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An Efficient Fuzzy-Based Vaccine Distribution Using Blockchain Technology

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Abstract: The COVID-19 pandemic has created unprecedented challenges in the global healthcare system. With the exponential spread and high mortality rates of the SARS-CoV-2 virus, the development, manufacturing, and distribution of COVID-19 vaccines have become a global priority. This paper proposes an Ethereum blockchain-based solution for supply chain management to address issues of safety, security, and traceability of vaccines. The solution maps authorized distributors to transport smart containers and manage data related to COVID-19 vaccine distribution and delivery. Fuzzy-based temperature monitoring and optimal distance for vaccine delivery are employed to mitigate wastage and ensure better performance. The proposed solution can significantly enhance the efficiency and effectiveness of the COVID-19 vaccine supply chain management system.

Keywords: Blockchain, Fuzzy logic, Supply Chain Management, Covid-19 vaccine

1. Introduction

Vaccinations, also known as immunizations, involve injecting a killed microbe to stimulate the immune system against the microbe and prevent disease. It is a simple, safe, and effective way to protect against harmful diseases before they can be contracted. However, the success of a worldwide immunization campaign is contingent upon the availability of an operational and transparent delivery chain that can be audited by all relevant stakeholders. Good transportation systems are critical for adequate vaccine storage, distribution, management, and administration of vaccine distribution, ensuring strict temperature control across the cold chain and improving efficiency in asset management information systems.

The primary objective of cold chain transportation is to ensure the continuous availability of high-quality vaccines from the manufacturer to the service endpoint, ensuring vaccination opportunities are not lost due to vaccine shortages. It is not enough to purchase adequate vaccines; they must also be transported safely to multiple locations and stored appropriately. Frequent temperature monitoring is necessary to prevent tampering and ensure product integrity and distribution. If vaccines are stored outside the recommended temperature range, their effectiveness can be reduced, leading to inadequate patient protection and resulting in the waste of thousands of dollars in vaccines.

A. Covid-19 Vaccination

In early December 2020, the first mass vaccination campaign was launched, and the COVID-19 dashboard began providing continuous updates on the total number of vaccine doses administered. The WHO coronavirus (COVID-19) dashboard also regularly reported the most recent official daily count of COVID-19 cases, deaths, and vaccine coverage across countries, regions, and territories. In addition to providing frequently updated resources for data visualization, sharing, and exploration, our intention with this dashboard is to direct users to other helpful and informative websites. Despite the enthusiasm generated by the development of COVID-19 vaccines, healthcare systems worldwide are now faced with the challenge of obtaining and distributing sufficient quantities to their populations. Table I displays cases of COVID-19 reported to WHO as of September 29, 2022.

TABLE I. Data Overview and Visualizations of Covid-19

	Reported in last 7 days	Cumulative
Cases	2,847,577	613,410,796
Death	8,338	6,518,749
Fully vaccinated	-	63.08%

B. Motivation

The task of vaccinating the global population against COVID-19 is a challenging supply chain management endeavor, and it is essential to be prepared for any such disasters in the future. The efficiency of the vaccination process relies heavily on the functionality and transparency of the distribution supply chain, which all stakeholders must be able to inspect.

C. Objectives

The primary objective of this paper is to develop a model that utilizes smart contracts and fuzzy logic to monitor the delivery of vaccines accurately and timely.

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We aim to present a supply chain management (SCM) model for COVID-19 vaccination based on blockchain and fuzzy logic.

D. Problem Statement and Contribution

The following research questions are addressed in an effort to find answers in this work:

- Q.1 How can the lack of coordination, vaccination losses, and false information about tracking vaccines be addressed?
- Q.2 How will the vaccine recipient know whether the vaccine received by him is valid or not?
- Q.3 How to decide which vaccine should be supplied when and where to eliminate vaccine wastage?
- Q.4 How can Supply Chain Management use fuzzy logic and blockchain to ensure the smooth delivery of COVID-19 vaccines?

This paper contributes to highlighting the significance of using blockchain technology and fuzzy logic in managing the COVID-19 vaccination supply chain. Our goal is to explore how these technologies can be combined to optimize vaccine delivery.

2. Literature Review

Vaccines are a delicate class of drugs that require proper handling to maintain their effectiveness. Heat exposure can be detrimental to the potency of vaccines and pose a threat to public health [1]. To ensure their quality, vaccines are typically distributed using a cold supply chain, where the temperature is closely monitored and controlled throughout storage and transportation [2].

The cold supply chain can be expanded to include additional sensitive goods, including fresh produce, frozen meals, photographic film, and pharmaceuticals. In cold supply chains, it's important to understand the differences between traceability and monitoring. Traceability refers to the accessibility of recorded data and facts about an object at any point during its life cycle. The formal name for such an object is a Traceable Resource Unit (TRU). There are two ways to achieve traceability in supply chains - retrospective TRU tracking (As soon as the process is over, it can be utilised to keep track of previous transactions) and real-time TRU tracking [3]. Identification techniques are necessary in any tracking system to distinguish TRUs from other components. Monitoring involves routinely tracking specific TRU features such as temperature, humidity, and light exposure. Keeping them around for future examination or, if necessary, violation detection, it is frequently necessary to put certain sensors and equipment in the containers in order to supply signals with the information required for monitoring.

Cold supply chains are a prime illustration of an application that requires monitoring. Monitoring is necessary so that any violations of a delicate product's requirement to be provided within a specific temperature range are instantly reported [4].

Efficient vaccine distribution planning is a crucial component of advanced ICT (Information and Communication Technology) solutions that support immunization campaigns [5], [6], [7]. Mathematical modeling has been employed to distribute vaccines for heterogeneous populations while ensuring equity and maximizing the number of immunization doses during an influenza outbreak [6], [7]. By using various heuristics and optimization techniques, the design of the distribution network can be improved [8]-[9], [10]. These approaches help to optimize the allocation of vaccines, enabling more efficient distribution and ultimately increasing the number of individuals who can be vaccinated.

Advancements in blockchain, machine learning, and other modern technologies have opened up new possibilities for sophisticated and cutting-edge systems in various industries, including healthcare [11]. One study aims to improve and expand immunization coverage in rural areas while ensuring transparency in the process [12]. This involves tracking the carrier's position, temperature, and humidity through IoT devices [13]-[14]. To address data privacy and confidentiality issues in healthcare, decentralization technologies built on blockchain are suggested. Recent studies have highlighted blockchain's potential applications during the COVID-19 pandemic, including decentralized tracking of contacts and symptoms and ensuring security and immutability [15]. In the context of the pandemic, blockchain has also been proposed for contact management applications, such as monitoring patient data interchange and supply chain management [16]. Combining IoT infrastructures with blockchain has demonstrated the possibility of developing trustworthy prediction systems to manage pandemic threats [17] and safely monitor people's travels while under quarantine [18]. Incentive-based strategies using blockchain technology have also been proposed to encourage patients to stay in quarantine and combat the COVID-19 pandemic [19].

According to some experts [20], industry supply networks can benefit from blockchain organization and management. In the pharmaceutical supply chain, when temperature control or stopping the sale of fake drugs is a priority, IoT and blockchain frameworks may provide a workable solution [21] [22]. In a blockchain, a machine learning recommendation system is integrated with a blockchain-based medicine supply chain management [23]. Hyperledger fabrics are utilized in the supply chain management system implementation to continuously track and monitor the drug distribution process. The N-gram and LightGBM models are then used to recommend the best medications to patients [24]. The Gcoin blockchain is suggested for drug data flow because it offers transparent drug transaction data and enables all participants in the medication supply chain to work together to thwart drug fraud.

There is limited literature on strategies that create blockchain-based platforms for vaccination delivery. According to [25], a blockchain management system using smart contracts is proposed to oversee vaccination supply chains, providing clients with recommendations for the best medications. Gcoin vaccination expiration and fraud recording are included in [24]. Machine learning algorithms are used to recommend the best vaccination strategies and medications. [26] advocates for using a blockchain to distribute the COVID-19 vaccine. According to the method, every step should be carefully considered, from conception to application, while new commercial chains are also taken into consideration, and blockchain is used to validate every action and track modification. Similarly, in [27], smart containers with IoT sensors are utilized to handle shipment, payments, legitimate receivers, and more. IoT devices are used to gather data on vaccine production, and it is stored on an enterprise blockchain to ensure immutability.

Fuzzy logic has been found to be useful in determining food quality and shelf life when paired with sensory data and sensing technology [28] [29] [30]. The fuzziness and uncertainty of environmental excursions for various food products as well as subjective assessments of food sensory scores, can be considered to enhance the model of food quality kinetics. This approach can be used to develop customized shelf life management for food products by integrating sensory evaluation and handling requirements throughout the entire supply chain using fuzzy logic. Therefore, using fuzzy logic to manage food shelf life can complement and extend, producing a dynamic and unique model of quality decline and shelf life.

Blockchain was invented by Satoshi Nakamoto, a mysterious character whose identity has remained unknown for most of his life. However, the use of blockchain technology in financial markets gained significant attention in September 2015 when nine major banks, including Goldman Sachs and Barclays, collaborated with R3 (an enterprise blockchain software firm) to establish guidelines for implementing blockchain technology [31]. At this point, blockchain was already the latest trend, with FinTech projects announcing new companies and initiatives almost daily. Implementing supply chain and logistics management (SCM) took more time. The community gradually became aware of the potential impact of blockchain on their sector. Transparency is one of the main promises of blockchain.

3. Supply Chain Management Using Blockchain

A. *Vaccine Cold Chain*

Vaccines should be kept in cold storage because they are chemical and biological products that are sensitive to both heat and cold. As shown in figure 1 Cold-chain flow, An efficient vaccine cold chain begins with the cold storage unit in the production facility, continues through the distribution and transportation of the vaccine, includes proper storage at the provider facility, and ends with the patient receiving the vaccination. From the place of manufacture to the place of use, the vaccines are transported and stored using a cold chain system to maintain the recommended temperature to keep the vaccines safe and efficient. However, the cold chain alone is insufficient to monitor other factors, such as lack of supplies, vaccine damage, gaps in rural areas, inaccurate information about vaccines, tracking, lack of coordination etc., so supply chain management is employed.

B. *Supply Chain Management (SCM)*

A supply chain that is temperature-controlled and includes all the machinery and practices associated with

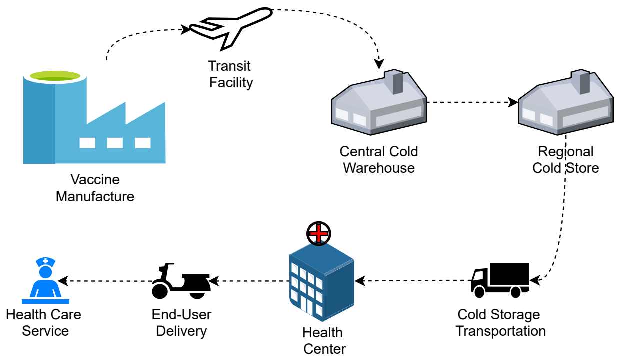

Figure 1. Cold-chain Flow

vaccination is called a cold supply chain. As shown in Figure 2, SCM helps to meet demand, increases customer value, fixes accountability, and aids in financial success. It guarantees that each health facility receives vaccines and information at the right time, in the right amount, under the right conditions and at the right temperature. The balance between supply and demand, cost and substitutes for shipment, stock, etc., must be taken into account.

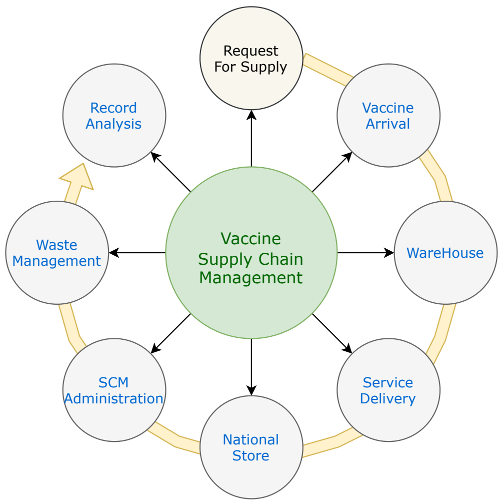

Figure 2. Supply Chain Management

1) *Benefits of SCM*

- The product flow is more effective because things are delivered faster to the end consumer.
- While assuring a high level of product quality, SCM minimizes delay and provides complete traceability and transparency in the movement of goods from supplier to customer.
- Through the compilation of historical reports, SCM aids in enhancing visibility into all transactions and accelerating the generation of supply chain insights.

2) *Challenges in SCM*

- There is a lack of vaccine transparency because there may be a distributor who has some information that we think is accurate, and then we find out that that information is not accurate.

- The database can also be tampered with, and someone can actually modify the record.
- How can vaccine recipients ensure that their shots have not been tampered with during storage and handling, endangering them and their social environment?
- It is also difficult to monitor and confirm whether vaccinations are being stored properly.

To overcome these challenges, we use Fuzzy-Based SCM in Blockchain technology.

C. Blockchain

Blockchain is an emerging technology that allows verifiable data to be stored in a decentralized and immutable ledger. In recent years, various industries have shown interest in it. Blockchain, in particular, is known to be a panacea and one that can replace current payment processing methods. The supply chain management and logistics communities are beginning to recognize blockchain's impact on their sector.

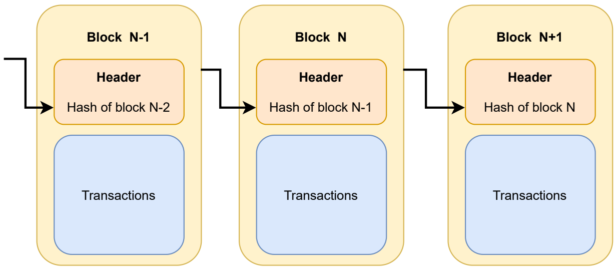

Figure 3. Blockchain Structure

A series of blocks form the blockchain, which can be thought of as a public ledger where all committed transactions are kept. The chain keeps expanding as additional blocks are added to it. Blockchain works in a decentralized manner. The entire set of transactions is contained in the blockchain, which comprises interconnected blocks. Fig. 3 shows a blockchain. Each block has a reference to the previous block, which is essentially a hash value of the previous block.

Blockchain has succeeded by combining several key technologies such as Digital Signature (based on cryptographic hash), Distributed Ledger Technology (DLT), Asymmetric Cryptography Mechanism and Consensus algorithm. As a result of its immutability, which prevents the previous data from being changed. Each participant who adds new data must hold themselves to a high degree of accountability. It provides complete tracking of every data and necessary additional information in real-time. Therefore, blockchain-based supply chain management platforms are very effective and reliable.

1) Mining of a Block

In the mining process, miners (a computational node) attempt to solve a computationally challenging *Proof of Work (PoW)* puzzle to add a new block. PoW is essential for security, which prevents fraud and makes trust possible. PoW ensures that miners cannot misrepresent transactions. PoW ensures that transaction history is securely indexed when data has tampered with. The miner who solves the puzzle first broadcasts the block to the blockchain network and the rest of the miners verify it for accuracy, and then the block is added to the blockchain. This mining makes it difficult for fraudulent nodes to traverse unscrupulous nodes.

Blockchain offers supply chain management solutions that maximise its efficiency, even though it is not a fix- for all supply chain management issues. Blockchain technology can address the supply chain management issues shown in Table II.

TABLE II. Opportunities gaining from Supply Chain Management

1. Data aggregation and visibility	
Challenges:	Manual, paper-based record keeping and reporting methods often result in fragmented, incomplete, and fake manifests, bills of loading, certifications, etc.
Opportunities:	All supply chain stakeholders can store and exchange this information safely and simultaneously with the help of blockchain record-keeping solutions.
2. Trust, Transparency, and Traceability	
Challenges:	Tracing the origin of defective COVID-19 vaccine components and the origin of already administered COVID-19 vaccines are also difficult tasks.
Opportunities:	The blockchain SCM can trace the entire geographic flow of a COVID-19 vaccine. It enables users to view vaccine certification, looks for irregular storage conditions, and follow the origin of faulty vaccine components, among other things.
3. Resolution of issues in real time	
Challenges:	Unplanned demand-and-supply and natural disasters often result in incorrect or delayed deliveries, which affect the manufacturing of COVID-19 vaccines.
Opportunities:	Weather-related or labor-related delays are almost always unavoidable. However, real-time solutions to these problems can be found with blockchain-based SCM. The situation that occurred can immediately set off actions.

4. Vaccine Management

Vaccine management refers to the overall process of ensuring that vaccines are stored, handled, transported, and administered safely and efficiently. One of the key components of vaccine management is minimizing vaccine wastage, which occurs when vaccines are not used before they expire or are discarded due to errors or mishandling during storage or administration.

A. Vaccine Wastage

Vaccine wastage may be caused by a variety of ingredients, including both the vaccine and the vaccinator. If a vaccination store has too many vaccines or something goes wrong, the entire stock may be wasted and may need to be thrown out. Vaccine waste is divided into "Unopened vials" and "Opened vials."

- **Unopened vials** Vaccine vials that are not opened may wastage due to expiration, exposure to heat or cold, breakage, missing from inventory, or be stolen. This type of waste occurs throughout the vaccination system, including distribution, transit and all storage facilities.

- **Opened vials** Opened vials that are wasted fall into this category: Like discarding any unused doses after a vaccination campaign ends. Being unable to consume the prescribed number of doses, if an opened vial goes beyond its appropriate temperature, inadequate reconstitution methods, immersing unsealed vials in water.

Damaged unopened vials should not be stored in cold storage as they can be accidentally mixed with the good vaccine. If they are to be kept for a period of time, such as until the accounting or audit process is completed, they should be kept apart from all usable vials, separate from all useful items, and clearly marked. And only usable vaccination supplies should be listed in stock records. In stock balance, there should be no contaminated or outdated vaccines.

B. Calculations of Vaccine Waste At the Service Level

- Vaccine requirements should be calculated considering the vaccine's wastage. If the wrong numbers are used, the nation could experience severe vaccination shortages or be unable to supply or increase wastage after the vaccination campaign ends. Therefore, it is imperative that all vaccination sites and the pharmacies that sell them are regularly monitored. When appropriate, such monitoring programs may provide advice on how to eliminate waste. The vaccination site regularly inspects its coverage areas and also checks the use and wastage of vaccines on a monthly basis at all service points. This process should be a self-audit and should be used to generate new data sets and report them to a higher level for vaccine management. The following structure might be used to describe the rate of vaccine usage and wastage.

$$Vaccine\ Usage = \frac{No.\ of\ dosages\ jabbed}{(L+M)-(N)} \times 100 \quad (1)$$

$$Vaccine\ wastage = 100 - Vaccine\ Usage \quad (2)$$

  - Where L is number of usable doses at the beginning of the period, M is number of dosages taken during the period and N is number of usable dosages available at the end of the period. Calculations should always be based on dosage calculations rather than vial counts. Calculations become more complicated when multiple vials are used because the number of doses in a vial may vary.

For example, if a vaccination center has 150 doses in stock and 1000 doses of 10-dose vials are received during the vaccination drive. Vaccination is started, and a total of 650 children have received their vaccines. If there are 300 doses in stock at the end of the vaccination campaign, then the rate of vaccine use and wastage is:

$$Vaccine\ Usage = \frac{650}{(150+1000)-300} \times 100 = 76\%$$

$$Vaccine\ Wastage\ (rate) = 100 - 76 = 24\%$$

C. What influences vaccine wastage

1) **Temperature Monitoring:** If the storage temperature of vaccines in the cold chain is not regularly monitored and controlled, there may be a risk that they will be exposed to unbearable temperatures, resulting in wastage. When a sensor fails or management fails, large amounts of vaccine can be wasted in a matter of hours. As a result, the country's vaccination programs could be put at risk, and the financial losses could run into lakhs of rupees.
2) **Substitute Cold-Chain:** In some circumstances, it may be helpful for some countries to use a different cold chain to receive additional vaccinations. when there is a vaccine shortage, a Push-down distribution approach is used for shipping from central vaccine store to intermediary retailers and then to immunization centers without a tracking number.
3) **Control Over Stocks:** To ensure efficient stock control, critical vaccination information must be recorded when they are distributed, stored, and taken out of the store for distribution. If the expiry dates are properly tracked and adhered to them, the Storekeeper can consume early expiry on the principle of Earliest-Expiry-First-Out (EEFO). When goods arrive at the store, time-temperature indicators such as Vaccine Vial Monitors (VVM)s should be checked and logged. During storage, the storage temperature should be closely monitored, and any change in the time-temperature indicators should be recorded.
4) **Distribution and Transportation** Vaccines with a short lifespan that cannot be utilised in the permitted period may be delivered to places if the earliest-expiry-first-out (EEFO) concept is not observed during the delivery.

5. Fuzzy Logic

Fuzzy Logic is logic that resembles human thought. When we consider how fast our CPU processes information and the principles of fuzzy logic, it becomes clear

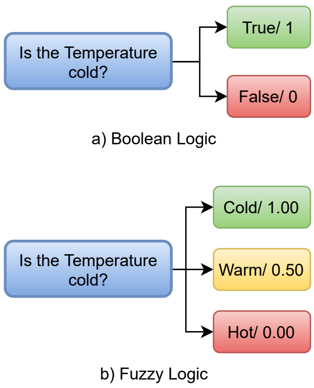

Figure 4. Boolean Fuzzy Logic

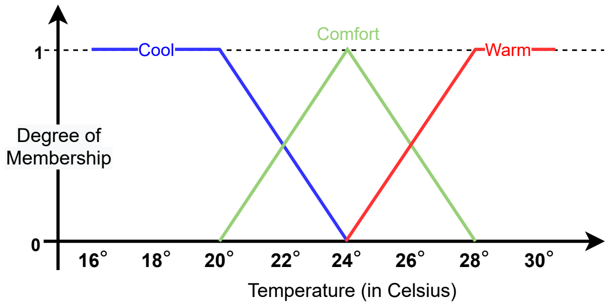

Figure 5. Membership Function using Triangular Membership Function

that it can make decisions much faster than we can. As shown in fig. 4, Fuzzy is basically an extension of *0* and *1* Boolean logic. The three logic operations *AND*, *OR*, and *NOT* are used in traditional logic theory, often referred to as *crisp logic* and that only accepts answers of *0* or *1*. Similar to traditional set theory, it assigns membership or non-membership objects to a class or group with clear mathematical limits; for example, *80° F* is warm and *81° F* is hot. This concept is often referred to as crisp set theory. In fuzzy logic, a degree of membership is constructed as the three operations *AND*, *OR*, and *NOT*; a number between *0* and *1*.

A. Fuzzy Sets

Fuzzy sets can be seen as an extension of classical sets. However, In fuzzy set, value may be one-half, quarter, or very small amount, whereas in classical sets value may either belong to or not belong to a set. For example, when we say something is cold or hot, we do not mean it is completely freezing or scorching. We often specify degrees of coldness or hotness regardless of whether the temperature is recorded in Celsius or Fahrenheit.

B. Linguistics Variables and their Values

Language-based variables are those that include words or entire sentences in the language that we use daily. Basically, linguistic values are made up of the values of linguistic variables. Suppose we have one input linguistic variable $Room\_Temp$ whose values are *Cold*, *Warm*, and *Hot*. And one output linguistic variable named $AC\_Command$ whose values are *Cool*, *Unchanged* and *Heat*.

$$Room\_Temp\,(T) = \{Cold, Warm, Hot\}$$
$$AC\_Command\,(AC) = \{Cool, Unchanged, Heat\}$$

C. Membership Function

A membership function $\mu(T)$ on set T define the value or point in a fuzzy set T from the range of *0* to *1* including *0* and *1* (Refer Eqn.3). Membership functions for temperature variable contain three values as input *Cool*, *Comfort* and *Warm*. As shown in Fig. 5, for value *cool* at $20°C$ membership value is *1* and at $24°C$ membership value is *0*, and equation 4 show the different membership values for *Cool* value.

$$\mu T\,(\cdot) \in [0,1] \tag{3}$$

$$\mu_{Cool}(x) = \begin{cases} 1 & if(x < 20°C) \\ \frac{24-x}{(24-20)} & if(-20°C \le x < 24°C) \\ 0 & if(x > 24°C) \end{cases} \tag{4}$$

Similarly, equations 5 and 6 show the membership value for *Comfort* and *Warm*, respectively.

$$\mu_{Comfort}(x) = \begin{cases} 0 & if(x < 20°C) \\ \frac{(x-20)}{(24-20)} & if(20°C \le x \le 24°C) \\ \frac{28-x}{28-24} & if(24°C \le x \le 28°C) \\ 0 & if(x > 28°C) \end{cases} \tag{5}$$

$$\mu_{Warm}(x) = \begin{cases} 0 & if(x < 24°C) \\ \frac{x-24}{28-24} & if(24°C \le x \le 28°C) \\ 1 & if(x > 28°C) \end{cases} \tag{6}$$

D. Fuzzy Rules

Fuzzy rules adopt a simple $IF - THEN$ rule with a condition and a conclusion. For example, we have the following statement to map the above membership functions to fuzzy rules.

$$IF\ (Room\_temp\ is\ warm)\ THEN\ (AC\_command\ is\ cool)$$

Here $(Room\_temp$ is $warm)$ is **Premise** and $(AC\_command$ is $cool)$ is **Consequent**.

6. Proposed Model

A. Blockchain-Based SCM Model

A blockchain-based vaccine supply chain management model has been developed using the Ethereum platform, with smart contracts written in Solidity language and fuzzy logic employed for decision-making. The module has been tested using Remix IDE and Ganache. However, it is important to note that for each transaction executed in the Ethereum blockchain, a fee (in ether) is paid. To implement a fuzzy logic-based supply chain model in Solidity, the first step is to define the rules and parameters for the fuzzy logic system. This involves identifying the input and output variables and their membership functions. Once the fuzzy rules are defined, a smart contract in Solidity is created to implement these rules. As shown in Figure 6, the Truffle framework includes a tool called Ganache, which provides a blockchain environment for creating, deploying, and testing Ethereum-based contracts.

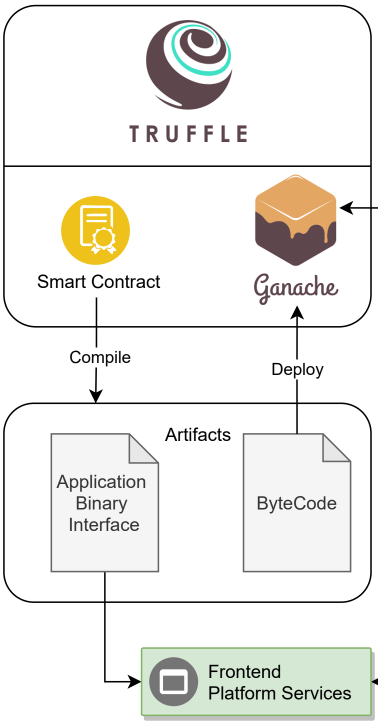

Figure 6. Proposed model for blockchain-based vaccine delivery

Figure 6 illustrates the proposed blockchain-based vaccine supply chain management model using fuzzy logic. The model includes input variables such as temperature, quantity, location, and time, which are used to determine the output variable - the optimized delivery distance. The model is designed to be flexible and adaptable to different vaccine supply chains, including cold chain vaccines like the COVID-19 vaccine.

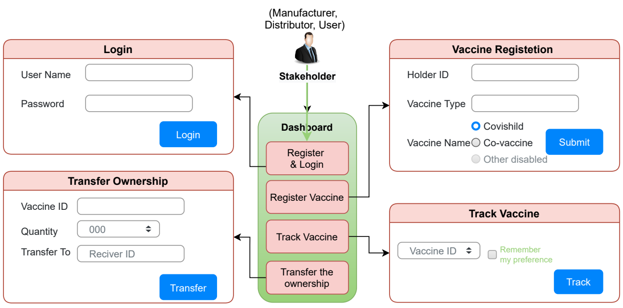

Figure 7. Front-end for Vaccine tracing

Fig. 7 shows the front-end, and how vaccines are traced. This architecture allows end users to trace vaccine delivery from the manufacturer to various intermediate storage centers, which provides transparency and coordination among all parties.

B. *Fuzzy Based Modeling*

As shown in Fig. 8, Decision Making using Fuzzy Logic following steps must be followed.

- **Step 1:** Identify the input and output variables and decide the descriptors for the same.
  Here two linguistic input variables are considered temperature (in °C) and validity (in days) (in how many days the vaccine will expire). And the output variable is distribution distance (in km). As shown in Table III, for the linguistic variable temperature {freeze, cold and warm} the descriptors are {F, C, and W} respectively.
  And as shown in Table IV, for the linguistic variable *validity* Far to Expiry, Around to Expiry and Close to Expiry, the descriptors are *FE, AE* and *CE* respectively.
  As shown in Table V, Similarly for Linguistic variable *distance to Delivery* {Very Short Distance, Short Distance, Medium Distance, Large Distance,

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Algorithm 1 Vaccine Tracing Procedure

1: Stakeholders (Manufacturer, Distributor, and User) can register by giving their name, password, and type. *UserID* is returned.
2: User must log in using *UserId* and Password.
3: Register the vaccination for the auction.
4: Stakeholders can view the vaccine and track its ownership and supply chain movements.
5: Decision-making with the help of Fuzzy Logic, to deliver the nearest validityExpiry date vaccine to the nearest vaccination center.
6: Changing the vaccines ownership to vaccination center, distributor, or other stakeholders as needed.

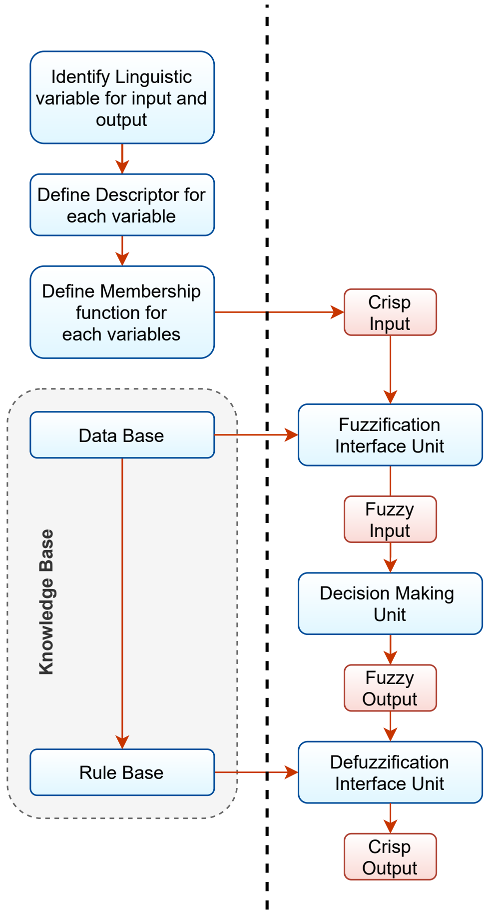

Figure 8. Decision Making Architecture

TABLE III. Descriptor for Temperature Input Variable

Temperature	Descriptor	Range for Membership
Freez	*F*	-25°C to 0°C
Cold	*C*	-25°C to 25°C
Warm	*W*	0°C to 25°C

TABLE IV. Descriptor for Validity Input Variable

Validity	Descriptor	Range for Membership
Close to Expiry	*CE*	1 to 30 days
Around to Expiry	*AE*	1 to 180 days
Far to Expiry	*AE*	30 to 180 days

Very Large Distance} for COVID-19 Vaccines, the Descriptors are {VSD, SD, MD, LD and VLD} respectively.

TABLE V. Descriptor for Distance to Delivery Output Variable

Distance	Descriptor	Range for Membership
Very Short Distance	*VSD*	0 to 200 Km
Short Distance	*SD*	0 to 400 Km
Medium Distance	*MD*	200 to 600 Km
Large Distance	*LD*	400 to 800 Km
Very Large Distance	*VLD*	600 to 800 Km

- **Step 2:** Define Membership function for each of input and output variables.
  (we use Triangular membership function).
  1) Membership function for Temperature

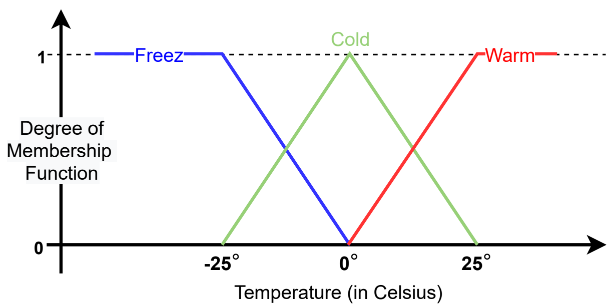

Figure 9. Membership Function for Temperature

$$Triangular(x) = \begin{cases} 0 & if\ (x < -25) \\ \frac{x-(-25)}{0-(-25)} & if\ (-25 \le x < 0) \\ \frac{25-x}{25-0} & if\ (0 \le x \le 25) \\ 0 & if\ (25 < x) \end{cases} \quad (7)$$

$$\mu_F(x) = \left\{ \frac{0-x}{0-(-25)} \quad if(-25 \le x < 0) \right. \quad (8)$$

$$\mu_C(x) = \begin{cases} \frac{x-(-25)}{0-(-25)} & if(-25 \le x \le 0) \\ \frac{25-x}{25-0} & if(0 < x \le 25) \end{cases} \quad (9)$$

$$\mu_W(x) = \left\{ \frac{x-0}{25-0} \quad , if(0 \le x \le 25) \right. \quad (10)$$

2) Membership function for Validity

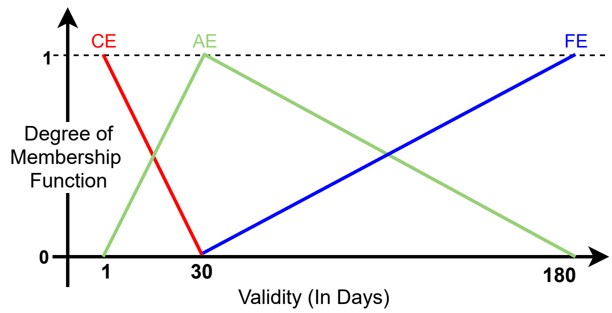

Figure 10. membership function for Validity

$$\mu_{CE}(y) = \left\{ \frac{30-y}{30-1} \quad , if 1 \le y \le 30 \right. \quad (11)$$

$$\mu_{AE}(y) = \begin{cases} \frac{y-1}{30-1} & if 1 \le y \le 30 \\ \frac{180-y}{180-30} & if 30 < y \le 180 \end{cases} \quad (12)$$

$$\mu_{FE}(y) = \left\{ \frac{y-30}{180-30} \quad , if 30 \le y \le 180 \right. \quad (13)$$

3) Membership Function for distance

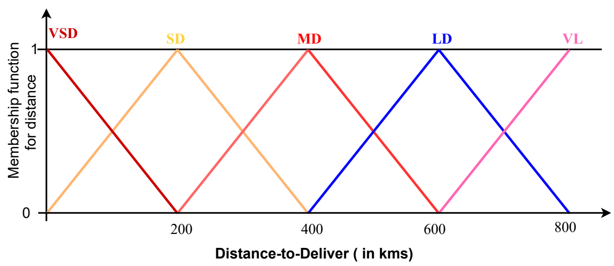

Figure 11. Membership function For Distance

$$\mu_{VSD}(z) = \left\{ \frac{200-z}{200-0} \quad , if 0 \le y \le 200 \right. \quad (14)$$

$$\mu_{SD}(z) = \begin{cases} \frac{z-0}{200-0} & , if 0 \le z \le 200 \\ \frac{400-z}{400-200} & , if 200 \le z \le 400 \end{cases} \quad (15)$$

$$\mu_{MD}(z) = \begin{cases} \frac{z-200}{400-200} & , if 200 \le z \le 400 \\ \frac{600-z}{600-400} & , if 400 \le z \le 600 \end{cases} \quad (16)$$

$$\mu_{LD}(z) = \begin{cases} \frac{z-400}{600-400} & , if 400 \le z \le 600 \\ \frac{800-z}{800-600} & , if 600 \le z \le 800 \end{cases} \quad (17)$$

$$\mu_{VLD}(z) = \left\{ \frac{z-600}{800-600} \quad , if 600 \le y \le 800 \right. \quad (18)$$

- **Step 3:** Form a Rule Base:

- *IF (temperature is F) ∧ (Validity is FE) → Distance for delivery is VLD*
- *IF (temperature is F) ∧ (Validity is AE) → Distance for delivery is LD*
- *IF (temperature is F) ∧ (Validity is CE) → Distance for delivery is MD*
- *IF (temperature is C) ∧ (Validity is FE) → Distance for delivery is LD*
- *IF (temperature is C) ∧ (Validity is AE) → Distance for delivery is MD*
- *IF (temperature is C) ∧ (Validity is CE) → Distance for delivery is SD*
- *IF (temperature is W) ∧ (Validity is FE) → Distance for delivery is MD*
- *IF (temperature is W) ∧ (Validity is AE) → Distance for delivery is SD*
- *IF (temperature is W) ∧ (Validity is CE) → Distance for delivery is VSD*

Temperature (x) \ Validity (y)	FE	AE	CE
F	VLD	LD	MD
C	LD	MD	SD
W	MD	SD	VSD

Figure 12. Rule Base Matrix

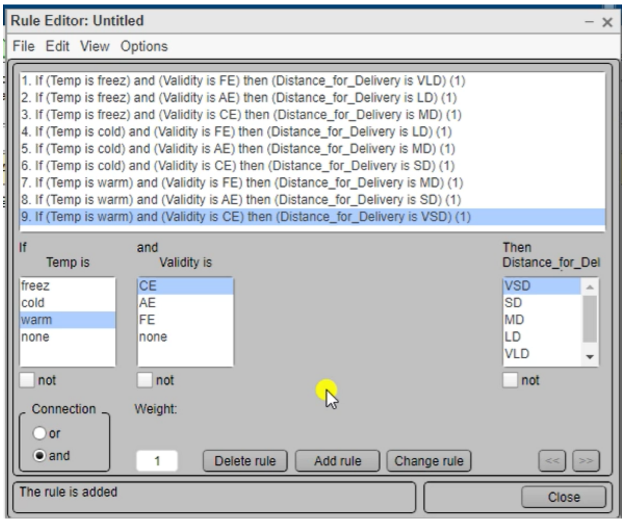

Figure 13. Formation of Rules

- **Step-4:** Rule Evaluation for a case, where Temperature *(x)* of COVID-19 is *2° C* and the validity *(y)* of vaccine is *20 days*. So the membership value for these parameters are as follows:

$$\mu_C(x) = 0.92$$
$$\mu_W(x) = 0.08$$
$$\mu_{CE}(y) = 0.344$$
$$\mu_{AE}(y) = 0.655$$

According to the rule base matrix, as shown in fig. 12, it leads to 4 rules:

- S_1: If Temperature is cold and validity is Around to Expiry
- S_2: If Temperature is cold and validity is Close to Expiry
- S_3: If Temperature is Warm and validity is Around to Expiry
- S_4: If Temperature is Warm and validity is Close to Expiry

So here we have to evaluate the strength of each rule, which are as follows:

$$\begin{aligned} S_1 &= min(\mu_C(x),\ \mu_{CE}(y)) \\ &= min(0.92,\ 0.344) = 0.344 \\ S_2 &= min(\mu_C(x),\ \mu_{AE}(y)) \\ &= min(0.92,\ 0.655) = 0.655 \\ S_3 &= min(\mu_W(x),\ \mu_{CE}(y)) \\ &= min(0.08,\ 0.344) = 0.08 \\ S_4 &= min(\mu_W(x),\ \mu_{AE}(y)) \\ &= min(0.08,\ 0.344) = 0.08 \end{aligned}$$

Temperature (x) \ Validity (y)	FE	AE	CE
F	-	-	-
C	-	0.655	0.344
W	-	0.08	0.08

Figure 14. Rule Matrix

Step 5: Defuzzification, means the method of getting one number from the output of the combined fuzzy set. since we use *Mean of Max* defuzzification technique.
Maximum Strength= $max(s_1, s_2, s_3, s_4) = 0.655 = S_2$
Here s_2 has the maximum strength, According to the rule base matrix (Fig. 12) the *MD* can be covered so the membership vale for *MD* is as follows:

$$\mu_{MD}(z) = \begin{cases} \frac{z-200}{400-200} & , if\ 200 \le z \le 400 \\ \frac{600-z}{600-400} & , if\ 400 \le z \le 600 \end{cases} \tag{19}$$

According to the fig. 12 and fig. 14, $\mu_{MD}(z)$ is 0.655,
For $200 \le z \le 400$:

$$0.655 = \frac{z_1 - 200}{200}$$
$$z_1 = 331\ km$$

For $400 \leq z \leq 600$:

$$0.655 = \frac{600 - z_2}{200}$$
$$z_2 = 469\ km$$

We take the mean of z_1 and z_2, that is:

$$z = \frac{331 + 469}{2} = 400\ km \tag{20}$$

So, if the temperature of the vaccine is 2° C (Input1) and the validity of the vaccine is 20 days (input2), Then we have to deliver the vaccine at a distance of approximately 400 km.

7. Model Analysis

The proposed model for a blockchain-based supply chain management system for vaccines utilizes fuzzy logic for decision-making (Refer fig. 15). The model is implemented using the Ethereum platform and smart contracts written in *Solidity*. The system is designed to be adaptable to various vaccine supply chains, including cold chain vaccines such as the COVID-19 vaccine.

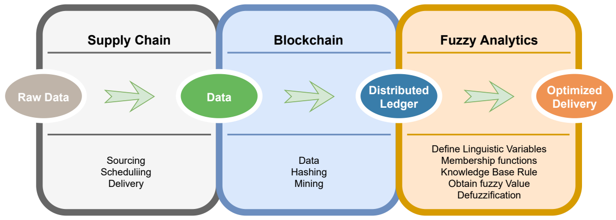

Figure 15. Proposed Model for vaccine Supply Chain using Blockchain and Fuzzy logic

This model can be applied to the current state of the COVID-19 vaccine and other cold-chain vaccine drives. Here we have used the *Mamdani Inference System* to calculate the delivery distance of the vaccine as an output. A snapshot of the same is shown in fig. 16.

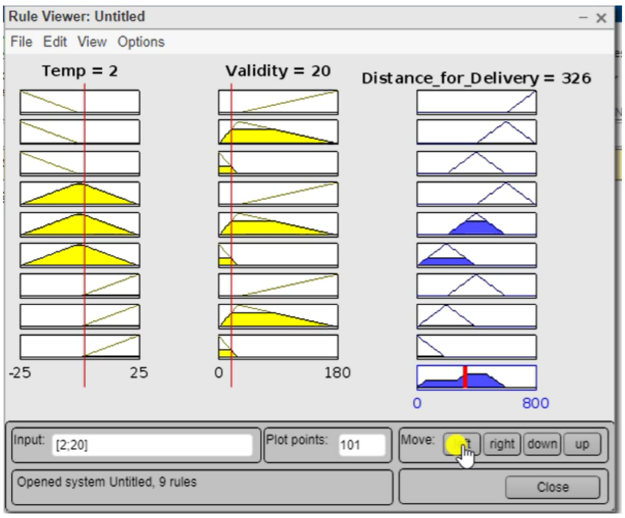

Figure 16. Snapshot of the Mamdani Inference System used to calculate the delivery distance of the vaccine as an output.

The algorithm for vaccine tracing involves stakeholders registering with their name, password, and type, logging in, registering the vaccination for auction, viewing the vaccine and following the owners. Smart contracts define these rules for optimized delivery of the vaccine to the nearest vaccination center, distributor, and other stakeholders, using fuzzy logic-based decision-making to deliver the nearest validity vaccine to the nearest vaccination center.

The steps involved in decision-making using fuzzy logic include identifying the input and output variables and deciding the descriptors for the same. Two linguistic input variables, temperature (in °C) and validity (in days), and the output variable, distribution distance (in km), are identified. The descriptors for the input variables are also provided, along with their ranges for membership.

Overall, the proposed model provides a secure and efficient solution for SCM of vaccines, with the ability to adapt to different supply chains and optimize delivery using fuzzy logic-based decision-making.

8. Conclusion and Future Work

In conclusion, the proposed model for a blockchain-based supply chain management system for vaccines using fuzzy logic has been presented in this paper. The model is designed to be flexible and adaptable to different vaccine supply chains, including cold chain vaccines like the COVID-19 vaccine. The model uses smart contracts to ensure transparency and trust among stakeholders and to prevent fraud and inappropriate transactions. The Mamdani Inference System has been used to calculate the delivery distance of the vaccine as an output. The prototype is developed using Solidity, Ganache, and Remix IDE, and it can be improved by including a priority-based system to prioritize vaccination center demands and distribute vaccines based on demand.

Overall, the proposed model provides a promising solution to the challenges faced in vaccine supply chain management, particularly in the case of the COVID-19 vaccine. The integration of blockchain technology and fuzzy logic-based decision-making can significantly improve the efficiency and effectiveness of vaccine distribution. The use of smart contracts ensures transparency and trust among stakeholders, and the flexibility of the model allows for its adaptation to different vaccine supply chains. Future work can focus on testing the model on a larger scale and incorporating additional features to further optimize the vaccine distribution process.

References

[1] Q. Lin, Q. Zhao, and B. Lev, "Cold chain transportation decision in the vaccine supply chain," *European Journal of Operational Research*, vol. 283, no. 1, pp. 182–195, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0377221719309075

[2] G. Prakash, A. P. Renold, and B. Venkatalakshmi, "Rfid based mobile cold chain management system for warehousing," *Procedia engineering*, vol. 38, pp. 964–969, 2012.

[3] P. Olsen and M. Borit, "The components of a food traceability system," *Trends in Food Science & Technology*, vol. 77, pp. 143–149, 2018.

[4] J. Lloyd and J. Cheyne, "The origins of the vaccine cold chain

and a glimpse of the future," *Vaccine*, vol. 35, no. 17, pp. 2115–2120, 2017.

[5] S.-I. Chen, B. A. Norman, J. Rajgopal, T. M. Assi, B. Y. Lee, and S. T. Brown, "A planning model for the who-epi vaccine distribution network in developing countries," *Iie Transactions*, vol. 46, no. 8, pp. 853–865, 2014.

[6] S. Enayati and O. Y. Özaltın, "Optimal influenza vaccine distribution with equity," *European Journal of Operational Research*, vol. 283, no. 2, pp. 714–725, 2020.

[7] Y. Yang, H. Bidkhori, and J. Rajgopal, "Optimizing vaccine distribution networks in low and middle-income countries," *Omega*, vol. 99, p. 102197, 2021.

[8] A. Riewpaiboon, C. Sooksriwong, N. Chaiyakunapruk, P. Tharmaphornpilas, S. Techathawat, K. Rookkapan, A. Rasdjarmrearnsook, and C. Suraratdecha, "Optimizing national immunization program supply chain management in thailand: an economic analysis," *Public Health*, vol. 129, no. 7, pp. 899–906, 2015.

[9] M. J. Keeling and A. Shattock, "Optimal but unequitable prophylactic distribution of vaccine," *Epidemics*, vol. 4, no. 2, pp. 78–85, 2012.

[10] P. Ignaciuk and Ł. Wieczorek, "Continuous genetic algorithms in the optimization of logistic networks: Applicability assessment and tuning," *Applied Sciences*, vol. 10, no. 21, p. 7851, 2020.

[11] T.-T. Kuo, H.-E. Kim, and L. Ohno-Machado, "Blockchain distributed ledger technologies for biomedical and health care applications," *Journal of the American Medical Informatics Association*, vol. 24, no. 6, pp. 1211–1220, 2017.

[12] R. T. Hasanat, M. A. Rahman, N. Mansoor, N. Mohammed, M. S. Rahman, and M. Rasheduzzaman, "An iot based real-time data-centric monitoring system for vaccine cold chain," in *2020 IEEE East-West Design & Test Symposium (EWDTS)*. IEEE, 2020, pp. 1–5.

[13] S. Khezr, M. Moniruzzaman, A. Yassine, and R. Benlamri, "Blockchain technology in healthcare: A comprehensive review and directions for future research," *Applied sciences*, vol. 9, no. 9, p. 1736, 2019.

[14] M. Hölbl, M. Kompara, A. Kamišalić, and L. Zlatolas, "A systematic review of the use of blockchain in healthcare. symmetry, 10, 470," 2018.

[15] D. Marbouh, T. Abbasi, F. Maasmi, I. A. Omar, M. S. Debe, K. Salah, R. Jayaraman, and S. Ellahham, "Blockchain for covid-19: review, opportunities, and a trusted tracking system," *Arabian journal for science and engineering*, vol. 45, no. 12, pp. 9895–9911, 2020.

[16] A. Kalla, T. Hewa, R. A. Mishra, M. Ylianttila, and M. Liyanage, "The role of blockchain to fight against covid-19," *IEEE Engineering Management Review*, vol. 48, no. 3, pp. 85–96, 2020.

[17] A. Fusco, G. Dicuonzo, V. Dell'Atti, and M. Tatullo, "Blockchain in healthcare: Insights on covid-19," *International Journal of Environmental Research and Public Health*, vol. 17, no. 19, p. 7167, 2020.

[18] J. Zhang and M. Wu, "Blockchain use in iot for privacy-preserving anti-pandemic home quarantine," *Electronics*, vol. 9, no. 10, p. 1746, 2020.

[19] M. Manoj, G. Srivastava, S. R. K. Somayaji, T. R. Gadekallu, P. K. R. Maddikunta, and S. Bhattacharya, "An incentive based approach for covid-19 planning using blockchain technology," in *2020 IEEE Globecom Workshops (GC Wkshps*. IEEE, 2020, pp. 1–6.

[20] P. Gonczol, P. Katsikouli, L. Herskind, and N. Dragoni, "Blockchain implementations and use cases for supply chains-a survey," *Ieee Access*, vol. 8, pp. 11 856–11 871, 2020.

[21] R. Singh, A. D. Dwivedi, and G. Srivastava, "Internet of things based blockchain for temperature monitoring and counterfeit pharmaceutical prevention," *Sensors*, vol. 20, no. 14, p. 3951, 2020.

[22] C. Antal, T. Cioara, M. Antal, and I. Anghel, "Blockchain platform for covid-19 vaccine supply management," *IEEE Open Journal of the Computer Society*, vol. 2, pp. 164–178, 2021, https://ieeexplore.ieee.org/ielx7/8782664/9349230/09382850.pdf. [Online]. Available: https://app.dimensions.ai/details/publication/pub.1136595002

[23] K. Abbas, M. Afaq, T. Ahmed Khan, and W.-C. Song, "A blockchain and machine learning-based drug supply chain management and recommendation system for smart pharmaceutical industry," *Electronics*, vol. 9, no. 5, p. 852, 2020.

[24] J.-H. Tseng, Y.-C. Liao, B. Chong, and S.-w. Liao, "Governance on the drug supply chain via gcoin blockchain," *International journal of environmental research and public health*, vol. 15, no. 6, p. 1055, 2018.

[25] B. Yong, J. Shen, X. Liu, F. Li, H. Chen, and Q. Zhou, "An intelligent blockchain-based system for safe vaccine supply and supervision," *International Journal of Information Management*, vol. 52, p. 102024, 2020.

[26] L. J. R. Lopez and N. B. Álvarez, "Blockchain application in the distribution chain of the COVID-19 vaccine: a designing understudy," 5 2020.

[27] H. Hasan, E. AlHadhrami, A. AlDhaheri, K. Salah, and R. Jayaraman, "Smart contract-based approach for efficient shipment management," *Computers & Industrial Engineering*, vol. 136, pp. 149–159, 2019.

[28] D. Chatterjee, P. Bhattacharjee, and N. Bhattacharyya, "Development of methodology for assessment of shelf-life of fried potato wedges using electronic noses: Sensor screening by fuzzy logic analysis," *Journal of Food Engineering*, vol. 133, pp. 23–29, 2014.

[29] D. M. Taghoy and J. F. Villaverde, "A fuzzy logic approach for the determination of cavendish banana shelf life," in *TENCON 2018-2018 IEEE Region 10 Conference*. IEEE, 2018, pp. 2467–2472.

[30] S. Basak, "Shelf life extension of tomato paste through organoleptically acceptable concentration of betel leaf essential oil under accelerated storage environment," *Journal of food science*, vol. 83, no. 5, pp. 1396–1403, 2018.

[31] S. Underwood, "Blockchain beyond bitcoin," *Communications of the ACM*, vol. 59, no. 11, pp. 15–17, 2016.

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