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A Blockchain based System for Safe Vaccine Supply and Supervision

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Keywords

safe, vaccine, system, supply, blockchain, supervision

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An Intelligent Blockchain-based System for Safe Vaccine Supply and Supervision

Abstract

Immunization is an indispensable mechanism for preventing infectious diseases in modern society, and vaccine safety is closely related to public health and national security. However, issues such as vaccine expiration and vaccine record fraud are still widespread in vaccine supply chains. Therefore, an effective management system for the supervision of vaccine supply chains is urgently required. As the next generation of core technology after the Internet, blockchain is designed to build trust mechanisms that can change current information management methods. Meanwhile, the development of machine learning technologies provides additional ways to analyze the data in information management systems. The main objective of this study is to develop a "vaccine blockchain" system based on blockchain and machine learning technologies. This vaccine blockchain system is designed to support vaccine traceability and smart contract functions, and can be used to address the problems of vaccine expiration and vaccine record fraud. Additionally, the use of machine learning models can provide valuable recommendations to immunization practitioners and recipients, allowing them to choose better immunization methods and vaccines.

Keywords: vaccine safety, vaccine blockchain, vaccine traceability, smart contract, machine learning

1. Introduction

Infectious diseases have been a curse on humanity since time immemorial. Indeed, human beings have been searching for ways to fight various types of infectious diseases for more than two thousand years. Immunization is a cost-effective way of curbing, or even eradicating, infectious diseases, and many diseases have been effectively controlled through vaccine immunization. However, in 2018, a great scandal surrounding Changchun Changsheng Biotechnology was reported in China and caused uproar among the population. As the second largest producer of the rabies vaccine in China, Changsheng Biotechnology was found to have forged reports and violated regulations when producing 250,000 doses of rabies vaccines for humans. According to the investigation report issued by the State Drug Administration (SDA), Changsheng Biotechnology's production and supply chain management of the freeze-dried rabies vaccine were found to be in serious violation of the Good Manufacturing Practice (GMP) standard. More seriously, the company was found to have falsified vaccine records. These actions led to indignation among the Chinese populace, and there has since been an urgent call to develop a credible anti-counterfeiting and traceability system that ensures vaccine quality and safety in vaccine supply chains.

Traditionally, vaccines have been monitored by government supervision departments, such as a lot release agency (Robert et al., 2015). In this case, regulators require random sampling tests to ensure vaccine safety. However, as it is possible to tamper with vaccine information, this method is not very effective in addressing the vaccine expiration problem. In order to reduce the risk of vaccine expiration, Dhandapani et al. (2019) propose the development of an economic order quantity (EOQ) model based on mathematical theorems to find an optimal vaccine replenishment time. However, this model has no effect on the vaccine expiration problem when caused intentionally, something that can result in great harm to society.

Li et al. (2017a) introduced an evolved form of immunization information systems in a Chinese prefecture. They showcased the applications of information technologies for managing immunization records, vaccine supply chains, and so on. However, this study did not refer to any specific system design. In fact, with the development of the Internet of Things (IoT) and information technologies, intelligent information management systems have been researched in the context of quality control in production, mainly based on blockchain (Nakamoto, 2008) and machine learning technologies.

As a distributed and decentralized technology, blockchain has been widely researched as a solution to the underlying trust and security issues in information management systems (Hughes et al., 2019). For example, Beck et al. (2017) explored the possible use of blockchain in business and information systems. In fact, the raw material records, production records, and circulation records of vaccine supply chains can be stored and traced in the blockchain.

Hence, the primary aim of this study is to address the question of problematic vaccines and develop a blockchain-based management system, namely a “vaccine blockchain,” to trace and manage the information in vaccine supply chains. Additionally, the vaccine blockchain system can provide valuable vaccine recommendation information to different users. The study aims to extend the research on information management systems by understanding how blockchain and machine learning technologies can be used in supply chain management. It is further expected that the findings will help other supply chains address management issues and the challenges of safety supervision. Through this enquiry, the study attempts to shed light on the following research questions:

RQ1: How can a system be developed such that it manages institutions in the vaccine supply chain?

RQ2: How can blockchain and machine learning technologies be used to supervise the operations of the vaccine supply chain management system?

The remainder of this paper is organized as follows. Section 2 presents a literature review, offers a brief introduction to related works in supply chain management, and discusses the challenges of using blockchain in the vaccine supply chain. In Section 3, we describe the theoretical background and methodology behind the vaccine blockchain system, in addition to detailing the smart contracts used for querying vaccine records and detecting expired vaccines. Section 4 shows the intelligent recommendation modules. Based on machine learning technologies, three intelligent recommendation models are introduced into the system. Section 5 presents experimental results and the analysis. Section 6 further discusses and reflects on the findings. Finally, Section 7 presents the conclusions, implications, limitations, and directions for future research.

2. Literature review

Ever-increasing numbers of researchers are realizing that blockchain technology is not limited in its use to virtual currency transactions, but that it can also be applied to information management systems. For example, Li et al. (2017c) proposed an energy blockchain, a secure energy trading system using consortium blockchain technology that addresses the security and privacy challenges caused by untrusted and nontransparent energy markets. Their results show that the energy blockchain is efficient within the industrial IoT (IIoT). Herbaut and Negru (2017) studied a method of using blockchain-powered smart contracts and a network service chain to support a user-centric content delivery ecosystem. By presenting an example, in which blockchain facilitates machine-to-machine (M2M) interactions, and establishing an M2M electricity market in the context of the chemical industry, Sikorski et al. (2017) explored the applications of blockchain technology relating to the Fourth Industrial Revolution (Industry 4.0). Thakur et al. (2019) explored using blockchain technology for land record management in India. Herein, we will introduce some studies of supply chain systems and the use of blockchain and machine learning technologies in the vaccine supply chain.

2.1 Emergency supply chain

Emergency supply chains have been studied extensively. For example, Dwivedi et al. (2018) investigated emergency supply chain management in developing countries, which is also referred to as vaccine supply. Gunasekaran et al. (2018) proposed research to further the understanding of complex humanitarian operations. Shareef et al. (2018) discussed some of the weaknesses and problems in emergency supply chains, as well as proposing the development of an effective emergency supply chain for disaster management.

Meanwhile, data analysis for emergency supply chain management has been widely studied. Simon et al. (2015) reviewed the ways social media tools are used in emergency situations. Akter and Wamba (2017) provided a review revealing the importance of big data in disaster management. Similarly, Prasad et al. (2018) discussed big data analytics in the humanitarian supply chain from the resource dependence perspective, which shows that big data analytics are important and useful in creating humanitarian services. Kim and Hastak (2018) analyzed emergent work based on social network data collected from Facebook. Kim et al. (2018) also analyzed social media data collected from Twitter to find the characteristics of the emergent social network. They showed that a good strategy for emergency agencies is to monitor the heterogeneous online network to expedite information diffusion during disaster response.

Dubey et al. (2019) studied the roles of big data analytics capability and organizational culture in disaster relief operations in the humanitarian supply chain. Elbanna et al. (2019) revealed the influence of social media on emergency management. All these pieces of research indicate that social media is a powerful tool for rapid information diffusion in an emergency. Hence, social media data in the vaccine supply chain are also collected for the purpose of training recommendation models in our vaccine blockchain system.

2.2 Blockchain technology in the supply chain

Many blockchain-related works have been published in the field of supply chains. Tian (2016) combined radio-frequency identification (RFID) and blockchain technology to develop a traceability system for the agriculture food supply chain. Ahmed and Broek (2017) studied the application of blockchain technology to food safety management. Lu and Xu (2017) proposed using blockchain technology to trace products through all stages of the supply chain. Andoni et al. (2017) proposed controlling energy supply with blockchain technology by exploiting its properties of decentralization and traceability. Queiroz and Samuel (2018) researched individual blockchain adoption behavior in India and the USA, and applied blockchain technology to the field of supply chains; a similar study is that of Queiroz et al. (2019). In order to connect rural Indians to global supply chain networks, Schuetz and Venkatesh (2019) proposed utilizing blockchain technology to alleviate the issue of financial exclusion in rural India. Tönnissen and Teuteberg (2019) explored the impact of blockchain technology on supply chain management based on multiple case studies. Behnke and Janssen (2019) applied blockchain technology to the traceability of the food supply chain, in addition to studying boundary conditions. Wong et al. (2019) investigated the effects of blockchain technology on the supply chain management of small and medium-sized enterprises (SMEs), and also analyzed the main factors affecting usage of blockchain in Malaysian SMEs. These studies show that blockchain technology is readily available in the supervision of supply chains to address the vaccine safety challenge.

Recently, Dolgui et al. (2019) presented a blockchain-based application and proposed an event-driven dynamic approach for solving the smart contract design problem in a supply chain system. Zhu and Kouhizadeh (2019) proposed the integration of supply chain management based on blockchain technology and investigated its influence on product deletion decisions. Kamble et al. (2019) utilized blockchain technology to implement traceability in the agriculture supply chain. Their study encouraged us to adopt blockchain for the establishment of relationships in the supply chain.

Saberi et al. (2019) analyzed applications based on blockchain technology and smart contracts for supply chain management to decrease opportunistic behaviors. Pan et al. (2019) explored the use of blockchain technology in enterprise production. Their study pointed out that blockchain could effectively build the internal trust relationship among supply chain members. However, their research did not provide a specific implementation method. All these studies show that blockchain technology is a promising direction for information management in product supply chains to implement traceability and management functions. Therefore, vaccine safety problems may be partly solved by blockchain technology.

2.3 Machine learning technologies in the supply chain

Machine learning technologies, especially deep learning, have promoted the development of artificial intelligence in the past few decades. Some studies have been conducted to apply machine learning technologies to supply chain management and analysis. For example, Ragini et al. (2018) applied machine learning models to analyze sentiment in disaster response and recovery, in order to develop better strategies for disaster environments. A sentiment analysis model is also incorporated into our system for vaccine environments. Zhang et al. (2019) designed an intelligent public information and warning system for disasters. In their study, sentiment analysis and deep learning technologies are used to analyze social media data during disasters.

There are also several examples of research trying to combine blockchain and machine learning technologies. For instance, Jang and Lee (2018) utilized Bayesian neural networks to predict Bitcoin price and obtained good prediction results. Mao et al. (2018) combined blockchain technology and machine learning models to analyze credibility evaluation text in the food supply chain.

Although blockchain technology has many advantages in supply chain management, very few studies, if any at all, have focused on the application of blockchain in safe vaccine supply and supervision. Hence, in this study, we design a vaccine blockchain system to provide tamper-proof vaccine records. The system can enhance the security and traceability ability of the vaccine supply chain.

3. Design of the vaccine blockchain system

Traditional and popular methods of vaccine traceability and supervision are still based on the number labeling method, and there are three major problems involved. First, numbers are easily counterfeited, which causes the hidden danger of forged records; second, the number system is too large to maintain on a nationwide scale; third, vaccine information is prone to being tampered with or deleted.

In comparison, the blockchain can provide trustworthy data records for vaccine traceability in the vaccine supply chain. When designing the vaccine blockchain system, each vaccine is assigned an RFID tag (Samuel & Chatfield, 2009; Samuel, 2012), which is used to input the vaccine information conveniently and without much human workload. Radio-frequency identification is a secure and mature technology that has been widely used in the public transport system and the membership card system, among others. It can also be used to solve the first two problems that exist in the number labeling method.

For the third problem, that of tampered records, in theory, records in a general information system with a central server are easily tampered with or deleted if the central server is attacked. However, the blockchain system is a multi-center (or no-center) system, and it is difficult to attack all nodes, in order to tamper with or delete records. Specifically, the vaccine blockchain system focuses on three main institutions in the supply chain, which are the lot release agency, vaccine enterprises, and the center for disease control (CDC). Records generated by these three institutions are permanently stored in the blockchain system, and it is almost impossible to tamper with or delete the records. In fact, to tamper with a record, more than half of nodes must tamper with the record synchronously, which is very difficult for any enterprise or institution to achieve. The records in the blockchain system are public and can be accessed by consumers and regulators for vaccine traceability.

As shown in Figure 1, the vaccine blockchain includes three components, which are the GMP chain, the Release chain, and the Inoculation chain. These three chains are maintained by three institutions in the vaccine supply chain, which are vaccine enterprises, the lot release agency, and the CDC. Generally, vaccines flow through these three institutions in turn, before being injected into immunization consumers. These three institutions use smart contracts to add or query vaccine records. These smart contracts are deployed to the vaccine blockchain and executed on the Ethereum Virtual Machine (EVM) (Grishchenko et al., 2018).

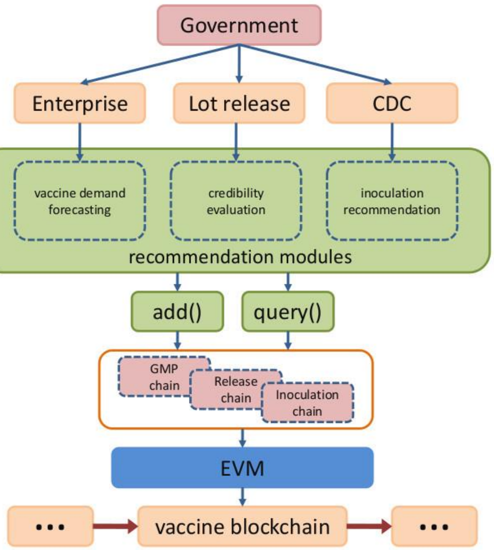

Figure 1: The architecture of the vaccine blockchain system.

Recommendation modules are designed and applied to provide suggestions and advice for use, which includes a vaccine demand forecasting module, a credibility evaluation module, and an inoculation recommendation module. The vaccine demand forecasting module is implemented by the machine learning model and trained using history vaccine demand data recorded in the blockchain. It can be used by vaccine enterprises to control vaccine production within a reasonable range, in order to relieve the vaccine expiration problem. The credibility evaluation module is implemented by the sentiment analysis model and trained using vaccine comments data stored in the blockchain. It can be used by the lot release agency to evaluate the credibility of vaccine enterprises. The inoculation recommendation module is provided to the CDC to inform users of the need for inoculating by using the historical inoculation records and infection records stored in the blockchain.

3.1 The GMP chain

A vaccine production enterprise is a special type of enterprise: on the one hand, vaccine enterprises seek to maximize efficiency, reduce operation costs, and improve operational efficiency; on the other hand, vaccine enterprises bear more social responsibility than ordinary enterprises, where production and operation processes are subject to strict supervision by the State Food and Drug Administration (SFDA). Generally, their production system must conform to the design in GMP standards (Kell & Sonnleitner, 1995), in order to record every process in vaccine production. Good Manufacturing Practice is a quality standard system for ensuring that products (food or drugs) are produced in a consistent manner. It is designed to minimize the risks involved in any production that cannot be eliminated by testing the final product.

As shown in (a) and (b) of Figure 2, GMP standards require enterprises to record the production information of each vaccine, including the product name, the batch number, the production date, the quality guarantee period, and so on. In fact, even in many enterprises with GMP certification, quality management is still poor, and it is difficult to ensure the effective operation of internal audit, external audit, and management review. Therefore, in the design of our vaccine blockchain, vaccine-related records are recorded on the blockchain, including at least three types of record, which are the batch packing record, the batch production record, and the inspection record, as shown in Figure 2.

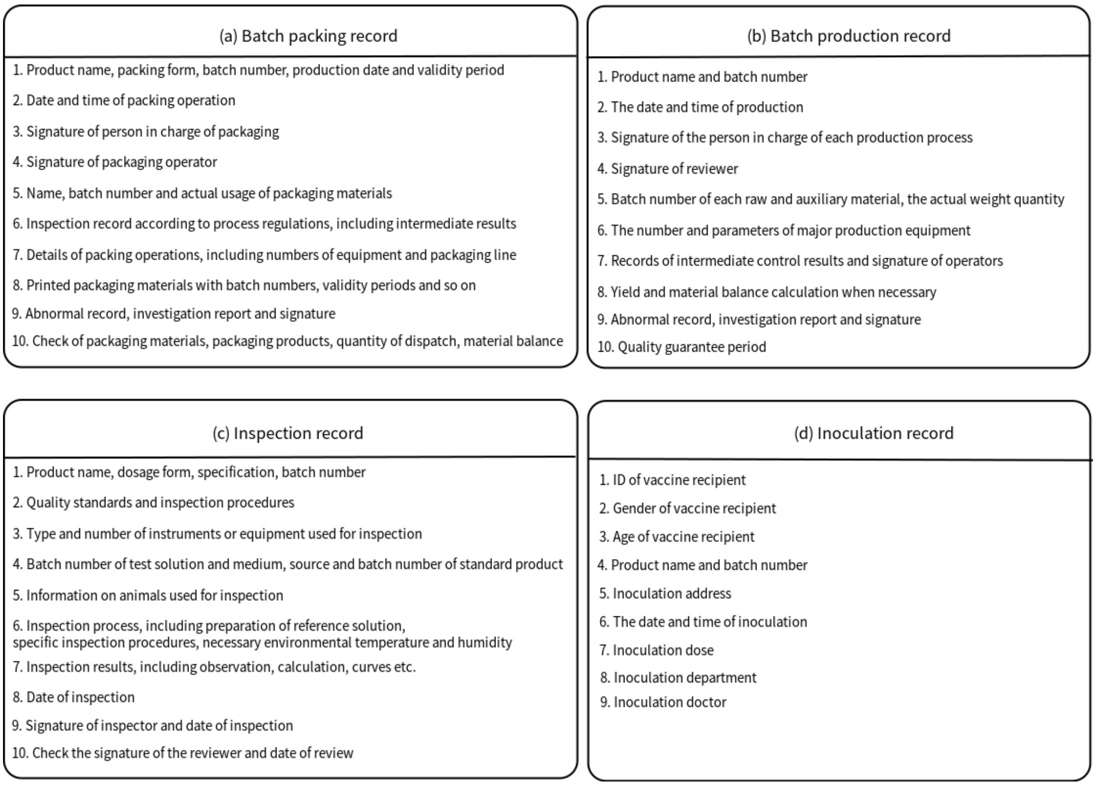

Figure 2: The batch packing record, batch production record, inspection record, and inoculation record of vaccines.

3.2 The Release chain

The vaccine enterprises with GMP certificates can apply for lot release, which refers to the process of evaluating vaccines before granting approval for release onto the market. The enterprises that fail the inspection or fail to approve the examination are not allowed to release their products. Generally, the process of vaccine lot release includes 10 steps: vaccine production, self-checking, filling in the application, form printing, quantity verification, applying for lot release, applying for sampling, spot sampling, sealing samples, and inspection, as shown in Figure 3. The first seven steps are conducted within enterprises, and the subsequent three steps (sampling, sealing up, and inspection) are carried out by the SFDA or other lot release agencies.

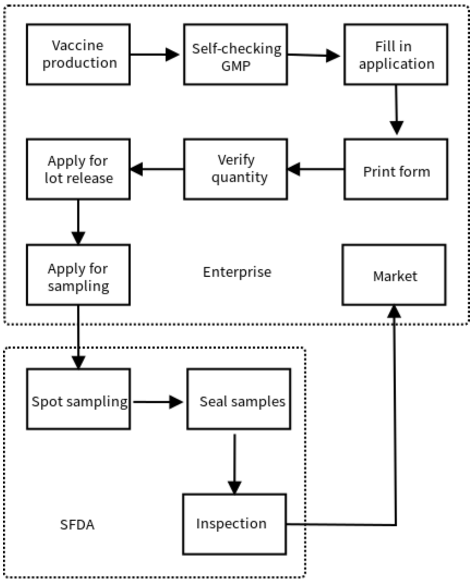

Figure 3: The process of vaccine lot release.

The first step is vaccine production, which should meet the GMP quality standards, as stated above. Then, the enterprises need to perform self-checking to ensure that the vaccines are highly effective and safe. After self-checking, the enterprises can apply for GMP certification from the drug administration. Next, enterprises collect the materials of vaccines and fill in the application form. Then, the application form is printed and the quantity of vaccines is verified. In the sixth step, the enterprises submit the application form and apply for lot release. The last step for the enterprises is to apply for vaccine sampling.

After receiving the vaccine sampling application, the SFDA arranges spot sampling in the factories of enterprises. Then, the vaccine samples are sealed and sent to the national inspection agency. Finally, if the vaccine samples pass the inspection, the enterprises are given permission to release the vaccines into the market.

During the whole process, mentioned herein, records of vaccine production submitted by enterprises are recorded on the GMP chain. Inspection records, which are added by the lot release agency, should also be recorded on the Release chain. After the lot release process, vaccines are sent to the CDC to be injected into vaccine recipients. When a user needs to be vaccinated, the user submits an injection application to the CDC and then gets vaccinated at the CDC. Meanwhile, the immunization record is submitted to the Inoculation chain.

3.3 The Inoculation chain

The Inoculation chain is used to store the immunization records. The main information in this chain is shown in Figure 2 (d), and includes basic information about vaccine recipients, the inoculation department, the injecting doctor, and so on. Herein, much personal information about vaccine recipients is omitted to protect privacy. The identification of the vaccine recipient is retained by the recipient and used to query personal inoculation information. As will be discussed later, the immunization records can be used to train the intelligent inoculation model, which can be used for intelligent inoculation recommendations to users. Hence, the Inoculation chain is also important for our system.

3.4 Block structure information

In traditional blockchain, a new block is generated by miners. Herein, the underlying architecture of blockchains is omitted, where as an available framework, namely Ethereum, is adopted by our system. Hence, only the block information will be discussed here.

The block in the vaccine blockchain system is used to store all vaccine-related information, which is presented in Figure 4. In our design, each block mainly consists of three types of transaction, which are uploaded by enterprises, the lot release agency, and the CDC. These transactions are made up of five data fields, including a time stamp, the sender, the recipient, the amount, and data records content. The time stamp records the transaction time. Sender represents the initiator of a transaction, which is usually one of the three institutions. For the vaccine blockchain, the fields of recipient and amount are set as null, and the records are stored in the "data" field. The records are organized as a hash table structure, which is a dictionary-like collection of unique keys and their values. The keys of these hash tables indicate the record categories, such as "production," "inspection," or "inoculation." The values of these hash tables exist in the form of an object, which contains record information and even other nested objects. With the hash table format, the records can be format-free when stored in the blockchain.

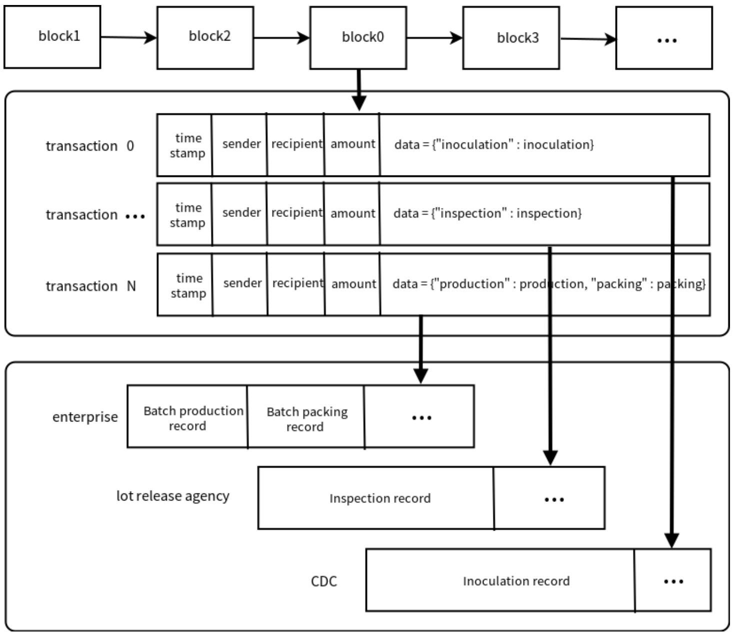

Figure 4: Block structure information of the vaccine blockchain.

3.5 Authority control

If enterprises, the lot release agency, or the CDC want to upload their records, they must apply for accounts (including a public key and a private key) from the government. Additionally, the government maintains accounts for these institutions. The institutions upload records with a private key signature, and the signature is verified by the vaccine blockchain system to ensure that the records are correctly submitted by the corresponding institutions. Accordingly, the government regularly checks records uploaded by these institutions. If there is any problem with the records, the corresponding institutions are investigated and potentially prosecuted.

3.6 Smart contracts for the vaccine supply chain

In order to further realize the supervision function, smart contracts (Grishchenko et al., 2018) are designed in the vaccine blockchain based on the Ethereum technology. Ethereum is a decentralized and open source application software platform based on blockchain technology, which allows users to build and use decentralized applications with blockchains, as stated in Wood (2014). In addition, it supports smart contracts, which are applications that run exactly as programmed, without any possibility of downtime, censorship, fraud, or third-party interference (Christidis & Devetsikiotis, 2016). The Ethereum platform enables developers to easily build and deploy decentralized applications (dapps) running in the EVM, which provides a runtime that can execute code written in smart contracts. By designing suitable smart contracts, our vaccine blockchain system can intelligently monitor the status of the system and provide query functions.

3.6.1 Detection of expired vaccines

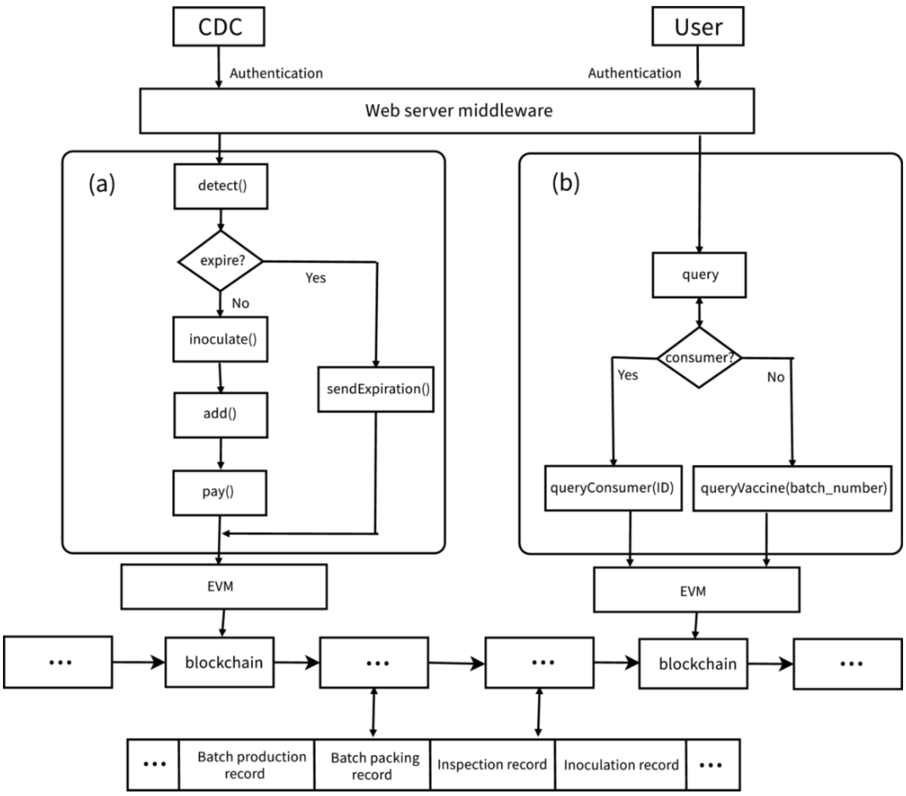

Figure 5: (a) Flow of expired vaccine detection; (b) Flow of vaccine information query.

Expired vaccine events have been the cause of great social shock in China. By using the vaccine blockchain designed in this paper, along with and smart contracts, this problem can be controlled effectively. Before inoculation, the CDC needs to execute a *detect()* function invoked on the web middleware, as shown in Figure 5 (a). The *detect()* function queries the production date and the quality warranty period of vaccines to determine whether those vaccines have expired. If the vaccines have expired, the *sendExpiration()* function is invoked to send the information about the expired vaccines to the blockchain system, and all the institutions receive the expiration information. Meanwhile, another *inoculate()* function is not executed and the *add()* function is not used to add the inoculation record. Also, the system does not execute the *pay()* function (details in Figure 7) to pay money to the CDC. In this way, the information about expired vaccines is broadcast through the whole vaccine supply chain as a reminder to the corresponding institutions, and the inoculation institution is not rewarded for forcibly injecting expired vaccines. Furthermore, the enterprises providing expired vaccines do not profit from it.

3.6.2 Vaccine information query

Once a vaccine accident occurs, the vaccine blockchain is used to trace the entire process of vaccine circulation to investigate and affix responsibility for the accident. Hence, the vaccine blockchain system provides the vaccine query functions, which are also implemented by smart contracts, as shown in Figure 5 (b). The smart contracts are launched by message calls provided by the Ethereum platform. The parameters of the query are stored in the data field of the message. Then, the system judges the identity via the parameters. Generally, two types of vaccine records can be queried: one type is the inoculation record, which is invoked by vaccine recipients; another type is the vaccine circulation record, which can be made by all three vaccine institutions (vaccine enterprises, the lot release agency, and the CDC). The chart flow is detailed in Figure 5 (b).

For personal inoculation record queries from consumers, the blockchain system invokes the *query(ID)* function, for which the input parameter *ID* is the consumer identification. This function traverses the Inoculation chain in the vaccine blockchain to find the information of the consumer, and it returns the results of all the consumer's inoculation records. For a vaccine circulation query initiated by the institutions, the blockchain system executes another *queryVaccine(batch_number)* function, for which the input parameter *batch_number* is the batch number of the vaccine. In this case, the function traverses the GMP chain and the Release chain to find the information of the vaccine, and the query results are returned.

3.6.3 Vaccine coin

```
// ERC Token Standard #20 Interface
contract ERC20Interface
{
function totalSupply() ;
function balanceOf();
function allowance();
function transfer();
function approve();
function transferFrom();

event Transfer();
event Approval();
}
```

Figure 6: The functions and events in the ERC20 standard.

To exchange values along the vaccine blockchain supply chain, a virtual currency like a payment system is needed. The ERC20 token standard describes the functions and events that an Ethereum token contract needs to implement. The functions and events in the ERC20 standard are shown in Figure 6, the parameters of which are omitted from this paper.

Traditionally, the CDC (or a hospital) purchases vaccines from enterprises, and consumers pay cash to the CDC in return for the vaccination. In this mode, cash transactions are carried out between enterprises and CDCs, and CDCs and consumers. Nevertheless, with the ERC20 interface, we can implement a token payment system to transfer a token balance. In our design, the vaccine coin (VaccCoin) is issued to replace the cash transactions between enterprises and the CDC, and between the CDC and consumers. The VaccCoin is always specified as having a conversion ratio of 1:1 with legal tender. Therefore, the value of VaccCoin is equal to the value of legal money.

As shown in Figure 7, consumers (vaccine recipients) first log in to the web middleware and buy the required amount of VaccCoins. After a successful vaccination (shown in Figure 7), the vaccine blockchain system calls the *pay()* function to finish the transaction. The *pay()* function first calls the *transferFrom()* function to transfer VaccCoins from the address of the consumer to the address of the CDC, with the amount of VaccCoins being the selling price of the vaccine (say, 100 VaccCoins). Next, the *transferFrom()* function is called once again to transfer VaccCoins from the address of the CDC to the address of the enterprises. This time, the amount of VaccCoins is the selling price less the income of the CDC (say, 30 VaccCoins), and the income of the enterprise is the remaining VaccCoins (say, 70 VaccCoins).

In fact, the vaccine coin mechanism can be used effectively to supervise vaccine quality. The problematic or expired vaccines will not gain income, which will urge these institutions to manufacture vaccines of high quality and sell them prior to the expiration date.

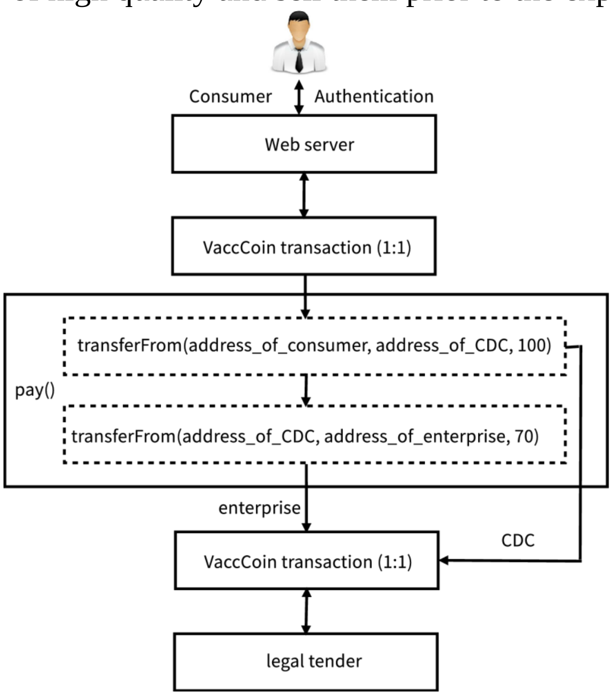

Figure 7: Flow of inoculation payment by VaccCoin.

4. Intelligent recommendation modules

This section will introduce the intelligent recommendation modules used in the vaccine blockchain system. It mainly includes three modules, which are the vaccine demand forecasting module for enterprises, the credibility evaluation module for the lot release agency, and the intelligent inoculation module for the CDC. According to Khan et al. (2010), traditional machine learning models for credibility forecasting include the decision tree (DT), naive Bayes (NB), random forest (RF), k-nearest neighbor (kNN), and support vector machine (SVM) models. A convolutional neural network (CNN) is a widely used type of deep learning model, which can capture specific features regardless of locality, as stated in LeCun et al. (2015). A long short-term memory (LSTM) network is another widely used type of deep learning model, which is adept at series forecasting, as described in Li et al. (2017b).

4.1 Vaccine demand forecast module

One of the main causes of vaccine expiration is the improper estimation of vaccine demand. Therefore, a model that can accurately predict vaccine demand is important for vaccine production plans. The records in the vaccine blockchain system can provide the total doses of vaccine consumed annually, which can be used to forecast vaccine demand for the next year.

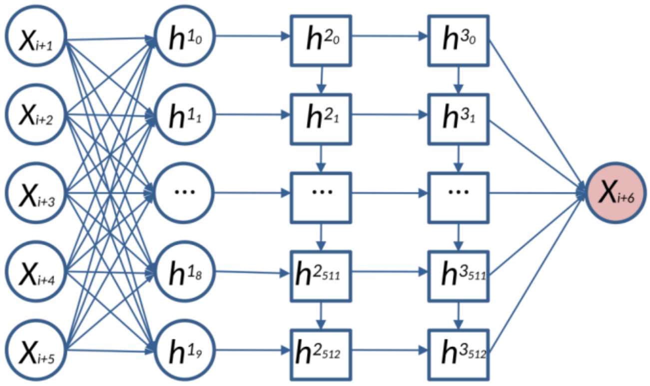

Figure 8: LSTM model for vaccine demand forecasting.

In this paper, we design an LSTM-based deep learning model to forecast demand for vaccines, as shown in Figure 8. In order to make the deep model sensitive to input data, one fully connected (FC) layer with 10 hidden nodes is placed before the LSTM layer. It can map the input series to a new vector space effectively, in order to better preprocess the raw series data. Two LSTM layers with 512 gate units are designed after the FC layer, and are used to learn internal characteristics. In our design, we use five consecutive sets of demand data to forecast the next one. Hence, the deep model is designed with five input nodes and one output node.

4.2 Credibility evaluation module

In general, credibility information is important for a lot release agency to determine the vaccine quality of enterprises. Hence, it would be useful if the vaccine system could inform the lot release agency about the credibility of vaccine enterprises. Based on the inoculation records in the vaccine system, we can further implement a supervision mechanism in the vaccine system. Typically, users can comment on inoculations supplied by different vaccine enterprises online, and the evaluation records are stored in the vaccine system as a credibility evaluation of these enterprises. Machine learning models and deep neural network (DNN) technologies are widely used for sentiment analysis (Ragini et al., 2018), and can be used to represent the credibility evaluation of enterprises and establish a credibility evaluation system to help regulators perform credibility checks on enterprises. In the vaccine blockchain system, we utilize both traditional machine learning models and DNN models to forecast the credibility of enterprises, in order to help the lot release agency evaluate the vaccine enterprises.

A convolutional neural network can be used to capture negative phrases and represent the evaluations of vaccine users. Using memory gate technology, LSTM can link current information with previous information. Hence, LSTM can analyze the sentiment of a comment message from an integral view. In our system, both CNN and LSTM are tested. Meanwhile, a mixed deep model (denoted as Mixed), taking both the advantages of CNN and LSTM, is also designed for vaccine enterprise evaluation. As shown in Figure 9, the Mixed model consists of both the LSTM module and the CNN module (including a convolution layer and a max-pooling layer). In this way, the Mixed model is designed to capture both position-independent negative phrases and the context relations. The comment samples are encoded using the word embedding method. Hence, each sentence is represented by a vector of length 200, which is used as the input vector in deep learning models. The output of the deep model is set as a Softmax function with two nodes, denoting the probability of a positive or negative.

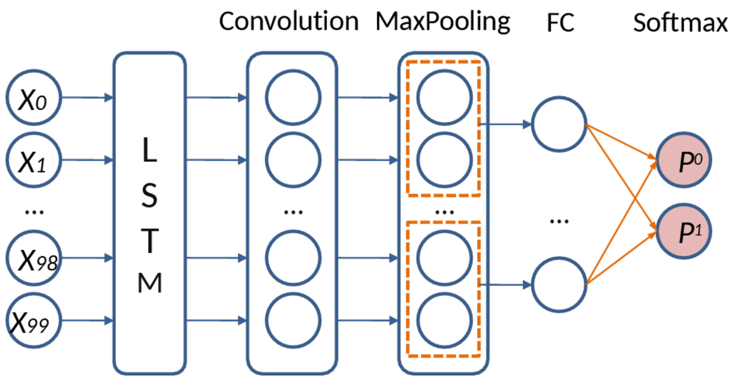

Figure 9: LSTM-CNN deep model for the credibility evaluation module.

4.3 Intelligent inoculation module

As stated above, the immunization information in the vaccine blockchain can be used for intelligent inoculation, which is implemented by an SVM model with radial basis function (RBF) kernel (Liu et al., 2011). In our design, four influenza-related features are selected to evaluate the probability of influenza. Then, the vaccine system reminds a user whether he or she needs to be vaccinated or not, according to the forecast result of the trained SVM model.

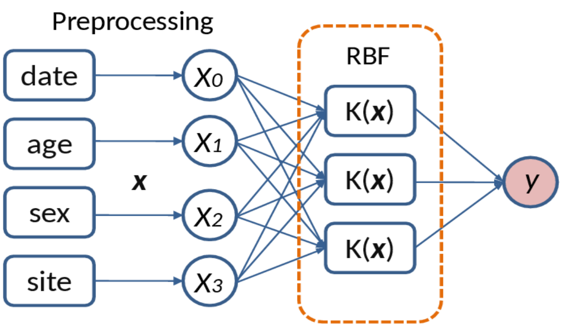

Figure 10: SVM model for the intelligent inoculation module.

As shown in Figure 10, four features are used as one input vector of the SVM model, which are receiving date, age, sex, and site. These four features make up a vaccination sample. The receiving date indicates the time of the vaccination, and the age field represents the recipient's age in years. The gender information is represented by the sex field, and the site field denotes the location of the vaccination. These four features are first preprocessed as floating-point numbers: the date is digitized as one of four numbers, representing the four seasons; the age is digitized as one number in years; the sex is digitized as one of two numbers; the site is digitized according to the postcode of the location. Meanwhile, the result of whether the user is infected or not is used as the output of the SVM model. That is, if the user is infected, the output probability is 1, otherwise it is 0.

5. System Simulation

This section will present the experimental results of the intelligent recommendation models used in the vaccine blockchain system, including the vaccine demand forecasting module for enterprises, the credibility evaluation module for the lot release agency, and the intelligent inoculation module for the CDC.

5.1 Vaccine demand forecast module

The dataset for vaccine demand forecast includes total doses of influenza vaccines (millions) in the United States from 1980 to 2017. The data from 1980 to 2011 are used as training data, and the remaining five years of data are used for testing.

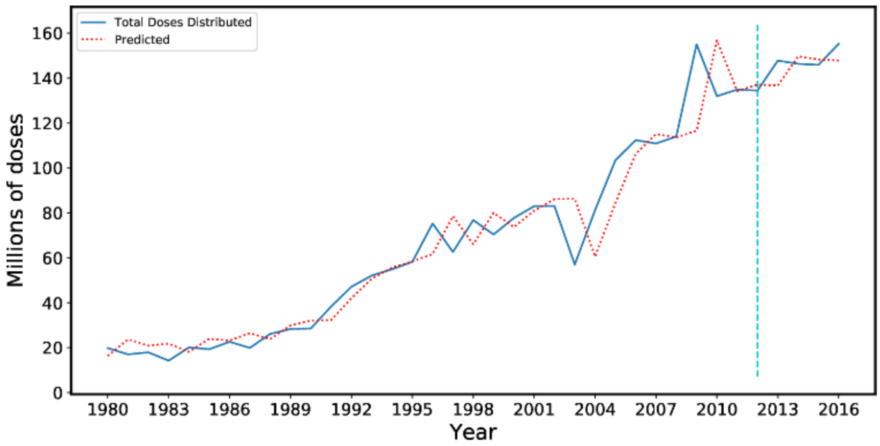

Figure 11: The vaccine demand forecast from the LSTM model.

The LSTM model is optimized by the adaptive moment estimation (Adam) algorithm, and the final forecast results are shown in Figure 11. We can see that the forecasted vaccine demand from 2012 to 2017 has a similar trend to the real doses of vaccines. The forecast errors of the mean absolute error (MAE) and the root mean square error (RMSE) are 0.042425 and 0.048866 (million doses), respectively. The average deviation rate is 4.41%, which indicates that vaccine demand can be well predicted.

5.2 Credibility evaluation module

The dataset used for the credibility evaluation module is collected from real online comment environments, which consist of a total of 16,764 comment sentences, including 8,053 negative comments and 8,711 positive comments.

Four metrics, including accuracy, precision, recall, and F1, as discussed in Jiang et al.

(2008), are measured to evaluate the performance of these models. The experimental results are shown in Table 1. We can see that deep learning models (CNN, LSTM, and Mixed) perform better than traditional machine learning models, including DT, NB, RF, kNN, and SVM. In the four metrics, we pay more attention to recall, which represents the recognition ability of vaccine enterprises with poor evaluation. In the traditional machine learning models, only SVM achieves a recall score of more than 80%. Compared with the traditional models, deep models provide a much higher accuracy rate in the experiments, and both the recall scores exceed 82%. The receiver operating characteristic (ROC) curves, as discussed in Drummond and Holte (2006), are drawn in Figure 12 to compare the deep models for credibility evaluation. Figure 12 clearly shows that CNN and LSTM have similar performances, both with an ROC area of 0.92, while the Mixed model performs best with an ROC area of 0.95. Meanwhile, LSTM performs better than CNN in three metrics, except for lower precision. It also obtains a higher recall than CNN of 83.91%. The Mixed deep models outperform all other models in the four metrics. Meanwhile, they achieve a highest recall of 86.38%, which indicates that it can be used for vaccine enterprise credibility evaluation.

Table1: Experimental results: credibility evaluation results based on machine learning and deep learning models.

Models	Accuracy (%)	Precision (%)	Recall (%)	F1(%)
DT	65.04	69.75	62.36	65.85
NB	71.75	67.73	71.36	69.50
RF	72.14	84.10	66.75	74.42
kNN	77.98	85.24	73.44	78.90
SVM	79.54	76.23	80.49	78.30
CNN	85.65	88.98	82.33	85.53
LSTM	86.07	87.54	83.91	85.69
Mixed	**89.65**	**92.92**	**86.38**	**89.53**

The **bold** results denote the best results

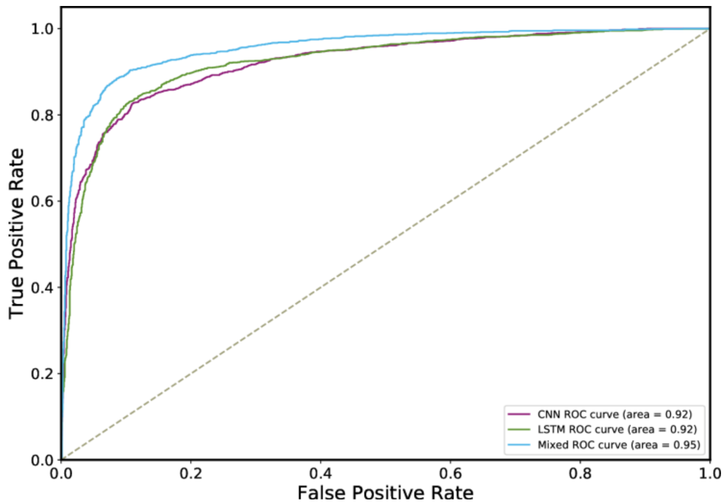

Figure 12: The ROC curves of the CNN model, the LSTM model, and the Mixed model for credibility evaluation.

5.3 Intelligent inoculation module

We collected 11,678 influenza samples and 11,678 health samples from the CDC for intelligent inoculation recommendation purposes. By training an SVM model using 90% of samples, we achieved a forecasting accuracy of 80.64% for the final 10% of test samples. That is, using historical vaccination records, the vaccine system can provide a trustworthy suggestion on whether a user needs to be vaccinated. In fact, the prediction method can be extended to model other infectious diseases. Hence, by combining blockchain and machine learning technologies, our system can intelligently remind users to inject corresponding vaccines.

6. Discussion

6.1 Main findings

Previous studies on vaccine safety have focused mainly on biological-based detection methods (White et al., 2012) and modeling of supervision institutions (Mcneil et al., 2014). Biological-based methods are ineffective in dealing with man-made security problems. Appropriate modeling is an important factor affecting supply chain operation. However, there is still a lack of relevant studies in this area. Yan and Zaric (2017) developed a model combining uncertainty in the manufacturing process, which includes a government health authority, a vaccine manufacturer, and the general population. However, this model is very limited in modeling the vaccine supply chain, and it still has great potential hidden danger around ensuring vaccine quality. In our study, enterprises, the lot release agency, and the CDC are selected as the three main institutions, which are very important for vaccine circulation in the supply chain. Meanwhile, this study proposed to design a system based on blockchain and machine learning technologies to manage these institutions in the vaccine supply chain. Owing to the advantages of blockchain, the proposed vaccine blockchain system eliminates the need for centralized control and provides reliable records for vaccine traceability, which makes the vaccine supply chain safer. We propose that blockchain be introduced into the vaccine supply chain to provide a trust mechanism for users. The vaccine records are stored in the blockchain, which makes it difficult for them to be tampered with and problematic vaccines can be traced easily by the system. Records stored in the blockchain can be used automatically to train machine learning models for intelligent recommendation modules, which enables the system to provide intelligent recommendation functions. Results indicate that the use of machine learning models can make up for the weakness of inflexibility and provide useful recommendation information. Also, smart contracts and the vaccine coin can be developed to provide a supervision mechanism for vaccine enterprises in the vaccine supply chain.

6.2 Implications for research

As a new technology with broad prospects for application, blockchain is being applied more and more frequently to build trust systems in the field of information management. For supply chains, it is helpful in constructing a reliable information management and traceability system (Tian, 2016; Ahmed & Broek, 2017; Lu & Xu, 2017; Behnke & Janssen, 2019). This study contributes to the extant literature in two ways.

First, this study provides further evidence that blockchain technology can help to build effective trust mechanisms between institutions and customers in supply chains. It indicates that regulators can apply blockchain technology to market management to ensure healthy competition among enterprises. Indeed, it contributes to a better understanding of how to apply blockchain technology in general supply chain management, beyond the immunization industry. Previous studies have paid attention to the application of blockchain in solving product management problems (Tian, 2016; Ahmed & Broek, 2017; Lu & Xu, 2017), taking advantage of the decentralized and high-trust distributed characteristics of blockchain technology. However, these studies mainly focused on the traceability applications and rarely provide insight into how smart contracts might be used to provide intelligent monitoring and warning services. Related works, such as Herbaut and Negru (2017), have studied the use of smart contracts in the network service chain. However, their work has not involved the product quality control problem. Our study indicates that smart contracts can also be used in supply chain systems to remind about product problems automatically based on tamper-resistant records. It provides evidence for the application of smart contracts in blockchain-based supply chain systems. In addition, virtual currency has been rarely researched in the current literature, and the application of virtual currency in supply chain management remains to be studied. Our study reveals that virtual currency can be well-designed in the supply chain management system for paying for valuable products, in order to encourage enterprises and institutions to improve their products and services. Thus, future researchers can pay attention to the application of virtual currency. Establishing a supply chain management platform based on blockchain technology can connect the supply chain alliance effectively, build a trusting supply chain ecosystem, and improve the outcomes of the supply chain member.

Second, as two types of popular technology widely investigated today, blockchain and machine learning are often used separately in supply chain systems (Mao et al., 2018). Some previous studies have applied blockchain technology to the field of supply chain management (Tönnissen & Teuteberg, 2019; Wong et al., 2019; Behnke & Janssen, 2019). However, these studies ignore the positive role of data record analysis in the supply chain. Some studies have also utilized machine learning methods to analyze the data records collected from supply chains (Ragini et al., 2018; Zhang et al., 2019; Mao et al., 2018); however, the reliability of these data records is not guaranteed. Indeed, there are still a limited number of studies that apply both blockchain and machine learning technologies to the supply chain system. Our study suggests that it will be of major benefit to supply chain systems to use both blockchain and machine learning technologies. Blockchain can be adopted to store reliable data records in the supply chain, which are exactly what machine learning models need to train reliable recommendation modules. In turn, these recommendation modules also help the supply chain to operate reliably and generate useful data records. Overall, this study indicates that the combination of blockchain and machine learning technologies can help form a virtuous circle and enhance supervision functions in the supply chain management system.

6.3 Implications for practice

This study also provides the following essential implications for practice. First, trust mechanisms are very important in normal supply chain operation. As shown in previous studies (e.g., Mcneil et al., 2014; Yan & Zaric, 2017), a reliance on personnel supervision increases the chance of corruption and fraud, which may cause serious security problems for society. Therefore, it is very important to explore how to manage, trace, and monitor products in supply chains based on the trust mechanism of blockchain technology. It can provide practical experience for regulators to build a more reliable supply chain management system through blockchain technology. Moreover, the application of smart contracts and virtual currency (vaccine coin) in supply chains can reduce the impact of human factors on product quality, thereby urging enterprises to improve the quality of products. The design of vaccine coin provides an example of how to use virtual currency to automatically control the benign running of the supply chain systems in accordance with the laws of the market.

Second, on the basis of reliability, intelligent modules can increase the flexibility of the supply chain. By using machine learning models, a virtuous circle in the supply chain management system can be created to establish accountability mechanisms, which opens a new avenue for studies exploring ways to utilize reliable blockchain records to optimize the supply chain management environment. This mainly covers three aspects. (1) The use of an appropriate vaccine demand forecasting model can maintain the ratio of remaining vaccines at about 4%, which corresponds to six million doses of vaccine. This indicates that the demand forecasting module may effectively control the output of products in supply chains and help to save billions of dollars every year. It can also be used for reference in many similar supply chain systems. Indeed, the correct prediction of product demand can help the government and enterprises to formulate appropriate production plans, which can reduce the waste of resources and relieve the problem of expired products, which is of great significance to supply chain management systems. (2) The use of the credibility evaluation module suggests that recommendation modules can also provide supervision mechanisms for products in supply chains. In this case, the enterprises producing inferior products will gradually lose their markets, which will further encourage enterprises to improve product quality. Hence, credibility evaluation modules can be well-designed for supply chain systems to strengthen the supervision and management of product quality. In some ways, it can also help to reduce the risk of expired products and problem products. Future researchers can pay attention to the application of recommendation models in supply chain management. (3) An intelligent health management system is attracting more and more attention. The use of historical inoculation records stored in the blockchain to predict users' inoculation demand can intelligently discover potential customers, which can make the supply chains run intelligently and effectively. In this way, the supply chain system can automatically analyze a user's condition and recommend suitable products. Therefore, the intelligent inoculation module has potential and referential significance for the next generation of medical information management system.

Third, as discussed earlier, previous studies mainly focus on applications based on the separate use of blockchain (Dolgui et al., 2019; Zhu & Kouhizadeh, 2019; Kamble et al., 2019; Saberi et al., 2019; Pan et al., 2019) or machine learning (Ragini et al., 2018; Zhang et al., 2019) technologies, and very few studies have ever paid attention to the combined application of these two technologies. Also, much of the previous research (e.g., Simon et al., 2015; Akter & Wamba, 2017; Kim & Hastak, 2018; Kim et al., 2018) mainly focuses on the analysis of public data, which might be erroneous, misleading, or may even have been tampered with. Our experimental results provide further empirical evidence that the introduction of blockchain technology into an information management system could increase the reliability of the information and data. Also, the introduction of machine learning technologies into supply chains can provide more intelligent supervision functions. The combination of blockchain and machine learning technologies can improve the accuracy of the information data, and ensure the normal operation of supply chain systems. In the field of vaccine production and supply, it is worthwhile implementing a supervision system to provide flexible and effective accountability, traceability, and recommendation functions for the vaccine supply chain. The combination of these two technologies has a wider research significance, and it can lead to a system that is both intelligent and trusted.

7. Conclusions

This paper examined the problem of applying blockchain technology to vaccine supervision. We designed a novel intelligent system for vaccine supervision in the vaccine supply chain. Meanwhile, smart contracts based on Ethereum for querying personal inoculation records and vaccine circulation were designed for consumers, vaccine institutions, and the government, to trace vaccine operation records. We demonstrated that the issue of vaccine accountability can be resolved using the vaccine blockchain system. Additionally, we also designed smart contracts to detect expired vaccines, while reminders of expired vaccines can be automatically sent to regulators and institutions in the vaccine supply chain. In addition, machine learning and deep learning models are also introduced into the vaccine system for intelligent vaccine recommendation and evaluation functions, as well as vaccine demand forecasting. The experimental results showed that blockchain technology could ensure that vaccine records are not tampered with, and machine learning technologies could learn the prevalent laws from these real records and make valuable recommendations for users.

7.1 Limitations and future research directions

Owing to its preliminary and exploratory nature, this study has a few limitations. In the present vaccine blockchain system, only enterprises, the lot release agency, and the CDC are considered, while in real environments, vaccine supply chains probably involve additional institutions. Therefore, more institutions in the vaccine supply chain should be taken into consideration in the future to enable the safety and trust in the entire vaccine blockchain system. In addition, the machine learning models in the recommendation modules can be improved with more collected data, and future work should focus on collecting more vaccine datasets and test more machine learning models for the vaccine blockchain system. Moreover, the system log records need to be collected and analyzed in future research to verify the effectiveness of the system. Information management in the health and medicine industry remains challenging. Our work represents a small step toward applying novel technologies to address the urgent vaccine supply chain problem.

Disclosure of interest statement

No potential conflict of interest was reported by the authors.

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