood-related data, like donation time and location, for both healthcare professionals and recipients.

[1]We consciously eschew ETH owing to its exorbitant smart contract execution expenses.

While many have gravitated towards the Hyperledger Fabric, Ethereum's potential hasn't been overlooked. A compelling use case, delineated by [10], presents an Ethereum-centric decentralized architecture. This structure exclusively empowers certified blood donation centers (CBDC) to manage blood and its components through deployable smart contracts. This system ensures procedural fidelity and plugs potential logistical gaps. An added advantage is the donor's ability to interface with the system using unique identifiers, such as social security numbers, paired with secure passwords.

Zooming into specific blood components, Peltoniemi et al. [18] analyzed the efficacy of decentralized blockchains in plasma management. Their approach ensures meticulous documentation of donor data prior to plasma extraction. Post extraction, an analytical assessment discerns the plasma quality.

In light of the foregoing exploration of blockchain-powered blood supply chain solutions, it's evident that while tremendous progress has been made in rectifying traditional system pitfalls, one persistent challenge remains unaddressed: incentivizing recurring blood donations. Our contribution to this discourse is a multifaceted model amalgamating Blockchain (specifically Ethereum), Smart Contracts, and Non-Fungible Tokens (NFTs). This model doesn't just oversee the blood supply chain but also introduces digital recognition mechanisms, like electronic donor certificates. An in-depth exposition of our model is detailed in the subsequent section.

B. Blockchain-based Medical Systems

Healthcare has always been a fundamental aspect of human life. With the advancement of technology and a growing concern for patients' data privacy and the immediate need for accessing data during emergencies, blockchain technology has emerged as a promising solution for many of the challenges faced by modern healthcare systems.

a) Emergency access in healthcare systems: Son et al. [19] stressed the importance of personal health records (PHR) due to their sensitivity and significance in healthcare. The authors identified the challenges faced during emergencies when it becomes cumbersome for patients to grant medical personnel access to their critical health records. They proposed an emergency access control management system built on the permissioned Hyperledger Fabric blockchain. The system leverages smart contracts to define rules and timeframes to handle emergencies, ensuring patients can restrict data access time.

Similarly, Le [20] introduced the Patient-Chain platform, a blockchain-based patient-centered healthcare system also built on Hyperledger Fabric. The system aims to protect patients' data during emergencies and provides a systematic approach to allow authorized personnel to access patient data during time-sensitive situations.

b) Medical waste management: The demand for medical equipment spiked significantly during the COVID-19 pandemic. However, the subsequent waste treatment processes often went overlooked. Le et al. [9] highlighted the independent waste treatment processes in hospitals that lack coordination and data sharing. The authors proposed the Medical-Waste Chain, a decentralized system built using Hyperledger Fabric technology. This system manages the waste treatment processes for used medical equipment and supplies, promoting transparent and efficient interactions between all involved stakeholders.

c) Blood supply chain management: With a rising demand for blood supply due to demographic shifts, traditional blood management information systems face challenges, such as the lack of detailed blood data, making the quality, supply, and demand management for blood quite challenging. In response, Le [14] introduced BloodChain, a blockchain-based system that improves blood information management. The system, constructed on Hyperledger Fabric, provides detailed data, including blood consumption and disposal metrics.

Quynh et al. [13] echoed similar sentiments about the changing population structure and its impact on blood supply. They introduced a novel system on Hyperledger Fabric to manage blood information effectively, addressing supply and demand challenges faced by national institutions.

d) Patient-centered healthcare systems: Duong [21] identified challenges in current healthcare systems regarding the privacy and sharing of medical data. The authors highlighted the necessity for a secure transaction mechanism to allow patients to monitor and control their health records. Proposing a solution, they introduced a patient-centered healthcare system using smart contracts via blockchain technology, releasing the complete code solution on GitHub to promote reproducibility and further improvement.

In another contribution, Duong [22] proposed a patient-centric system based on smart contracts. Emphasizing patients' control over their health records, the authors used Smart Contract on both Hyperledger Fabric and Ethereum Blockchain to improve care coordination. Through six algorithms, they interacted with different components of the healthcare system, showcasing the system's efficiency through simulation results.

In summary, while blockchain technology offers a plethora of solutions to address various challenges in the healthcare sector, from managing blood supply chains to medical waste, its paramount feature remains in ensuring the privacy and security of patient data. Future research might look into integrating these blockchain-based systems with other emerging technologies to further improve healthcare operations and patient experiences.

III. METHODOLOGY

This section elucidates the conventional models of blood donation and its associated documentation methods. We further introduce a novel methodology incorporating Blockchain technology, smart contracts, and Non-Fungible Tokens (NFTs) to modernize the system of transporting, storing, and authenticating blood products.

A. Conventional Blood Donation and Management Process

As depicted in Fig. 1, the conventional blood donation system operates through four primary channels. Donors, depending on their geographical proximity, have the option to donate at: (a) healthcare centers; (b) medical facilities; (c) hospitals; or (d) portable blood collection stations [23]. The fourth option, (d), is a transient solution such as pop-up stations during weekends or holidays. This approach is not only geared towards encouraging potential donors but also addresses challenges in regions where there are obstacles to blood collection using the first three methods. Once the blood is collected, it is transported to specialized facilities or institutions equipped with blood storage systems. This collected blood undergoes separation into components like red and white blood cells, platelets, and plasma. Simultaneously, donor data is recorded and stored securely for communication purposes.

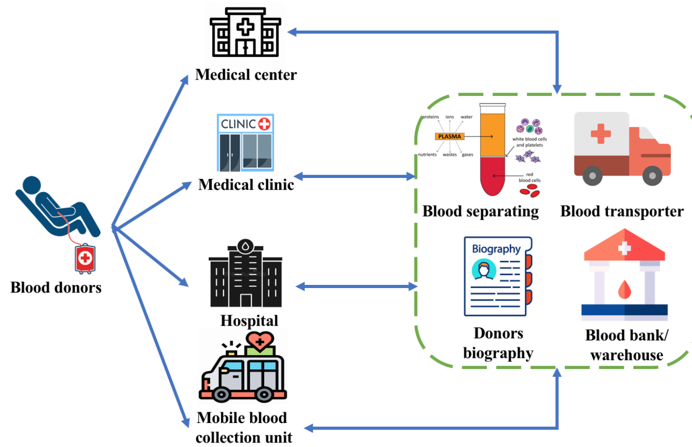

Fig. 1. Conventional system of blood donation and management.

Fig. 2. Conventional blood donor certification.

In terms of documentation, Fig. 2 elucidates the process of obtaining a donor certificate from an institution, such as a hematology center. Such certificates serve as a moral boost for donors. Moreover, they ensure that donors receive equivalent blood volume in situations where they might require it due to certain health conditions. Detailed critiques and evaluations regarding the shortcomings of this method have been discussed in the Introduction[2]. The subsequent subsection outlines our innovative proposal that leverages blockchain, smart contracts, and NFT technology.

B. Revolutionizing Blood Donation and Management via Blockchain, Smart Contracts, and NFT

The core objective of our research is to formulate an advanced system that enhances blood utilization across med-

[2]Refer to our earlier publications for a deeper dive into the challenges of conventional methodologies [14].

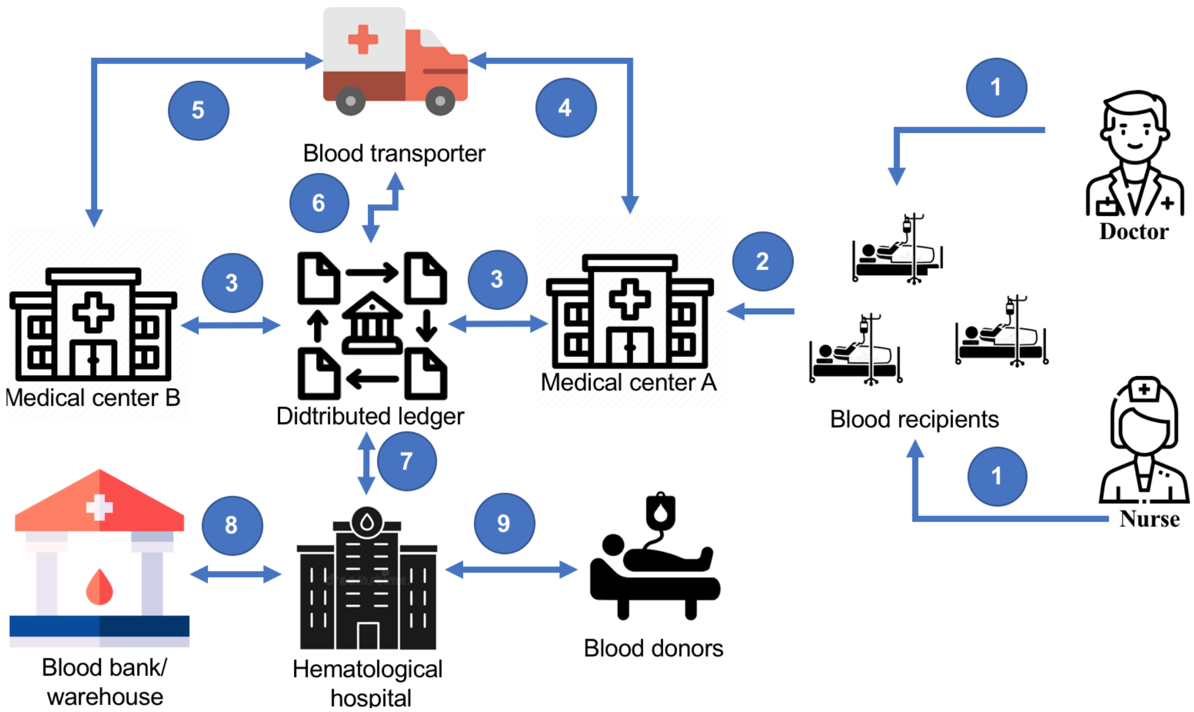

Fig. 3. A novel blood donation and management paradigm utilizing blockchain, smart contract, and NFT technologies.

ical establishments and offers inventive means to motivate individuals to regularly donate. In this context, we propose a dual model that harnesses the capabilities of blockchain, smart contracts, and NFTs to circumvent existing limitations.

Fig. 3 suggests an interconnected model for blood donation and its management among healthcare facilities within a specified region, e.g., a city. The first step encompasses clinical examinations and treatments offered by physicians to their patients, who might be potential recipients of blood. Should there be a necessity for blood, a requisition is forwarded to the concerned institution. Two scenarios can arise: either the institution has an adequate blood stock or faces a shortage. In the latter scenario, the requirement is logged onto a distributed digital ledger. This system then scans affiliated institutions for the requisite blood type. Upon locating a matching facility, a carrier is mobilized. Vital data points such as timings and locations are recorded onto the digital ledger. In situations where local healthcare facilities are devoid of the needed blood type, the system communicates with specialized hematology centers or scans regional blood banks. If there still remains a deficiency, potential donors are contacted for collections.

Fig. 4 delineates the procedure for NFT issuance which serves as a digital blood donation certificate. Before the NFT's generation, donor's consent and institutional validation (e.g., from a hematology center) are imperative. We extend distinct services to each stakeholder, culminating in the creation of a digitalized version of the donor certificate. This data, alongside pertinent documentation, is recorded on the distributed ledger, leading to the production of an NFT via predefined functions in the smart contract.

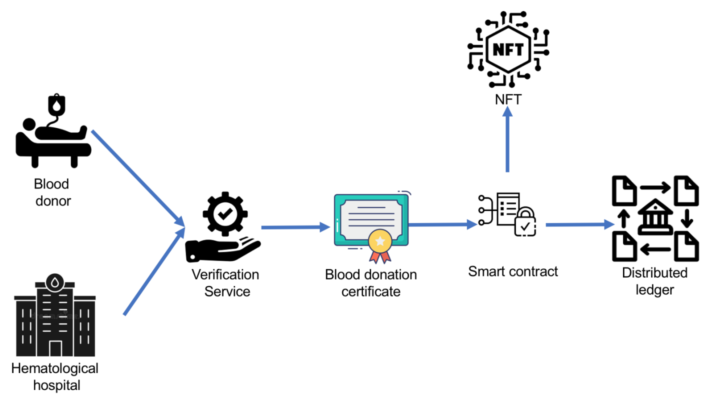

Fig. 4. Process of issuing digital blood donation certificates leveraging NFT technology.

IV. Implementation

This practical model serves dual purposes: (i) management of blood and its by-products data on the blockchain platform encompassing creation, querying, and updates, (ii) instantiation of NFTs for donor contributions, serving as a motivation for continued blood donation. Moreover, we present the sample of the managing blood resources leveraging on Binance Smart Chain as a deployment sample.

A. Data and NFT Initialization

As depicted in Fig. 5, the process begins by generating comprehensive data on blood and its derivatives. This encompasses details about the donors, their contact specifics (e.g., address, unique identification code), specifics about blood and its components, and their respective shelf lives. Given the

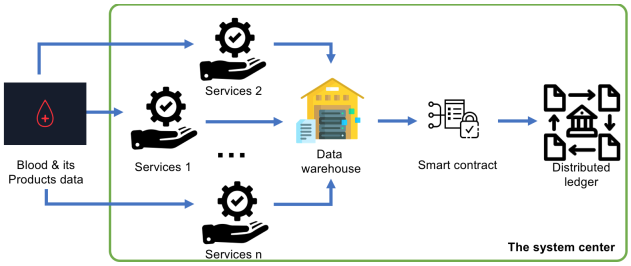

Fig. 5. Process of data and NFT initialization.

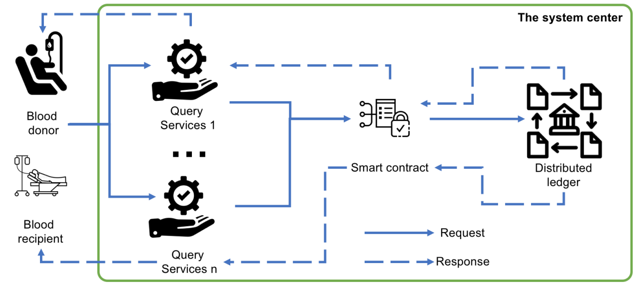

Fig. 6. Data retrieval process.

varying storage needs and lifespans of different blood products, categorization is vital. Moreover, the system archives details about the recipients, blood type requirements, and the medical professionals overseeing the procedures. Concurrent storage support is enabled on the distributed ledger, allowing multiple users to engage simultaneously, thereby reducing latency.

The data structure for a blood component, such as red blood cells, is represented as:

```
redBloodCellsData = {
"donorID": donorID,
"medicalStaffID": medicalStaffID,
"bloodType": blood type,
"institutionID": institutionID,
"volume": volume,
"validityPeriod": validity period,
"packageID": packageID,
"timestamp": timestamp,
"location": current location,
"status": null,
};
```

Besides the primary data attributes, the system monitors the real-time status of blood components in storage. This status attribute indicates if the blood product is in storage or has been dispatched for medical use. This dynamic tracking, combined with time and location data, aids in real-time logistics management.

For initializing NFTs, the structure encapsulates the blood donation details as:

```
NFTBloodDonation = {
"donorID": donorID,
"bloodType": blood type,
"donationCount": donation occurrences,
"totalVolume": accumulated volume donated,
"lastDonationDate": most recent donation date
"blockchainAddress": blockchain address
};
```

This ensures a comprehensive, immutable record of each donation, aiding in efficient management and donor recognition.

B. Data Retrieval

Fig. 6 outlines the steps involved in the data retrieval mechanism. Leveraging a distributed model, it permits multiple users to concurrently access the system. Donors and recipients might seek insights into storage processes, donation frequency, or upcoming donation schedules. Medical professionals, on the other hand, might access donor details for outreach or future donation drives.

C. Data Update Mechanism

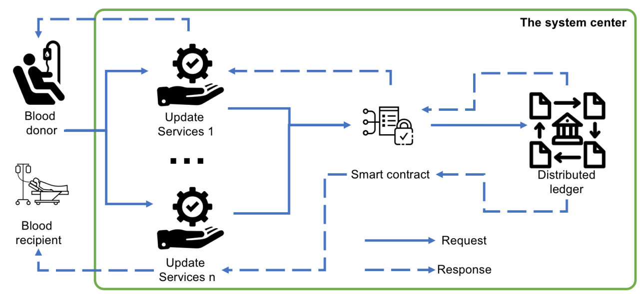

Fig. 7. Procedure for data updates.

As demonstrated in Fig. 7, the data updating procedure only commences post data verification. If the sought data isn't present on the blockchain, a non-availability message is relayed to the user. In case of updates, the process fetches existing data and modifies relevant attributes such as blood volume or donation frequency. For NFTs, any major update triggers the generation of a new NFT, ensuring historical records remain untouched.

D. Managing Blood Resources using Binance Smart Chain

The Binance Smart Chain (BSC) has been identified as an ideal candidate for managing blood resources, given its compatibility with the Ethereum Virtual Machine (EVM) and its optimized transaction performance. As such, the proposed model is primarily evaluated and implemented on BSC, but compatibility with other platforms is also maintained. Here, we discuss the specifics of the implementation on BSC, showcasing transaction details, NFT creation, and the process of NFT transfers.

Fig. 8 details our deployment of the system on BSC. It showcases attributes essential for evaluating and comparing transaction performance across different blockchain platforms. This snapshot is a representative case, with similar settings applied when deploying on other platforms. Transaction details like the transaction fee, gas limit, and gas price provide a

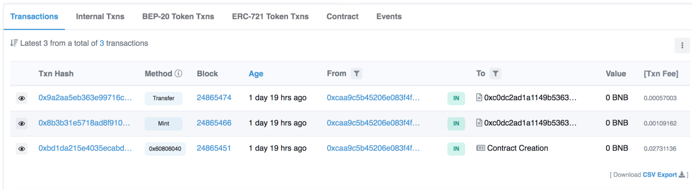

Fig. 8. A snapshot illustrating transaction details on Binance Smart Chain. The attributes highlight the cost implications and performance of a transaction, specifically for our blood management use case.

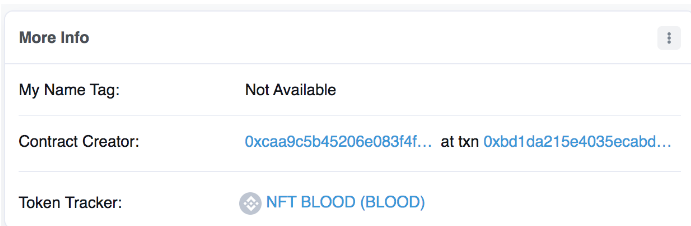

Fig. 9. Depicting the NFT creation process on BSC. This highlights the structured format of our NFTs, tailored to represent blood donations and their associated attributes.

comprehensive insight into the cost-effectiveness of operations on the chain.

The NFT creation process, visualized in Fig. 9, follows a structured format. Each NFT is intricately designed to represent blood donations, capturing essential details like the donor's information, blood type, and donation history. Such a tokenized representation not only ensures data integrity and authenticity but also promotes transparency in the system.

Fig. 10. A detailed representation of NFT transfer operations on BSC. The process ensures secure, transparent, and traceable transfer of NFT ownership.

The transfer of NFTs, especially in a sensitive domain like blood resource management, demands high levels of security and traceability. Fig. 10 provides a comprehensive overview of the NFT transfer operations. Leveraging the ERC721 standard ensures that each NFT transfer is not just secure but also accompanied by clear traceability, promoting trust among participants.

While Binance Smart Chain plays a pivotal role in our implementation, it's essential to recognize the versatility of our model. We have deployed and evaluated the system on several EVM-compatible platforms, including Binance Smart Chain[3], Polygon[4], Fantom[5], and Celo[6]. Implementations and results across these platforms, especially focusing on cost metrics like transaction fees and gas utilization, are detailed in the ensuing Evaluation section.

[3]https://github.com/bnb-chain/whitepaper/blob/master/WHITEPAPER.md
[4]https://polygon.technology/lightpaper-polygon.pdf
[5]https://whitepaper.io/document/438/fantom-whitepaper
[6]https://celo.org/papers/whitepaper

V. Evaluation Scenarios

A. Transaction Fee Analysis

Table I showcases the transaction fees of distinct operations, namely Contract Creation, NFT Creation, and NFT Transfer, across four pivotal blockchain platforms: BNB Smart Chain, Fantom, Polygon, and Celo. These platforms, known for their support of the Ethereum Virtual Machine (EVM), differ significantly in their fee structures.

Contract creation, a foundational operation for initiating any decentralized application, bears varying costs across platforms. BNB Smart Chain requires approximately 0.02731136 BNB, equating to $8.37. This competitive fee is attributed to the Binance Smart Chain's infrastructure and its optimization for reduced costs. Conversely, Fantom, known for its efficient contract deployment, charges a lower fee of 0.009576826 FTM or about $0.001860. Polygon, a Layer-2 scaling solution, boasts an even more affordable rate at 0.006840590024626124 MATIC ($0.01), emphasizing its aptitude for micro-transactions. Finally, Celo, focusing on mobile-centric blockchain solutions, demands a modest 0.0070973136 CELO, translating to around $0.004.

The surge in NFT (Non-Fungible Token) popularity necessitates a comprehension of minting costs. On the Binance Smart Chain, a fee of 0.00109162 BNB or $0.33 is levied for this operation. Fantom's fee structure is notably lower for the same, standing at 0.000405167 FTM ($0.000079). Polygon, with its emphasis on affordable transactions, charges a mere 0.00028940500115762 MATIC, a negligible amount in fiat terms. Celo's rate for NFT creation is comparably minimal at 0.0002840812 CELO or roughly $0.000.

Transferring ownership of NFTs, a procedure that consumes computational resources for validation and recording, also incurs diverse costs across these platforms. BNB Smart Chain's fee is 0.00057003 BNB or $0.18. Fantom's cost stands at 0.0002380105 FTM, approximately $0.000046. Polygon continues its trend of affordable operations, charging 0.000170007500612027 MATIC, which is negligible in fiat currency. Similarly, Celo's fee for this process is 0.0001554878 CELO, equating to about $0.000.

In sum, this detailed exploration of Table I underscores the variable costs of primary blockchain operations across different platforms. It's paramount for stakeholders to not just consider these transaction fees, but also weigh other platform-specific factors, such as security, scalability, and community backing, when determining the most suitable blockchain for their endeavors.

B. Gas Limit Analysis

Table II distinctly portrays the gas limits for crucial blockchain operations across four salient platforms: BNB Smart Chain, Fantom, Polygon, and Celo. The gas limit is a quintessential parameter, representing the maximum amount of gas units that a sender is willing to expend on a transaction. It's a protective mechanism to ensure that transactions don't unintentionally consume all the sender's funds due to errors in contract logic or malicious intentions.

Starting with the Contract Creation, a cardinal operation that establishes the foundation for decentralized applications:

TABLE I. TRANSACTION FEE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.02731136 BNB ($8.37)	0.00109162 BNB ($0.33)	0.00057003 BNB ($0.18)
Fantom	0.009576826 FTM ($0.001860)	0.000405167 FTM ($0.000079)	0.0002380105 FTM ($0.000046)
Polygon	0.006840590024626124 MATIC($0.01)	0.00028940500115762 MATIC($0.00)	0.000170007500612027 MATIC($0.00)
Celo	0.0070973136 CELO ($0.004)	0.0002840812 CELO ($0.000)	0.0001554878 CELO ($0.000)

TABLE II. GAS LIMIT

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,136	109,162	72,003
Fantom	2,736,236	115,762	72,803
Polygon	2,736,236	115,762	72,803
Celo	3,548,656	142,040	85,673

TABLE III. GAS USED BY TRANSACTION

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,136 (100%)	109.162 (100%)	57,003 (79.17%)
Fantom	2,736,236 (100%)	115,762 (100%)	68,003 (93.41%)
Polygon	2,736,236 (100%)	115,762 (100%)	68,003 (93.41%)
Celo	2,729,736 (76.92%)	109.262 (76.92%)	59,803 (69.8%)

- BNB Smart Chain has set its gas limit at 2,731,136. This platform's optimization for rapid and cost-efficient transactions is manifested in its relatively streamlined gas limit, ensuring the smooth deployment of smart contracts without unnecessary overheads.
- Fantom and Polygon, both with a gas limit of 2,736,236 for this operation, have nearly identical values. The similarity might stem from their shared objective of optimizing EVM compatibility and transaction efficiency, ensuring developers migrating from Ethereum find a familiar environment.
- Celo, with a more generous gas limit of 3,548,656, emphasizes flexibility. This platform, renowned for its mobile-centric approach, might accommodate more comprehensive contracts with intricate features, necessitating a higher gas allowance.

Moving to the realm of NFTs, a booming sector within the blockchain industry:

- For NFT Creation, BNB Smart Chain allocates a gas limit of 109,162. Given the proliferation of NFTs on this chain, a harmonized gas limit helps stabilize the costs associated with minting.
- Both Fantom and Polygon, with their synchronized limits of 115,762, demonstrate an equilibrium in accommodating the minting processes, potentially reflecting common optimization strategies.
- Celo, in line with its previously observed trend, sets its limit at 142,040, granting developers more leeway for intricate NFT-related operations.

Lastly, for NFT Transfer:

- BNB Smart Chain, maintaining its ethos of streamlined operations, sets a limit of 72,003, balancing efficiency with the necessary computational power.
- Fantom and Polygon, true to their aforementioned synchronization, both allocate 72,803 units. This congruence underscores their shared emphasis on facilitating swift and seamless NFT transfers without incurring undue costs.
- Celo's value stands at 85,673, slightly higher than the others. This platform's propensity for granting a broader gas berth might be to ensure all encompassing NFT functionalities, including meta-transactions and layered transfers, are seamlessly accommodated.

Table II elucidates the diverse gas limits across blockchain platforms. These figures are not just mere numbers; they embody each platform's philosophy, optimization strategies, and focus areas, guiding developers and stakeholders in their blockchain endeavors.

C. Gas Used by Transaction Analysis

Table III provides an intricate breakdown of the gas consumption for pivotal operations across BNB Smart Chain, Fantom, Polygon, and Celo platforms. The values illustrate the proportion of the gas limit consumed by each operation, revealing the actual computational overheads associated with the actions. Notably, an operation's efficiency can be deduced by its gas consumption percentage. Lower percentages indicate optimized contract functions, while higher values may hint at the operation's complexity or inefficiencies.

Starting with the pivotal operation of Contract Creation:

- BNB Smart Chain, Fantom, and Polygon all exhibit a consumption of 100%. This denotes that these platforms optimally utilize the gas limit for the operation, ensuring that the smart contracts are deployed efficiently without wastage or excess.
- Celo stands at 76.92%, suggesting that the platform's contract creation process might be optimized further or that the operations contain redundant computations, consuming lesser than the allocated gas limit.

Delving into the NFT realm:

- For NFT Creation, both BNB Smart Chain and Celo consume 76.92% of the gas. It could indicate shared optimization techniques or similar contract structures.
- Fantom and Polygon, with a consumption rate of 100%, indicate an exhaustive use of the allocated gas, mirroring their performance in contract creation. Their contracts for NFT creation might be exhaustive

or meticulously tailored to use the entirety of the allocated gas.

When it comes to NFT Transfer:

- BNB Smart Chain has a consumption rate of 79.17%. This indicates a reasonably efficient transfer operation, ensuring a smooth transition of assets across addresses.
- Fantom and Polygon, with identical figures of 93.41%, suggest a higher computational need or a more comprehensive process to ensure asset security during transfer.
- Celo consumes 69.8% of the gas. This might denote an optimized transfer mechanism or a more straightforward procedure compared to other platforms, leaving a portion of the allocated gas unutilized.

To encapsulate, Table III unearths the intricacies of gas consumption patterns across platforms, serving as a barometer to gauge operational efficiencies and offering invaluable insights to developers and users alike.

D. Gas Price Analysis

The cost of executing a transaction on a blockchain is determined by the gas price, which is multiplied by the gas used. Gas prices essentially dictate the fee paid to miners or validators for transaction inclusion in a block. Table IV elucidates the set gas prices for different operations on various blockchain platforms.

BNB Smart Chain:

- The gas price remains consistent across all operations, being set at 10 Gwei (or 0.00000001 BNB). Given BNB Smart Chain's commitment to providing scalable and low-cost transactions, a stable gas price ensures predictability for users and developers.

Fantom:

- At 3.5 Gwei (or 0.0000000035 FTM) for all operations, Fantom offers an even lower gas price than BNB Smart Chain. The consistent pricing reflects Fantom's operational efficiency and its design geared towards a high throughput.

Polygon:

- Polygon's gas prices, though varied minutely, hover around 2.5 Gwei. The slight variations, albeit minor, could be due to the inherent floating-point imprecisions or perhaps due to a dynamic gas price setting algorithm, though the former seems more plausible.

Celo:

- The gas prices for Celo operations are set at approximately 2.6 Gwei (0.0000000026 CELO). Interestingly, the maximum fee per gas, capped at 2.7 Gwei, gives users a ceiling for potential fluctuations, ensuring transaction costs remain within predictable bounds.

In summation, gas prices are pivotal in determining the overall cost of a transaction. As platforms strive for mass adoption, ensuring competitive, consistent, and transparent gas prices is essential. It not only fosters trust but also encourages application development and user participation by making operations financially feasible.

VI. Discussion

The exploration and comparison of the gas metrics across various blockchain platforms, specifically BNB Smart Chain, Fantom, Polygon, and Celo, provide a compelling view of the operational efficiencies, cost structures, and user experiences offered by each. These metrics, while technical, carry profound implications for the broader blockchain ecosystem, developers, and end-users alike. Here, we delve deeper into the repercussions and broader perspectives.

A. Operational Efficiencies and Scalability

Gas prices: A consistent gas price, as seen in BNB Smart Chain and Fantom, speaks volumes about a platform's predictability. While lower gas prices are invariably attractive for users and developers, consistency ensures that users can predict costs, allowing for better financial planning and resource allocation. The minute variation in Polygon's gas price could be indicative of a more dynamic approach to network congestion and resource management, although this merits further investigation.

Gas used: The efficiency of a blockchain platform can also be gauged by looking at the gas used for each operation. A higher percentage indicates a more efficient utilization of resources, whereas a significantly lower percentage may suggest that transactions are either too complex or the network overestimates the required gas.

B. Cost Structures

Economic implications: Low and predictable transaction costs, like those of BNB Smart Chain and Fantom, can be major drivers for mass adoption. High transaction costs can deter users, especially for micro-transactions or frequent operations. Economically, for blockchain platforms to find widespread use in daily applications—be it in finance, gaming, or supply chain—keeping transaction costs low is paramount.

Developer attraction: For developers, the economic viability of deploying and running applications on a blockchain platform is essential. Platforms that offer competitive gas prices and consistent cost structures are likely to attract more developers, fostering a richer ecosystem of decentralized applications (DApps).

C. User Experience and Predictability

The end-user experience is invariably tied to costs. Unexpectedly high transaction costs can deter users, leading to a lack of trust in the platform. As seen with Celo's capped maximum fee per gas, providing users with a cost ceiling ensures that they are not caught off guard by potential price spikes, thus enhancing user trust and experience.

TABLE IV. GAS PRICE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)
Fantom	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)
Polygon	0.000000002500000009 MATIC (2.500000009 Gwei)	0.00000000250000001 MATIC (2.50000001 Gwei)	0.000000002500000009 MATIC (2.500000009 Gwei)
Celo	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)

D. Future Directions

Broadening the scope for mainstream acceptance: As we venture into the broader adoption of blockchain technology, an imperative is to ensure transactions remain swift and economically viable. The present data from the four platforms hints at the directionality of this progression. However, while these platforms seem poised for mainstream integration, there is an evident need for extended empirical studies on a variety of use-cases to further this claim.

Innovations and evolutions on platforms: The dynamism of the blockchain sphere cannot be overstated. Our current analysis captures just a fleeting moment in its evolution. Anticipating the future, it's plausible to expect innovations that can redefine cost structures, enhance scalability, and introduce pioneering pricing strategies. The adaptability of these platforms will be tested, necessitating agile and proactive advancements to keep pace.

Harmonizing cross-platform dynamics: The imminent expansion of the blockchain ecosystem suggests an escalation in inter-platform operations. A profound understanding of individual platform cost structures is essential to streamline these multi-chain interactions and ensure economically efficient cross-communication.

Future Explorations and Implementations:

E. A Glimpse into the Upcoming Endeavors: Future Explorations and Implementations

1) Delving into Advanced Algorithms and Data Structures:

- Purpose: To probe deeper into the blockchain dynamics and bring to light the implications of more sophisticated processes on transactional overheads.
- Highlight: A particular emphasis will be placed on encryption mechanisms. Given their significance in ensuring data security and confidentiality, it's imperative to understand their transactional costs in the blockchain realm.

2) Real-world Deployment of Our Proposed Model:

- Objective: To transition from theoretical frameworks to real-world applications, offering tangible solutions that can be assessed and refined.
- Case in point: We're gearing up to integrate a recommendation system on the FTM mainnet. This move seeks to harness the potential of the platform while testing the feasibility and efficiency of our model in a live environment.

3) Addressing Privacy-Related Complexities:

- Context: In today's digital age, user privacy and data protection have soared in importance. However, our current research hasn't delved deeply into this domain.
- Future directions: We'll be diving into:
  - Access control mechanisms [24], [25]: Exploring how permissions are granted or denied within the blockchain, ensuring only authorized entities can access pertinent information.
  - Dynamic policy frameworks [26], [27]: Understanding how policies that govern data access and usage can be dynamically altered, offering flexibility while maintaining security.

4) Infrastructure-Driven Approaches: Amplifying User Interactivity and System Efficiency:

- Objective: To enhance the user experience, making it more interactive, efficient, and user-centric.
- Strategies under consideration include:
  - gRPC [28], [29]: A high-performance, open-source framework that can potentially supercharge remote procedure calls, ensuring seamless communication between services.
  - Microservices architecture [30], [31]: Breaking down an application into small, loosely coupled services, each running its process, enabling swift deployments and scaling.
  - Dynamic message transmissions [32]: Adapting the mode and format of message transmissions based on real-time requirements and constraints.
  - Brokerless systems [33]: Direct communication mechanisms eliminating intermediaries, aiming to reduce latencies and enhance data transmission rates.

At its core, the incorporation of these systems and approaches is about amplifying user interactions, making the systems more intuitive, responsive, and efficient, potentially through strategies such as API-driven calls.

In sum, the implications of our current gas metrics study pave the way for a host of future explorations. As we advance, the amalgamation of these findings will be instrumental in tailoring platform strategies, aligning developer priorities, and refining user experiences.

VII. CONCLUSION

By harnessing the transformative capabilities of blockchain technology, smart contracts, and Non-Fungible Tokens (NFTs), our work offers an innovative reimagination of the blood donation paradigm. Our contributions, including the integration of blockchain in the blood supply chain, the introduction of NFT-driven electronic certification for donors, and the realization of these concepts through proof-of-concept smart contracts, underscore the promise our solutions hold.

Additionally, our commitment to platform optimization, particularly through rigorous deployment trials across Ethereum Virtual Machine (EVM) supportive platforms, emphasizes the tangible and practical significance of our research. Our decision to sidestep Ethereum due to its high cost implications epitomizes our dedication to ensuring that our innovations are not just technologically advanced, but economically viable and accessible.

In sum, our research transcends mere technological advancements. By intertwining technology with a cause as noble as blood donation, we aspire to drive change, save lives, and amplify the significance of every donor's invaluable contribution. As we look forward, we remain optimistic about the transformative impact of our work, not just on the medical landscape but on society at large.

Acknowledgment

We express our profound gratitude to Engineer Le Thanh Tuan and Dr. Ha Xuan Son for their invaluable guidance and insights throughout the brainstorming, implementation, and evaluation stages of this work. Further appreciation goes to FPT University Cantho Campus, Vietnam, for their unwavering support and contributions to this research endeavor.

References

[1] X. S. Ha, T. H. Le, T. T. Phan, H. H. D. Nguyen, H. K. Vo, and N. Duong-Trung, "Scrutinizing trust and transparency in cash on delivery systems," in *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*. Springer, 2020, pp. 214–227.

[2] X. S. Ha, H. T. Le, N. Metoui, and N. Duong-Trung, "Dem-cod: Novel access-control-based cash on delivery mechanism for decentralized marketplace," in *2020 IEEE 19th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*. IEEE, 2020, pp. 71–78.

[3] H. T. Le, N. T. T. Le, N. N. Phien, and N. Duong-Trung, "Introducing multi shippers mechanism for decentralized cash on delivery system," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 6, 2019.

[4] H. X. Son and E. Chen, "Towards a fine-grained access control mechanism for privacy protection and policy conflict resolution," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 2, 2019.

[5] N. Duong-Trung, X. S. Ha, T. T. Phan, P. N. Trieu, Q. N. Nguyen, D. Pham, T. T. Huynh, and H. T. Le, "Multi-sessions mechanism for decentralized cash on delivery system," *Int. J. Adv. Comput. Sci. Appl*, vol. 10, no. 9, 2019.

[6] N. T. T. Le, Q. N. Nguyen, N. N. Phien, N. Duong-Trung, T. T. Huynh, T. P. Nguyen, and H. X. Son, "Assuring non-fraudulent transactions in cash on delivery by introducing double smart contracts," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 5, pp. 677–684, 2019.

[7] H. H. Luong, T. K. N. Huynh, A. T. Dao, and H. T. Nguyen, "An approach for project management system based on blockchain," in *International Conference on Future Data and Security Engineering*. Springer, 2021, pp. 310–326.

[8] K. L. Quoc, H. K. Vo, L. H. Huong, K. H. Gia, K. T. Dang, H. L. Van, N. H. Huu, T. N. Huyen, L. Van Cao Phu, D. N. T. Quoc *et al.*, "Sssb: An approach to insurance for cross-border exchange by using smart contracts," in *International Conference on Mobile Web and Intelligent Information Systems*. Springer, 2022, pp. 179–192.

[9] H. T. Le *et al.*, "Medical-waste chain: a medical waste collection, classification and treatment management by blockchain technology," *Computers*, vol. 11, no. 7, p. 113, 2022.

[10] M. Çağlıyangil, S. Erdem, and G. Özdağoğlu, "A blockchain based framework for blood distribution," in *Digital Business Strategies in Blockchain Ecosystems*. Springer, 2020, pp. 63–82.

[11] N. Duong-Trung, H. X. Son, H. T. Le, and T. T. Phan, "Smart care: Integrating blockchain technology into the design of patient-centered healthcare systems," in *Proceedings of the 2020 4th International Conference on Cryptography, Security and Privacy*, ser. ICCSP 2020, 2020, p. 105–109.

[12] E. J. Baek, H. O. Kim, S. Kim, Q.-E. Park, and D.-J. Oh, "The trends for nationwide blood collection and the supply of blood in korea during 2002 2006," *The Korean Journal of Blood Transfusion*, vol. 19, no. 2, pp. 83–90, 2008.

[13] N. T. T. Quynh *et al.*, "Toward a design of blood donation management by blockchain technologies," in *Computational Science and Its Applications–ICCSA 2021: 21st International Conference, Cagliari, Italy, September 13–16, 2021, Proceedings, Part VIII 21*. Springer, 2021, pp. 78–90.

[14] H. T. Le *et al.*, "Bloodchain: a blood donation network managed by blockchain technologies," *Network*, vol. 2, no. 1, pp. 21–35, 2022.

[15] S. Kim and D. Kim, "Design of an innovative blood cold chain management system using blockchain technologies," *ICIC Express Letters, Part B: Applications*, vol. 9, no. 10, pp. 1067–1073, 2018.

[16] S. Lakshminarayanan, P. Kumar, and N. Dhanya, "Implementation of blockchain-based blood donation framework," in *International Conference on Computational Intelligence in Data Science*. Springer, 2020, pp. 276–290.

[17] K. Toyoda, P. T. Mathiopoulos, I. Sasase, and T. Ohtsuki, "A novel blockchain-based product ownership management system (poms) for anti-counterfeits in the post supply chain," *IEEE access*, vol. 5, pp. 17 465–17 477, 2017.

[18] T. Peltoniemi and J. Ihalainen, "Evaluating blockchain for the governance of the plasma derivatives supply chain: How distributed ledger technology can mitigate plasma supply chain risks," *Blockchain in Healthcare Today*, 2019.

[19] H. X. Son, T. H. Le, N. T. T. Quynh, H. N. D. Huy, N. Duong-Trung, and H. H. Luong, "Toward a blockchain-based technology in dealing with emergencies in patient-centered healthcare systems," in *Mobile, Secure, and Programmable Networking: 6th International Conference, MSPN 2020, Paris, France, October 28–29, 2020, Revised Selected Papers 6*. Springer, 2021, pp. 44–56.

[20] H. T. Le *et al.*, "Patient-chain: patient-centered healthcare system a blockchain-based technology in dealing with emergencies," in *International Conference on Parallel and Distributed Computing: Applications and Technologies*. Springer, 2021, pp. 576–583.

[21] N. Duong-Trung *et al.*, "Smart care: integrating blockchain technology into the design of patient-centered healthcare systems," in *Proceedings of the 2020 4th International Conference on Cryptography, Security and Privacy*, 2020, pp. 105–109.

[22] ——, "On components of a patient-centered healthcare system using smart contract," in *Proceedings of the 2020 4th International Conference on Cryptography, Security and Privacy*, 2020, pp. 31–35.

[23] H. Le Van, H. K. Vo, L. H. Huong, P. N. Trong, K. T. Dang, K. H. Gia, L. V. C. Phu, D. N. T. Quoc, N. H. Tran, H. T. Nghia10 *et al.*, "Blood management system based on blockchain approach: A research solution in vietnam," *IJACSA*, vol. 13, no. 8, 2022.

[24] H. X. Son, M. H. Nguyen, H. K. Vo *et al.*, "Toward an privacy protection based on access control model in hybrid cloud for healthcare systems," in *International Joint Conference: 12th International Conference on Computational Intelligence in Security for Information Systems (CISIS 2019) and 10th International Conference on EUropean Transnational Education (ICEUTE 2019)*. Springer, 2019, pp. 77–86.

[25] H. X. Son and N. M. Hoang, "A novel attribute-based access control system for fine-grained privacy protection," in *Proceedings of the 3rd International Conference on Cryptography, Security and Privacy*, 2019, pp. 76–80.

[26] S. H. Xuan, L. K. Tran, T. K. Dang, and Y. N. Pham, "Rew-xac: an approach to rewriting request for elastic abac enforcement with dynamic policies," in *2016 International Conference on Advanced Computing and Applications (ACOMP)*. IEEE, 2016, pp. 25–31.

[27] H. X. Son, T. K. Dang, and F. Massacci, "Rew-smt: a new approach for rewriting xacml request with dynamic big data security policies," in *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*. Springer, 2017, pp. 501–515.

[28] L. T. T. Nguyen *et al.*, "Bmdd: a novel approach for iot platform (broker-less and microservice architecture, decentralized identity, and dynamic transmission messages)," *PeerJ Computer Science*, vol. 8, p. e950, 2022.

[29] L. N. T. Thanh *et al.*, "Toward a security iot platform with high rate transmission and low energy consumption," in *International Conference on Computational Science and its Applications*. Springer, 2021.

[30] ——, "Toward a unique iot network via single sign-on protocol and message queue," in *International Conference on Computer Information Systems and Industrial Management*. Springer, 2021.

[31] L. N. T. Thanh, N. N. Phien, T. A. Nguyen, H. K. Vo, H. H. Luong, T. D. Anh, K. N. H. Tuan, and H. X. Son, "Ioht-mba: An internet of healthcare things (ioht) platform based on microservice and brokerless architecture," *International Journal of Advanced Computer Science and Applications*, vol. 12, no. 7, 2021. [Online]. Available: http://dx.doi.org/10.14569/IJACSA.2021.0120768

[32] L. N. T. Thanh *et al.*, "Uip2sop: A unique iot network applying single sign-on and message queue protocol," *IJACSA*, vol. 12, no. 6, 2021.

[33] L. N. T. Thanh, N. N. Phien, H. K. Vo, H. H. Luong, T. D. Anh, K. N. H. Tuan, H. X. Son *et al.*, "Sip-mba: A secure iot platform with brokerless and micro-service architecture," 2021.