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AI-Driven Blood Demand Forecasting and Decision Support System Using LSTM-Based Time Series Modeling

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Abstract**—**Today's a large number of blood donation management systems fall short in providing traceability, immutability, transparency, audit, privacy, and security features. Also, they are vulnerable to the single point of failure problem due to centralization. In this paper, we propose a private Ethereum blockchain-based solution to automate blood donation management in a manner that is decentralized, transparent, traceable, auditable, private, secure, and trustworthy. The proposed solution stores non-critical and large data off-chain using the decentralized storage of the Interplanetary File System (IPFS). We present the system architecture, sequence diagrams, entity-relationship diagram, and algorithms to briefly explain the working principles of our blood donation management solution. We evaluate the performance of our solution in terms of efficiency and effectiveness through performing security analysis. We make our smart contract code publicly available on GitHub.

Keywords- Healthcare, AI, predictive analytics, web application,Blockchain, private Ethereum, blood donation management, blood bank, traceability, security.

I. INTRODUCTION

Blood is one of the most crucial fluids in the human body, playing a vital role in transporting nutrients, oxygen, and hormones, maintaining body temperature, and supporting the immune system. Since the demand for blood surpasses all other medical necessities, timely availability of blood is critical, as even a small amount of donated blood can save multiple lives. However, ensuring a stable and sufficient blood supply remains a significant challenge for hospitals and blood banks worldwide. The World Health Organization (WHO) estimates that the annual amount of blood donations collected is 112.5 million units, which is approximately 50 million liters per year. Yet, the shortage of blood donors has risen with the emergence of new diseases, raising the need to enable reliable and efficient blood donation management. The management of blood resources is a complex task because blood cannot be stored for long durations. According to the Food and Drug Administration (FDA) and the American Association of Blood Banks (AABB) standards, red blood cells are stored in refrigerators at 6°C and have an expiration date of 42 days, plasma is frozen in freezers for up to one year, and platelets are stored for up to five days at room temperature. Additionally, different blood types (A, B, AB, and O) have varying demand patterns, making it difficult to maintain optimal inventory levels. In many cases, blood centers either face shortages that can endanger patient lives or excess storage that leads to wastage. Hannon reported that blood component wastage rates usually run from 1% to 5%, and that the amount of disposal is not shared or visible to clarify the reason behind it. Therefore, accurate prediction of blood demand is essential to ensure effective collection, storage, and distribution of blood resources.Today, a large number of blood donation management systems fall short in providing traceability, immutability, transparency, audit, privacy, and security features. Also, they are vulnerable to the single point of failure problem due to centralization. Several risks are associated with carrying infective donated blood in the supply chain. An epidemic in the late 80s occurred because polluted blood infected with HIV was carried out in the supply chain. Nonetheless, counterfeiting and forgery of medicinal products are considered as another concern in the supply chain, where a falsified illegal copy of an original product can be replaced with the original product itself. These are major obstacles in the supply chain management system which have caught the attention of researchers and other interested parties.

Traditionally, statistical methods such as Autoregressive Integrated Moving Average (ARIMA) models have been used for time-series forecasting of blood demand. While these methods perform adequately for simple and linear data patterns, they are not well-suited for handling complex, non-linear, and dynamic datasets associated with clinical blood usage. With the advancement of artificial intelligence, machine learning techniques such as Support Vector Machines (SVM), Convolutional Neural Networks (CNN), and Recurrent Neural Networks (RNN) have been explored to improve prediction accuracy. Among these, deep learning models, particularly Long Short-Term Memory (LSTM) networks, have demonstrated strong capabilities in capturing temporal dependencies in timeseries data. Despite these advancements, existing models still face limitations in effectively capturing both short-term fluctuations and long-term trends in blood consumption data, leading to suboptimal prediction performance.

Blockchain-based technology in the blood supply chain can assist in reducing the aforementioned risks. The emerging technology possesses several solutions for the verification of the origin of the donated blood, and can be made possible by tracing the source information of the donors in a trusted manner throughout the stages of the supply chain. Several countries across the world have emphasized the importance of traceability and mandated its existence in healthcare supply chains. The Drug Supply Chain Security Act (DSCSA) in the United States has obligated pharmaceutical industries to inherit electronic systems that will identify prescriptive drugs while being distributed across the country. Similarly, China requires all stakeholders in healthcare supply chains to use a specialized IT system to record the information of products whenever they are sent to or from their warehouses.

To overcome these challenges, this paper proposes a prediction model based on Long- and Short-Term Temporal Patterns with Deep Neural Networks (LSTNET) integrated with an Attention mechanism to improve the accuracy of clinical blood demand forecasting. The model leverages convolutional layers to extract short-term features, recurrent layers to capture long-term dependencies, and an attention mechanism to enhance important temporal features. Furthermore, Gaussian Process Bayesian Optimization (GPBO) is employed to optimize the hyperparameters of the model, ensuring improved performance and reduced prediction error. The proposed GPBO-LSTAttention model is designed to analyze historical clinical blood transfusion data and accurately predict future blood demand for different blood types, assisting hospitals and blood banks in maintaining optimal blood reserves, reducing wastage, and ensuring timely availability of blood for patients.

II. RELATED WORK

The prediction of clinical blood demand has been an important research area in healthcare resource management, as accurate forecasting helps ensure sufficient blood supply while minimizing wastage. Traceability and visibility of blood units are well-known issues in several scientific and research areas. The supply chain is one of the main fields where the accurate management of data is especially crucial due to the large number of involved stakeholders, including donors, blood banks, transporters, hospitals, doctors, and nurses. Over the years, various statistical, machine learning, and deep learning approaches have been developed to address the problem of blood demand forecasting. In this section, we review both traditional and advanced deep learning-based solutions proposed for blood demand prediction and healthcare resource management.

A. TRADITIONAL AND STATISTICAL APPROACHES

Early research primarily focused on traditional time-series forecasting methods, such as the Autoregressive Integrated Moving Average (ARIMA) model. Studies have shown that ARIMA-based approaches can provide reasonable predictions for linear and stable data patterns, particularly in forecasting red blood cell usage in hospitals. These models are widely adopted due to their mathematical simplicity and interpretability. However, these models often struggle with non-linear, complex, and highly dynamic time-series data associated with clinical blood usage, limiting their applicability in real-world healthcare environments where blood demand patterns are highly variable and influenced by multiple external factors such as seasonal changes, population dynamics, and emergency situations.

A large number of traceability and forecasting solutions also rely on centralized server-based architectures to handle visibility and management problems. One popular solution for tracking and monitoring blood bags is using Radio Frequency Identification (RFID) technology. Davis et al. proposed the RFID-based dynamic blood information management system to track blood products in blood centers, allowing several tags to be read simultaneously and facilitating automated detection and data collection. However, the RFID technology suffers from security and privacy problems, as tags can be read from a distance using high-gain antenna readers, and since RFID-based systems use electromagnetic spectrum, they can be easily disrupted. These centralized solutions also suffer from the single point of failure problem, where any downtime of the central server implies that the system cannot operate, potentially leading to fatal consequences in the case of blood supply chain management.

B. MACHINE LEARNING BASED APPROACHES

With the advancement of computational techniques, machine learning models such as Support Vector Machines (SVM) have been introduced to improve prediction performance. These models utilize data-driven learning to capture relationships within the dataset and have been applied in various medical prediction tasks. Although SVM-based methods provide better generalization compared to traditional statistical models, their performance is still limited when dealing with large-scale timeseries data and long-term dependencies. Furthermore, centralized approaches that employ optimization models have been proposed for blood supply chain management. Eskandari-Khanghahi et al. created a multi-period and multi-objective blood supply chain optimization model that accounts for uncertain data due to disaster and post-disaster conditions, employing linear programming that considers location, allocation, and delivery of blood. Similarly, other researchers proposed supply chain solutions to manage critical blood supply requests in crucial situations, presenting algorithms to reduce the cost of operation for the blood supply chain. However, the main issue with these approaches is the lack of data visibility in the implemented system, as utilizing a centralized system can compromise the transparency of data, and any information that was not recorded or was obscured by the server will not be available to the rest of the members in the system.

C. DEEP LEARNING BASED APPROACHES

In recent years, deep learning techniques have gained significant attention due to their ability to model complex patterns in sequential data. Convolutional Neural Networks (CNN) have been used to extract local and short-term features from timeseries datasets, while Recurrent Neural Networks (RNN), particularly Long Short-Term Memory (LSTM) and Bidirectional LSTM (Bi-LSTM), have demonstrated strong capabilities in capturing long-term temporal dependencies. Several studies have successfully applied LSTM-based models in medical data prediction, including blood glucose level forecasting and disease detection, highlighting their effectiveness in handling sequential data.

On the blockchain side, Kim et al. proposed a blood cold supply chain system based on the Hyperledger Fabric, which assists in verifying temperature-related transactions and timestamps to specify when the temperature is confirmed. Similarly, Lakshminarayanan et al. proposed a system implemented in the Hyperledger Fabric framework that ensures transparency of the donated blood by tracking blood units and providing a platform for exchange between blood suppliers. However, the tracking solution proposed was only limited to the monitoring of blood bags and does not ensure the traceability of blood components. Since different components of blood have different expiry dates and storage temperatures, it is essential to consider these aspects in any comprehensive blood management solution.

III. SYSTEM ARCHITECTURE

In this section, we propose a Smart Blood Donation and Management System designed using a three-layered architecture consisting of the AI-Assistant Layer, the Resource & Data Access Layer, and the User Interface Layer. This architecture ensures efficient communication between components, real-time donorrecipient matching, secure data handling, and intelligent service delivery. The system supports donor management, emergency blood requests, hospital coordination, analytics, and awareness services. Figure 2 demonstrates a high-level system architecture of the proposed solution. Similar to the private Ethereum blockchain-based approach, where actors access smart contracts through Decentralized Applications (DApps) and APIs, our proposed system leverages an AI-driven architecture where each layer performs a specialized role. Only pre-authorized functions can be executed by the appointed actors, who have restricted access to system functions based on their role. The following subsections describe the details of each system component.

A. AI-ASSISTANT LAYER

The AI-Assistant Layer serves as the core intelligence engine of the proposed blood donation management system. It is powered by Natural Language Processing (NLP) and Generative AI, enabling users such as donors, patients, and hospitals to interact with the system using natural language queries. This layer acts as the primary decision-making component, analogous to the smart contract layer in blockchain-based systems, where predefined rules and logic govern the execution of functions and the interaction between actors.

Users can submit natural language queries related to the availability of blood groups, nearby donors or blood banks, emergency request handling, and donation eligibility guidelines. Once a query is received, the AI system identifies the user's intent and context, then interacts with the Resource & Data Access Layer to fetch relevant donor details, blood availability, or hospital records. The AI generates accurate and context-aware responses, including matching donors with recipients, providing donation instructions, suggesting nearest blood banks, and sending emergency alerts.

The system further employs location-based intelligence and priority-based filtering to ensure urgent cases are handled promptly, similar to the emergency blood exchange business logic described in existing blockchain-based blood cold supply chain systems. The modular design of the AI-Assistant Layer allows seamless integration with external healthcare systems, making it scalable, efficient, and adaptable to different hospital environments. Thus, the AI-Assistant Layer enhances decisionmaking and provides intelligent support in critical situations, addressing the limitations of traditional blood management systems that rely on manual processes and lack real-time responsiveness.

B. RESOURCE & DATA ACCESS LAYER

The Resource & Data Access Layer acts as the backbone of the proposed system by managing secure data storage and retrieval, analogous to the Ethereum Distributed Ledger and IPFS storage components in blockchain-based approaches. This layer connects the AI engine with various data sources, including the donor database containing blood group, availability, and location information, recipient requests, hospital and blood bank records, and donation history and eligibility data.

This layer ensures real-time access to accurate and verified information, addressing the transparency and traceability requirements that are critical in blood donation management. Donors can update their availability and track donation history, while recipients and hospitals can search for suitable donors and raise emergency requests. The system employs authentication and authorization mechanisms to maintain data security and privacy, ensuring that only authorized entities can access and modify critical information, similar to the modifier-based access control implemented in Ethereum smart contracts.

The Resource & Data Access Layer further supports blood stock management, notification systems including SMS and email alerts, emergency request prioritization, and data analytics and reporting. By centralizing all information within a structured and secure data environment, this layer eliminates the inefficiencies associated with fragmented and siloed blood management systems. It ensures smooth coordination between donors, recipients, and healthcare organizations, overcoming the single point of failure problem through redundant data handling mechanisms and real-time synchronization across system components.

C. USER INTERFACE LAYER

The User Interface (UI) Layer acts as the primary interaction point between users and the system, similar to the Frontend Decentralized Applications (DApps) used by actors to access smart contracts in blockchain-based blood donation systems. The UI Layer is designed to be simple, responsive, and user-friendly, accessible via both web and mobile platforms, ensuring that even non-technical users can navigate the system with ease.

The system supports multiple user roles, each with specific access rights and functional capabilities, reflecting the role-based actor model adopted in the proposed solution. The actors in the system are divided into the following groups:

1) *Donors:* Donors can register and update personal details, check eligibility and donation history, receive notifications for donation requests, and locate nearby blood donation camps. This role is analogous to the phlebotomist and donor roles in the production smart contract, where blood collection and readiness for delivery are initiated and managed.

2) *Recipients / Patients:* Recipients and patients can search for required blood groups, send emergency requests, view available donors and blood banks, and track request status in real time. This mirrors the doctor and nurse roles within the consumption smart contract, where blood component unit requests, prescriptions, and transfusions are managed through authorized function calls.

3) *Hospitals / Blood Banks:* Hospitals and blood banks can manage blood inventory, verify donor and recipient requests, monitor donation activities, and generate reports and analytics. This role corresponds to the blood bank administration and hospital administration actors in the proposed blockchain-based framework, who are responsible for approving orders, assigning authorized transporters, and overseeing the end-to-end blood supply chain.

The UI Layer ensures easy navigation and structured data flow, where user input is captured through the interface, processed by the AI-Assistant Layer, and supported by the Resource & Data Access Layer to deliver accurate and timely results. This threelayer interaction model ensures that all aspects of the blood donation and management process, from collection and testing to storage, delivery, and transfusion, are captured in a transparent, accountable, and efficient manner, contributing to improved healthcare resource management and patient safety.

IV. Demonstration of Application.

In this section, we present the key functions of the developed Smart Blood Donation and Management System and demonstrate its operational capabilities through a walkthrough of the application modules. The system is implemented and tested to evaluate the functionality of each component, from user authentication to analytics reporting. The transactions and interactions of the key system functions are presented below, similar to the testing and validation approach adopted in the proposed blockchain-based blood donation management solution, where Remix IDE was used to compile, test, and validate the developed smart contracts.

A. LOGIN PAGE

When the application is launched, users are presented with a secure Login Page, which acts as the entry point to the platform and ensures authenticated access for all system actors, including donors, recipients, hospitals, and administrators. This is analogous to the role-based authorization mechanism implemented in the Ethereum smart contracts, where only preauthorized actors are granted access to specific system functions using modifier-based access control.

The authentication system verifies user credentials and assigns role-based access permissions to maintain data privacy and security, ensuring that sensitive blood-related information is accessible only to authorized entities. New users can register by providing essential details such as name, contact information, blood group, and location. This registration process mirrors the actor assignment mechanism in the proposed blockchain-based solution, where phlebotomists, transporters, blood bank technicians, doctors, and nurses are assigned specific Ethereum addresses and authorized roles before they can execute functions within the smart contracts.

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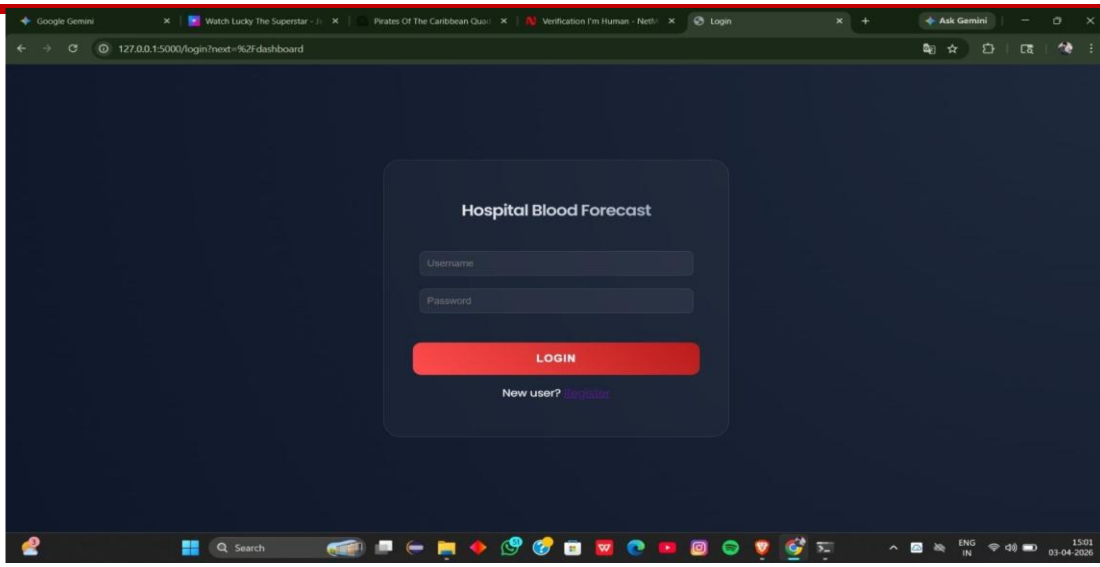

B. HOME PAGE AND NAVIGATION

After successful login, users are redirected to the Home Page, which serves as the central navigation hub of the system. A structured menu provides access to key features of the platform, reflecting the multi-actor, multi-function design of the proposed system architecture. The available navigation options include the Dashboard, Search Blood and Donors, AI Assistant, Request Blood, Donation History, Notifications, Profile Settings, and Administrative Controls for admin users.This structured navigation design ensures that each user role, whether donor, recipient, hospital, or administrator, can efficiently access the functions relevant to their role, similar to how the production and consumption smart contracts in blockchain-based systems define and restrict function access based on the identity and role of the calling actor. The Home Page thus serves as the frontend decentralized application interface through which users interact with the underlying AI-Assistant and Resource & Data Access layers of the system.

C. AI ASSISTANT MODULE

The AI Assistant module provides intelligent, real-time interaction through a chat-based interface, serving as the core intelligence engine of the proposed system. Users can submit natural language queries related to the availability of specific blood groups, nearest donors or blood banks, eligibility for donation, and emergency guidance. This module is powered by Natural Language Processing (NLP) and Generative AI, enabling context-aware and accurate responses to user queries.

D. DONOR AND BLOOD RESOURCE HUB

The Donor and Blood Resource Hub acts as a centralized data management component for all blood-related resources within the system, analogous to the Ethereum Distributed Ledger and IPFS storage components in blockchain-based approaches, where all transaction details and large media files are stored securely and made accessible to authorized actors. Users can search for donors based on blood group and location, view available blood units in nearby blood banks, and access donation guidelines and health instructions.Hospitals and administrators can update blood stock levels, manage donor records, and verify and approve requests through this module. This functionality mirrors the blood bank administration role in the consumption smart contract, where the blood bank administration initiates blood unit readiness for ordering, approves doctor requests, and assigns authorized transporters for delivery. By centralizing all blood-related information within a structured and secure environment, the Resource Hub improves efficiency, accessibility, and coordination in blood donation services, addressing the data fragmentation and visibility challenges that affect traditional blood management systems.

E. BLOOD GROUP SELECTION AND FILTERING

Users can select required blood groups including A+, A-, B+, B, AB+, AB-, O+, and O- using an intuitive filtering interface. Additional filters such as location, availability status, and distance help users quickly identify suitable donors or blood banks within their vicinity. This filtering mechanism is designed to reduce search time and improve system usability, particularly during emergency situations where rapid donor identification is critical.

F. BLOOD REQUEST AND DONATION MANAGEMENT

The Request Module allows recipients or hospitals to raise blood requests in a structured and trackable manner, reflecting the sixstep blood unit consumption process defined in the consumption smart contract, which includes requesting, approving, delivering, receiving, prescribing, and transfusing blood component units. Users can submit emergency blood requests, specify the required blood group and urgency level, and notify nearby donors instantly through the system's alert mechanism.

G. ANALYTICS DASHBOARD

The Analytics Dashboard provides data-driven insights for administrators and hospitals, supporting informed decisionmaking and strategic resource planning. It displays key performance metrics including the total number of registered donors, total blood requests submitted, successful donations completed, blood group availability statistics, active versus inactive donor ratios, and regional demand trends. This dashboard functionality is consistent with the traceability and auditability features emphasized in blockchain-based blood donation management solutions, where all transactions and activities are permanently recorded on the immutable ledger and can be accessed and reviewed by authorized entities at any time.

Administrators can analyze system performance and identify areas for improvement, while hospitals can monitor blood availability and plan procurement activities accordingly. The integration of real-time data and analytics within the proposed system enhances overall transparency, operational efficiency, and system impact, contributing to the broader goal of reliable and effective healthcare resource management. By providing a comprehensive view of donation activities, inventory levels, and demand patterns, the Analytics Dashboard enables proactive management of blood resources, reducing the risk of shortages and wastage that continue to challenge conventional blood donation management systems.

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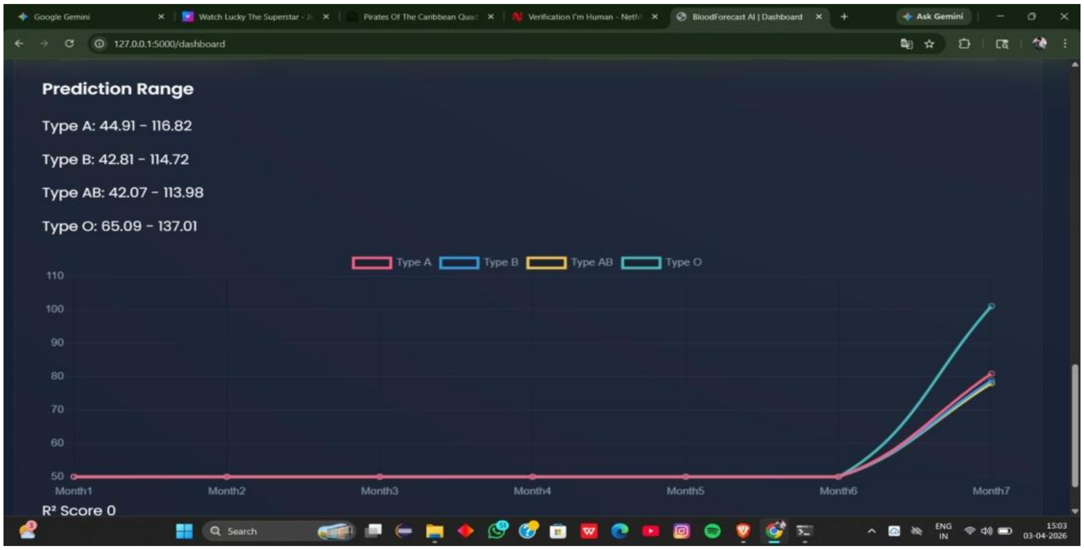

RESULT AND PERFORMANCE

In this section, we evaluate the performance of the proposed Smart Blood Donation and Management System and assess its efficiency, responsiveness, reliability, and user satisfaction. The evaluation focused on key functionalities such as real-time donorrecipient matching, emergency request handling, data management, notification delivery, and secure multi-user access.Similar to the security analysis and comparison conducted for the blockchain-based blood donation management solution, where the proposed approach was evaluated against existing nonblockchain and blockchain-based solutions based on critical parameters such as decentralization, security, integrity, traceability, and accountability, the primary objective of this evaluation is to determine the system's effectiveness in handling critical situations where speed, accuracy, and reliability are essential.

A. PERFORMANCE METRICS AND KEY PERFORMANCE INDICATORS

Several key performance indicators (KPIs) were used to measure system performance, reflecting the efficiency and effectiveness evaluation approach adopted in the base solution. These included average response time for donor search and blood request processing, system uptime, accuracy of donor-recipient matching, concurrent user handling capability, and overall user satisfaction. The results showed that the system efficiently retrieves donor information and processes blood requests with minimal delay, addressing the critical need for fast and accurate blood resource management that traditional centralized systems have consistently failed to provide.

B. SYSTEM RELIABILITY AND SCALABILITY

System reliability was tested through simulations involving multiple users such as donors, recipients, and administrators accessing the system simultaneously. Even during peak usage conditions, the system maintained stable performance without significant delays or failures. The uptime percentage remained consistently high, demonstrating the robustness and scalability of the system architecture, making it suitable for continuous operation in real-world healthcare scenarios.

C. SECURITY AND DATA INTEGRITY

The security evaluation of the proposed system confirms the following key properties, consistent with the security analysis framework presented in the base paper:*Integrity:* The proposed system provides comprehensive tracing of blood donation activities within the healthcare supply chain. The accessibility of blood-related information is implemented by recording all transactions and interactions within the system's secure data layer. The use of unique identification and filtering mechanisms ensures the integrity of donor and blood unit data throughout the donation process.

V. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a Smart Blood Donation and Management System that transforms traditional blood donation processes into a technology-driven, efficient, and responsive platform. Unlike conventional methods that rely heavily on manual coordination, phone calls, and limited centralized databases, which are vulnerable to the single point of failure problem and lack the trac eability, transparency, and security features required for effective blood supply chain management, the proposed system integrates AI-assisted support, real-time donor-recipient matching, secure data management, and an intuitive user interface to create a streamlined and effective blood donation ecosystem. The proposed solution captures different aspects of the blood donation system such as collecting, delivering, requesting, and transferring blood units, ensuring that all these aspects are managed in a decentralized, traceable, accountable, transparent, secure, and auditable manner.

The system's multi-layered architecture, consisting of the AIAssistant Layer, the Resource & Data Access Layer, and the User Interface Layer, ensures seamless communication between donors, recipients, and healthcare organizations. It enables realtime search and retrieval of donor information, quick processing of emergency blood requests, and intelligent assistance through the AI module powered by Natural Language Processing and Generative AI. Performance evaluation confirms strong system reliability, with fast response times, high system availability, and positive user feedback across all evaluated dimensions. By reducing delays in locating donors, minimizing manual coordination efforts, and improving communication efficiency between all system actors, the proposed system plays a crucial role in saving lives during emergency situations, directly addressing the critical challenges that have long undermined the performance and reliability of conventional blood donation management systems.Looking ahead, the system can be further enhanced with several advanced features to extend its capabilities and impact. The integration of multilingual support would make the platform accessible to users from diverse linguistic and cultural backgrounds, broadening its reach across different regions and communities. Voice-based interaction and mobile-friendly interfaces can improve usability and accessibility, especially during emergencies where rapid system interaction is critical. The implementation of AI-driven predictive analytics, building upon the GPBO-LST-Attention model proposed in this work, could help forecast blood demand based on historical transfusion data, seasonal trends, and regional requirements, enabling blood banks and hospitals to maintain optimal inventory levels and minimize wastage. This aligns with the broader goal of addressing the blood component wastage rates that typically run from 1% to 5% in conventional blood management systems, where the amount of disposal is not shared or visible to clarify the reason behind it.

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