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Blockchain-based Covid Vaccination Registration and Monitoring

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Abstract

Covid-19 (SARS-CoV-2) has changed almost all the aspects of our living. Governments around the world have imposed lockdowns to slow down the transmissions. Fortunately, we have found the vaccine, in fact a good number of them. However, managing the testing and vaccination process of the total population is a mammoth job. However, there is always delay or data silo problems in multi-organizational works. Therefore, streamlining this process is vital to improve the efficiency and save more lives. Because of its effective data sharing mechanism among different entities with a number of security features, Blockchain can be an effective tool for different applications in the health sector. Furthermore, Blockchain provides a distributed system along with greater privacy, transparency and authenticity. In this article, we have presented a blockchain-based system that seamlessly integrates testing and vaccination system, allowing the system to be transparent. The instant verification of any tamper-proof covid-19 test result is developed which will be served as “Test Certificates”. A transparent and efficient vaccination system has also been exhibited and implemented as the “Digital Vaccine Passport” (DVP) system. The infection rate based prioritization will ensure a transparent and fair vaccination process as well as tackle the distribution issue of the limited amount of vaccine. The comparative review with other existing works is also discussed, highlighting a clear difference with the existing works. Our proposed system is distinctive on the basis of prioritization of vaccines and seamless integration of test certificates and vaccine passports which will aid in controlling the pandemic situation. This system will also be handy in case of tackling any future pandemics initially.

Keywords: Covid-19, Blockchain, Solidity, Digital Vaccine Passport, Vaccination.

1. Introduction

Information technology (IT) is playing a vital role in the fight against covid-19. It helps to evaluate the outbreak of the covid-19 pandemic, coronavirus statistical breakdown, identifying covid-19 through various symptoms and vaccine advancement [1]. It is heavily used for contract tracing around the world. However, these systems are designed and maintained independently. Therefore, they cannot communicate with each other. It is challenging for policymakers to get a consolidated view of transmission, testing, and vaccination. In addition, trust in the testing data and vaccination data was in question, especially in developing countries. For instance, there was a case of test fraud in Bangladesh. Hospitals in Bangladesh named Regent hospital, JKG healthcare, and Shahabuddin hospital were caught scamming people by creating fake covid tests, wrong treatment and a series of other irregularities. These cases raised serious trust issues amongst people both inside and outside the country [2, 3, 4]. Moreover, having a large number of candidates for vaccination while the vaccine supply is limited, might create chaos.

Blockchain is a distributed ledger technology, which can address the limitations of the current mechanism in many applications. For example, it can help to integrate multiple systems and at the same time allows all the parties to interact with the plans without interfering with others. All the parties will maintain the system, and the system will automatically update if there is any activity in the system. However, it will automatically stop any unlawful activity. It provides a transparent view of the data to all the parties, and it helps to build trust. It also prevents any corruption as nobody can manipulate the data. If anybody provides any wrong input purposefully, it can be detected as it is a transparent system. The bad actor can be easily identified and held responsible as they cannot change the record in the system due to the immutability of the blockchain.

Blockchain contributes vastly to the healthcare sector. A blockchain-based medical record system was implemented to help patients keep their logs more securely. A distributed ledger like blockchain helps those data to be kept private and safe. That is why there have been a number of researches where blockchain has been utilized in different capacities, e.g. in recording personal health data where the data privacy, flexibility, and authenticity were ensured [5, 6, 7]. Blockchain has been useful in different aspects of the management of covid-19 pandemic, and thus, a risk notification system and location and bluetooth based contact tracing system had been implemented

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to ensure tamper-free services [8]. Furthermore the Chinese University of Hong Kong has proposed a concept, describing the structure of a blockchain based vaccine passport with health records [9]. Blockchain can also assure the safety, security, transparency and traceability for distributing covid vaccines [10]. Double layer Blockchain has been used for recording vaccine production and information also. Using a timestamp, the information of enterprises and vaccines becomes tamper-proof, and the validity period of the vaccine is measured. In line with these works, this article presents an integrated blockchain-enabled testing and vaccination system. The core distinctive contributions of the articles are as follows:

- Designing a blockchain-based system that can seamlessly integrate testing and vaccination mechanisms.
- Prioritization based vaccination for fair distribution.
- Implementation of a QR-based “Digital Vaccine Passport” (DVP) mechanism which will reduce the corruption in covid testing and vaccination.

This system has been developed and integrated in the Ethereum public (test) network for now. The main actors of the system are holder, issuer, vaccine provider, authority and verifier. Every entity will be registered to the system after the authentication of the authority for eradicating any kind of false registration issue. The Issuer issues “Test Certificates” to the holder after the Covid-19 test which can be used afterwards for verifying a health status by the verifier. The test results are also used by the authority for the prioritization of vaccination in order to avoid any chaos. The prioritization is based on a hypothesis of vaccinating the highly infected areas in a descending order of infection ratio. This vaccination process will strictly follow the priority list. The vaccine provider will issue a “Vaccine Passport” to the holder after the inoculation is being done which can be used as a certificate of covid-19 immunity in the time of verification.

We have discussed the the background knowledge in section 2. System requirements and design are discussed in Section 3 and Section 4 respectively. In section 5, we have discussed about the implementation and methodology. Performance evaluation is presented in Section 6. The comparison of the proposed technology with respect to the state of the art blockchain technology is discussed in Section 7. We have concluded this article by relating the findings and the future research directions in Section 8.

2. Background & Related Work

As mentioned, there are two different aspects of our proposed model: the testing and the vaccination. We will discuss both aspects separately in the next two subsections.

2.1. Covid Testing and Reporting Systems

Several works have been done with immunity passports, covid certifications, covid testings, “Digital Health Passport” (DHP) based on blockchain [11]. All of these terms are the

same, but they have been named differently. Those have been discussed below. Already a prototype app has been developed where users testing reports are generated with better transparency as it is developed under blockchain technology [12]. Benchmarking results have also been shown there. A QR code based verification system has been developed where users’ data are kept hidden. The ICT division of the Government of Bangladesh introduced a centralized app called “SUROKKHA” [13]. Using the app the Bangladesh government is currently running the vaccination process.

DHP is based on the secured distributed network (blockchain) that works as a health passport [14]. DHP can be used for work and traveling to various places and helps regain a country’s economy. It proves that the person is not affected or the person already has immunity from covid-19. DHP is a proactive measure that helps to prevent the virus from spreading more. Works have been done on “Digital Contract Tracing” (DCT) which also carries both benefits and some limitations [15]. A blockchain-based covid-19 vaccination passport, offering the vaccination status of an individual where the user’s identity has been ensured by retina scanning [16]. Masek’s Algorithm has been used for generating greyscale eye images. One’s vaccine status is updated by taking his/her biometric data and the vaccination info. The encrypted version of the bio-metric data is stored in the blockchain platform. Both bio-metric information and blockchain provide higher security and scalability. An immunity testing certification based on blockchain has also been proposed where the user’s data has been registered on a blockchain platform regulated by the government [17]. Hospitals are also included there for testing purposes. User’s bio-metric data have been gathered, which enriches security. Contact tracing has also been implemented by collecting user’s phone number, geolocation and timestamp. An app has also been developed to store user’s testing information on the blockchain platform, which offers trustworthiness. Additionally, Artificial Intelligence (AI) algorithms are used for tracking patient’s location details and self-testing [18].

2.2. Vaccination Prioritization

It is not possible to vaccinate the whole world overnight, even in a month, as vaccine production is limited, a prioritization-based vaccination can ease the way of vaccination to ensure a fair vaccination process. Even in countries like Bangladesh, it is a crying need. To set priorities at first, we should consider the prioritizing criteria.

In the case of a flu outbreak, how to distribute finite vaccination supply is now being debated [19]. Traditional vaccination tactics target individuals most at risk for serious consequences, such as seniors, but they overlook (1) the distinctive pandemic pattern of mortality risk migrating to younger ages, and (2) the projected poorer vaccine effectiveness in elderly, and (3) variations in the number of years left to live as a function of age. George Washington University combined these factors to predict the number of life years lost (YLL) at a specific age and the number of life years saved in a future pandemic based on

the mortality patterns of the three historical pandemics, vaccine efficacy by age and the structure of the US population in 2000. A group of analysts utilized a numerical demonstration to compare five age-stratified prioritization methodologies for inoculation [20].

The role of artificial intelligence (AI) and machine learning (ML) is recognized as a crucial method in the field of screening, predicting, forecasting, contact tracing and drug development for covid-19 pandemic. “Deep Convolutional Neural Network”, “Support Vector Machine”, “Random Forest” and “XG-Boost classifier” were some of the selective assessing methods that were executed on the databases related to the pandemic [21]. As reported by a study of MIT, calls for disposing of prioritization for SARS-CoV-2 immunization are being developed in the midst of concerns that prioritization decreases inoculation speed [22]. They utilized an “SEIR” model to consider the impacts of inoculation dispersion on open well-being, comparing the prioritization approach and speed beneath moderation measures that are either facilitated amid the antibody roll-out or maintained through the conclusion of the widespread period. Another model called “SIDARTHE” was combined for estimating the spread of Covid-19 along with a data-based model which demonstrates the new cases of fatality rate and the cost of a healthcare system based on studying the Italian case [23]. Another research proposed “Hierarchical Priority Classification eXtreme Gradient Boosting” algorithm with a view to priority categorization for covid-19 vaccine administration using an Italian dataset, containing Electronic Health Record data of 17k patients and evaluated its effectiveness [24].

According to the US National Academy of Medicine (NAM) three groups have been emphasized to be vaccinated [25]. At first, the front line covid-19 health workers like Doctors, Nurses, and so on. Secondly, the people working in the sectors like education with in-person attendance, food supply, child-care, etc., are at high risk for covid-19. Finally, the third category is those people who are already sick from severe health conditions. Prioritizing the third category has been recommended by both UN and NAM. The University of California has evaluated the ideal allotment of a limited immunization supply within the United States over bunches separated by age and essential worker status, which compels openings for social separation [26]. In any case, based on the objective, more youthful essential workers are prioritized to control spread or seniors to straightforwardly control mortality. The prioritization is also done based on the age and the occupation where there exists a high infection rate [27]. However, age was emphasized more than occupation. For occupation, the people whose presence in work contributes higher in GDP received higher priority.

A Symptom prediction model based on AI has been used to classify symptoms under 12 classes [28]. Those classes have been set by analyzing health data of 74 hospitals in Tehran, Iran. Among KNN, ANN, LDN, Random Forest, and Naive Bayes, Random forest achieved a good ROC and AUC weighted mean. However the vaccine prioritization about which vaccination program should be continued parallelly along with covid-19 vaccination, is a prime concern [29]. The analysis of pediatric vaccination programs in the USA during the covid-19 pandemic

shows the decrease of ordering the pediatric vaccines. This will make the children severely vulnerable towards covid-19.

In our approach, we have developed an algorithm for setting up the priorities. For this, the algorithm, at first, identifies the areas with a higher positive ratio according to the test result, as such areas can be considered as high risk areas. After testing every user of our system, the algorithm can easily set the priorities based on the high risk areas. Interestingly, all these activities can be carried out seamlessly: by pressing a single button, the system can calculate the ratio and sort the list in descending order according to the ratio. Then, the vaccination can start according to that ratio. The system will not allow the inoculator to vaccinate people from less risk (i.e., less priority) areas at first. If he does so, he will get caught because there will be a miss-match between the vaccine storage data in our system and the available vaccines in the storage. Because of using blockchain here, systems data alteration is not possible. As the most vaccines have multiple doses, we have developed the system to allow a low risk area to be vaccinated only when the first dose is completed in a high risk area.

2.3. Blockchain

Blockchain is a decentralized system and very useful for accountability and transparency. It is a tamper-proof digital ledger technology used to find the solution to real-life issues [30]. Since its invention, blockchain has been utilized in many fields as a smart contract and transaction system. Blockchain allows monetary functions to be performed in a distributed way through some cryptocurrencies such as Bitcoin, Ethereum, Litecoin, Monero and Zerocash [31]. Blockchain has brought the concept of decentralization where there will not be any central authority to take control over a system. While transactions happen these transaction records are received by the nodes of the network. Those will not be added to the network as a block until the acceptance of existing nodes of the network which is called verification. For adding a block in the network, a consensus needs to be achieved among the validators.

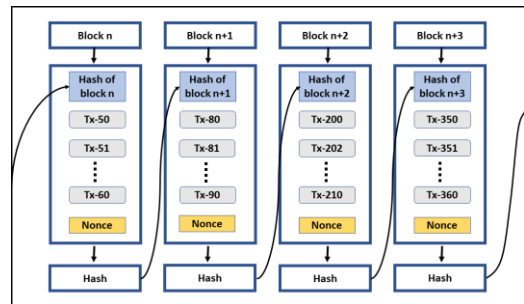


Figure 1: Structure of a blockchain

In Bitcoin, a novel consensus algorithm called *Proof of Work* (*PoW*) has been introduced [32]. In this algorithm, the validators are called miners who are responsible for creating a valid block of transactions according to predetermined prerequisites. The block contains the hash of the previous block which has already been added to the chain and verified by the nodes (Figure

1). POW implicitly defines the capability needed for a miner to add a block in the chain. Miners compete with each other to find a 32 bit number known as nonce. For example, to add a block miners need to find a 32 bit number in which there will be a certain number of zero as the first numbers which change according to the network configuration. However, one can not make that number by force. To solve this miners have to use lots of computational power to find the number at first. Among all, the first miner who solves the puzzle and broadcasts the block in the network gets rewards for their computational efforts. By that time the others who have been trying to solve that puzzle, cancel their mining process and take the hash of that block and try to solve the next block. After competing with this much of computational efforts it is assured that the miners did not cheat.

3. System Requirements

Many organizations these days ask their employees to show covid-19 test certificates to get back into the office. Furthermore, many countries have restricted their borders from foreigners unless they produce the evidence that they are vaccinated. Besides, the whole vaccination process might create chaos since there are many candidates but not enough vaccines to inoculate. On top of that we have seen many cases of fraud covid-19 tests and unauthentic certification, which causes trust issues. Therefore, we need a proper and efficient system to bring back the trust in authority.

Considering the above mentioned issues, the proposed blockchain-based system needs to meet the requirements stated below:

1. **Fairness and Transparency:** The vaccine distribution should be prioritized based on disease severity within the areas. The area at the top of the red zone list (where the ratio of positive and test cases is higher) must be inoculated first. The candidates who are tested covid-19 negative will get the higher priority. In this way, the vaccination process can be done without any chaos with transparency and fairness. To achieve that the system should store all the data and can automatically prioritize the area and the cohort.
2. **Battle Corruption:** In a traditional IT (Information Technology) system, it is always possible to alter the original data if the authority wants. Since it is centralized, the authority has the power over the system. Therefore, we need a decentralized or distributed system which cannot be changed or manipulated by one single authority.
3. **Seamless Integration:** In multi-organizational systems, it always causes delays or data silos decreasing the network's throughput, but in our blockchain-based proposed model, both testing and vaccination system and the prioritization for vaccination are seamlessly integrated for transparency and user flexibility.
4. **Cyber Attack Resilient:** The system should be designed in a way that it can withstand any cybersecurity attack.

3.1. Process in the System

Figure 2 gives a visual representation of our model. We have implemented a web-based blockchain application where all the operations are performed.

4. System Design

In this research, our main concern is presenting a covid-19 testing certificate and prioritization-based safe vaccination system followed by a vaccination passport for Bangladesh that has not been implemented yet. In our proposed system, there are five entities: "Holder", "Issuer", "Vaccine Provider", "Verifier", and "Authority/Government". The activities of each entity are as discussed next.

Authority/Government: The authority will be the person or organization who governs the whole system. It has to bear the initial deployment cost of the project. The verified registration of each entity except the verifier will be ensured under the governance of the authority. It will accept or reject their sign up requests based on the NID (National Identity) of the holder and license number of the issuer and vaccine provider(s). These two will be checked using the government's central database. Also, it will report to the system about new batches of vaccines as soon as it is received providing every detail of it. Since the whole system aims to facilitate the holders or citizens of the country and ensure that no one's fundamental rights are violated, proper distribution of vaccines should be established. There is no alternative to prioritize the candidates for vaccination. The authority will be playing this vital role of prioritization by pressing a single button.

Issuer: Issuers are the designated persons who issue test results of covid-19. After the covid-19 tests, test results will be provided to the holders by issuers in the form of QR (Quick Response) code which will serve as test certificates.

Vaccine Provider: Vaccine providers are the hospitals who have the vaccine for mass inoculation. The priority list is strictly maintained under the system while the inoculation process is ongoing, so there will be no scope for venality. After the vaccination of each holder, the vaccine provider will provide them a "Digital Vaccine Passport" (DVP) in the form of a QR code.

Holder: Holders are the general people who will be inoculated. After the test and vaccination, each citizen will receive two QR codes, the test certificate and the digital vaccine passport, which will serve them as a gateway license to the restricted areas due to the pandemic. A holder can also control his/her profile privacy settings and see the information about the priority list and vaccine storage for gaining the trust.

Verifier: Verifiers are not required to register into the system, since they do not have any direct activities in the system. Offices, organizations, educational institutions, airports authority, etc. can play the role of verifiers to check a person's eligibility for accessing the restricted areas due to pandemic. For doing so a verifier can simply scan the QR codes of the holder's test certificate and digital vaccine passport and will confirm the necessary information about that holder. Since the entire process

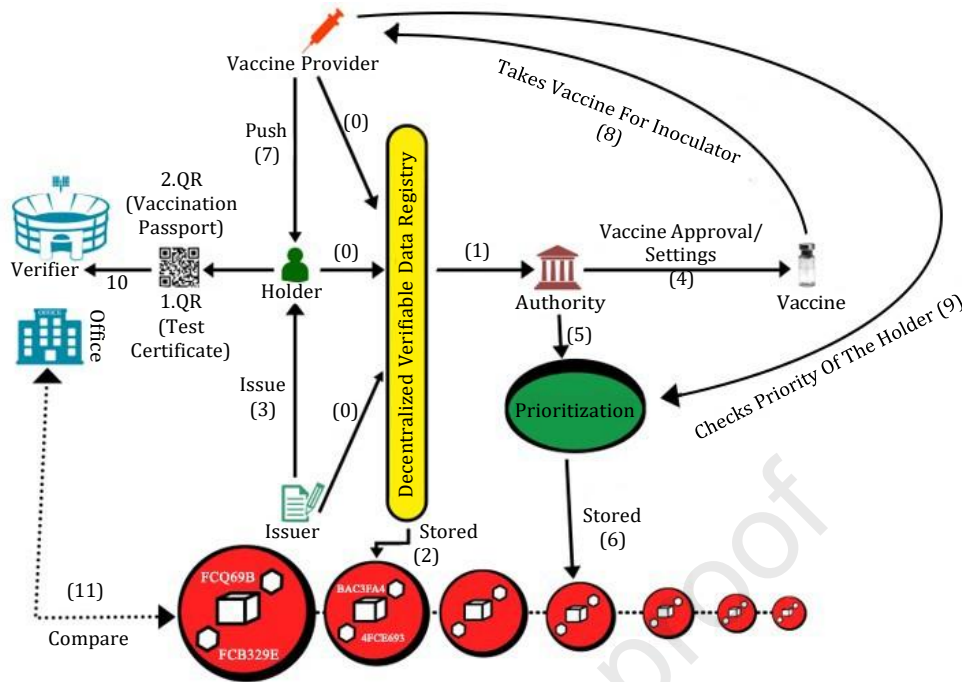


Figure 2: Workflow and use-case of covid-19 test certification and vaccination model.

is maintained under a blockchain network, it can achieve high transparency and fairness.

The steps within the workflow of the system (Figure 2) are discussed next.

- **Prerequisite/ “On-boarding” step:** The on-boarding is a three-step process as discussed next:

Step-0: Every vaccine provider, issuer and holder have to make a request to sign up to the system as per their specific roles. It is a two-step process.

Step-1: For identity authentication, their roles and professions are then verified by the governmental authority. Their sign up requests will be approved or rejected on the basis of the authentication of their provided data. Providing false information may cause permanent banning if detected.

Step-2: Each user can access the system if and only if their sign up request is accepted and has an entry to the blockchain.

- **Issuing Covid Test Results:** The end-users will provide their information like name, age, location and photo to register themselves for testing. Then they will apply for testing. The authorized issuers will provide the test result. In **Step-3**, the test result along with the issuer’s ID will be generated as a QR code. This QR code can be used as a **Test Certificate (QR1)**.
- **Vaccine Approval/Settings:** The authority has access to store the vaccines data and update the vaccines storage only by positive margin if new batches are imported. This is regarded as **Step-4**.

- **Prioritization:** As the vaccine production and distribution towards several countries are limited in quantity, a monitored and authentic way is a crying need. At first, we have generated a location-wise ratio of positive cases among total tested cases. The higher rate locations are then selected as a high priority area as the affected cases and spreading probability are higher there. We know that vaccines are essential for those who do not have any immunity against the virus. Therefore, in **Step-5**, the negatively tested people are prioritized to mitigate the spreading of this deadly virus. The list of the holders after prioritization is stored in blockchain for a fair and transparent vaccination. This list will be checked at the time of each and every inoculation (**Step-6**).

- **Inoculation:** The inoculation is a three-step process as discussed next:

Step-7: The vaccine provider is allowed for facilitating the inoculation process and providing the vaccine passport.

Step-8: Vaccine providers request the authority for vaccines to continue the inoculation process.

Step-9: Vaccine providers will ask the holder for showing his/her test certificate and check whether the holder is eligible or not for the current inoculation wave according to the priority list.

After inoculation, the holder’s vaccination information along with the vaccine provider’s ID will be generated as a QR code. This QR code can be used as a **Vaccination Passport (QR2)**. By doing these, the proper and efficient way of vaccination of those limited vaccines will be ensured.

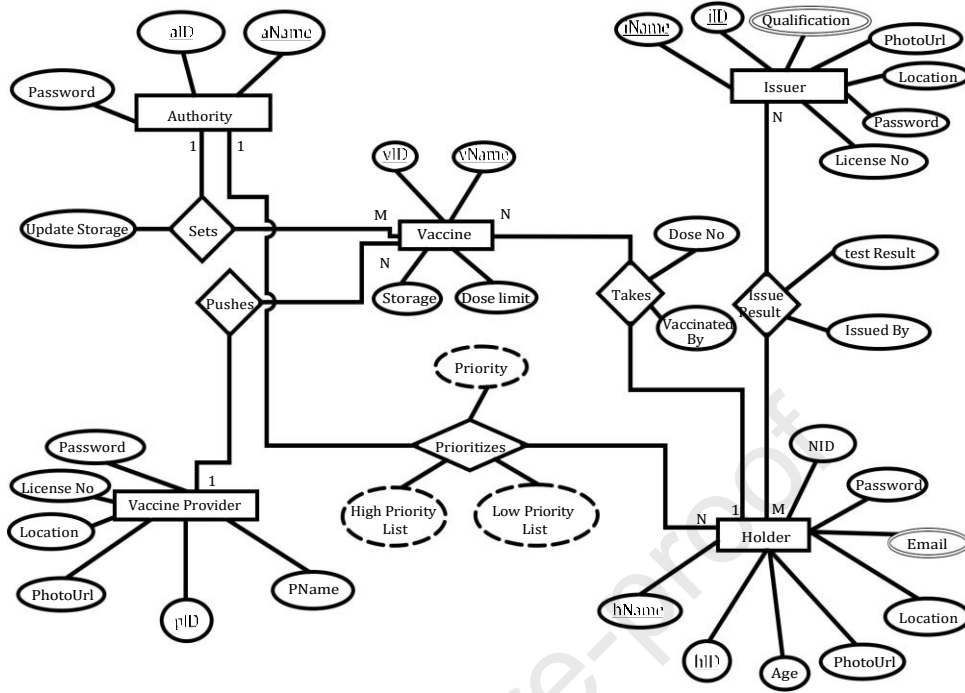


Figure 3: ER Diagram.

- **Verification:** The verifier can be any organization where it is necessary to ensure public safety. By this, a tamper-proof authentic result will be generated as these all are happening in the blockchain platform.

Step-10: Verifiers can extract the **QR1** code to verify whether any individual is tested positive or negative (**Test Certificate**) and to verify whether any individual has taken a vaccine, the **Vaccination Passport** or **QR2** code will be extracted.

Step-11: The information underneath the both QR codes are compared to the blockchain hashes for checking its validity as shown in Figure 2.

4.1. Data Storage and Management

Figure 3 is the entity-relationship (ER) diagram of the proposed model, which represents the attributes that are stored for each entity (authority, issuer, vaccine provider, holder, vaccine) in their respective database. The hash of each entity's name, id, and the hash of the priority list is stored in the blockchain since they are the primary key of the traditional database and must be securely stored ensuring their integrity.

5. Implementation

In this section, we present the detailed implementation¹ of the proposed system. The system was implemented on top of

¹Source Code: <https://github.com/Salekin-Nabil/VaccineChain>

Ethereum blockchain. The code was written in Solidity programming language on the Remix IDE, which is also used to compile and evaluate smart contracts. We have built three smart contracts so far; namely *dhp* (Digital Health Passport), *vaccination* and *locationInfo*. Figure 4 represents the class diagram of our project. The attributes of each structure are as shown in this figure and the methods are explained below.

The *dhp* smart contract and *vaccination* smart contract can be associated with each other and both can be associated with the *locationInfo* smart contract, but the *locationInfo* smart contract is fully independent. Firstly, the *dhp* smart contract is used for the **covid-19 test certificate**. It includes the information about the issuer and the holder. Secondly, the *vaccination* smart contract is used for the **vaccination passport** or a certification of vaccination which includes 3 structures namely: vaccine, authority and vaccine provider. Finally, the *locationInfo* smart contract is used to store the location information to prioritize them according to the rate of covid-19 positive cases and utilize them as per needed (i.e. calculating total number of tests, total covid-19 positive cases, total vaccine receiving candidates in an area). The system has been deployed on Ethereum Rinkeby test network [33].

5.1. Methodology

The following parts go into the specifics of each smart contract.

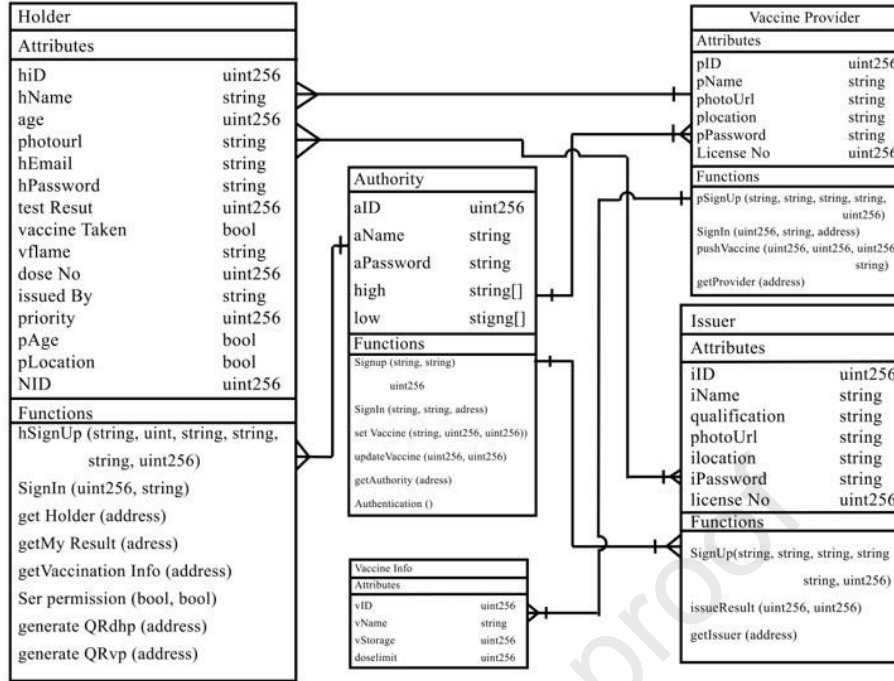


Figure 4: Class Diagram of the Proposed Blockchain-based System

5.1.1. dhp: SignUp (all interfaces in general)

During the sign up process, an individual wallet owner can sign up for different roles (i.e. Authority, Issuer, Vaccine Provider, Holder) (Figure 5).

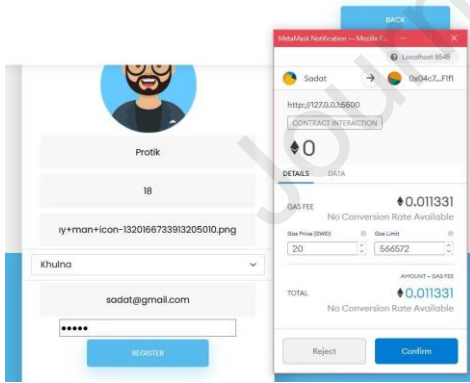


Figure 5: Sign Up.

To verify a wallet, there are four checkers are used with a view to identifying whether that wallet belongs to a role or not. It will also check whether the wallet is already registered for that specific role or not. After the initial checkers are satisfied, users can move forward to the main registration process by providing the necessary details. This function will then send an event to all of the involved entities, informing them of the change and the time. When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so that their records are modified appropriately. In future, we can also include captcha to improve the security of the login [34].

5.1.2. dhp: SignIn

During sign in, a new hash is generated combining the wallet address of the owner, the system ID (SID) of the user and password for verification. To verify the new hash, it is matched with all other combined hashes that already exist in the system regarding the specification of the user. A flag is used to determine whether the wallet is valid or not and redirected to the desired role's menu as per Algorithm 1.

Algorithm 1: dhp: SignIn

```

Initialisation of SID, Password, Address. (Address holds
the Ethereum Address of the function caller);
Flag = "None";
if new hash == existing Issuer hash then
| Flag = "issuer";
else if new hash == existing Holder hash then
| Flag = "holder";
else if new hash == existing Authority hash then
| Flag = "authority";
else if new hash == existing Vaccine Provider hash then
| Flag = "vaccine provider";
else
| Show an error or failed to Sign In.;
end if

```

5.1.3. dhp: Issue Result (Issuer)

In case of issuing a test result the test will be done by the issuer first and then it has to be issued to the system Figure 6. In this algorithm, the owner of the issuer wallet is the only authorized entity that can issue test results to a holder. To verify that

a wallet belongs to a verified issuer, the address of the function caller would be checked to increase the security level. After the initial checkers are satisfied, the issuer can move forward to the insertion of the test result by providing the necessary details (holder ID, test result). This function will then send an event to all of the involved entities, informing them of the change and the time.

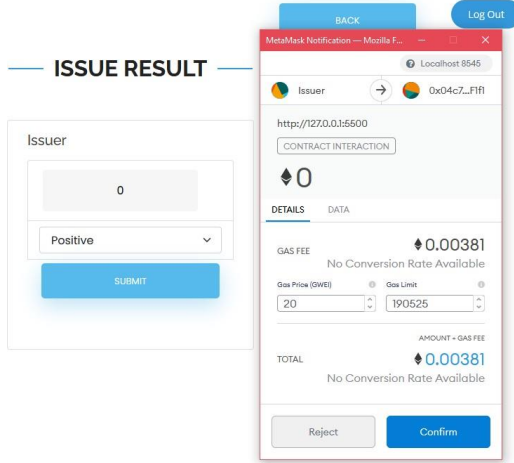


Figure 6: Test Result Issue.

When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so that their records are modified appropriately.

5.1.4. Vaccination: Add Vaccine and Update Vaccine (Authority)

The user interface of adding vaccines to the approved list is shown in Figure 7. In this algorithm, the owner of the authority wallet is the only authorized entity that can add new vaccines to the system. To verify that a wallet belongs to a verified authority the address of the function caller would be checked to increase the security level. After the initial checkers are satisfied, the authority can move forward to the insertion of the vaccines by providing the necessary details (**vaccine name, storage, dose limit**).

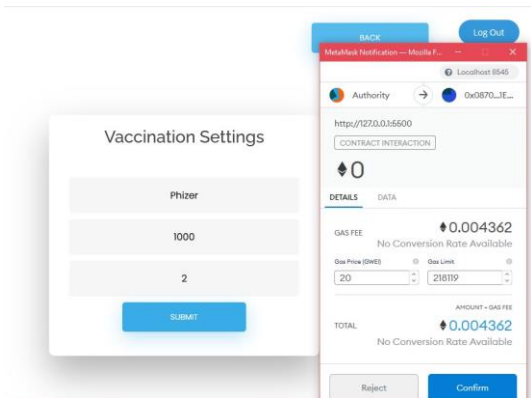


Figure 7: Add/Update vaccine.

This function will then send an event to all of the involved entities, informing them of the change and the time. When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so that their records are modified appropriately.

5.1.5. Vaccination: Prioritization (Authority)

Prioritization can be done using Algorithm 2. In this algorithm, the owner of the authority wallet is the only authorized entity that can prioritize the holders for vaccination according to their location and test results (the negative holders of covid-19 who belong to the red zone area on the basis of positive case ratio per total number of tests). To verify that a wallet belongs to a verified authority, the address of the function caller would be checked to increase the security level. After the initial checks, the authority can move forward to make a priority list of all the holders existing at that moment who have tested themselves with just a single click and everything else would be executed in the backend.

Algorithm 2: vaccination: Prioritization - TX

Initialization of caller address.;

Authority Checker();

$j=8, k=0;$

while $j < 16$ **do**

if $Totaltest > 1$ **then**

while traversing the entire holder's length **do**

if the holder has Positive result after testing Covid-19 & &

 holder location == running location **then**

 Set the holder's name to the low priority list;

 Increase the number that belongs to the running (j) priority;

 Holder Priority = j;

else if the holder has Negative result after testing Covid-19

 & & holder location == running location **then**

 Set the holder's name to the high priority list;

 Increase the number that belongs to the running (k)

 priority;

 Holder Priority = k;

end if

$j++;$

$k++;$

end while

end if

end while

Since we are prioritizing the citizens of the eight divisions of Bangladesh and each division has two categories of holders (positive/negative), there are (8×2) 16 levels of priority to prioritize the holders. The covid-19 negative holders who belong to the division which is at the top of the red zone list will be at the top priority for vaccination and they will be marked as the first level priority which indicates they should be vaccinated during the first wave of vaccination. Similarly the rest of the covid-19 negative holders will be marked by a level of priority from 2 to 8 according to the position of their division at the red zone list. The covid-19 positive holders will be marked by the levels of priority from 9 to 16 following the same pattern of the red zone list. This function will then send an event to all of the involved entities, informing them of the change and the time. When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so

that their records are modified appropriately.

5.1.6. Vaccination: Authentication and Approval of Issuer, Vaccine Provider and Holder Registration (Authority)

Users can be added to the approved list of the respective role such as an issuer, vaccine provider and holder registration using the following method. In this method, the owner of the authority wallet is the only authorized entity that can approve a user to enroll themselves to the system. To verify that a wallet belongs to a verified authority, the address of the function caller would be checked internally to increase the security level. After the initial checkers are satisfied, the authority can move forward to the authentication process with the help of the given details provided by the users while registering (**for vaccine providers and issuers - license number, for holders - NID**). This function will then send an event to all of the involved entities, informing them of the change and the time. When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so that their records are modified appropriately.

5.1.7. Vaccination: Inoculation/Push Vaccine (Vaccine Provider)

The First Dose: The inoculation process can be started in an unbiased way using Algorithm 3. In this algorithm, the owner of the vaccine provider wallet is the only authorized entity that can push vaccines to the holders. To verify that a wallet belongs to a verified authority, the address of the function caller would be checked to increase the security level. After the initial checkers are satisfied, the vaccine provider can move forward to the inoculation process. Lower priority holders cannot be inoculated while higher priority holders are yet to be inoculated. Due to the long time interval between each dose, lower priority holders can be inoculated after all the higher priority holders have finished taking their first doses. This function will then send an event to all of the involved entities, informing them of the change. When interacting with the relevant entities, the blockchain client (BC) and gateway can use this event as part of its filtered events so that their records are modified appropriately.

The Second Dose and Holder Elimination From The Priority List: The inoculation process can be successfully completed in an unbiased way using Algorithm 4. After completing the final dose the holder account will be removed from the vaccination priority list.

5.1.8. dhp: Profile Permission (Holder)

A holder can set the permission of his profile to indicate what to show and what not, the user interface of it is shown in Figure 8. The owner of the Holder wallet is the only authorized entity that can change his/her profile permission. Following the initial check (e.g. checking the address of the function caller), the Holder can move forward to the permission setting process. This function will then send an event to all of the involved entities as discussed above.

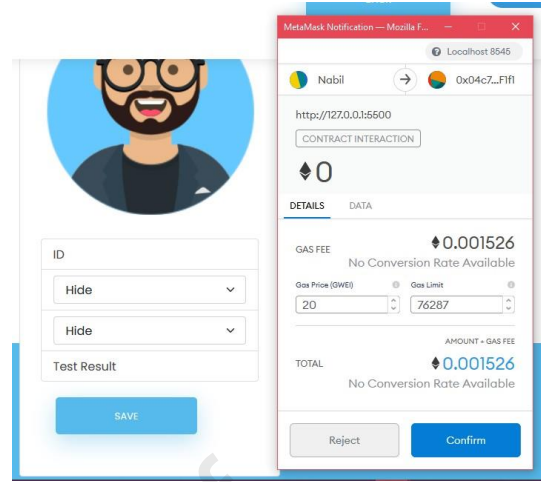


Figure 8: Permission Settings.

5.1.9. dhp: Test Certificate (Holder)

A holder can generate a QR code which has the information of his/her covid-19 test result (Figure 9).

Algorithm 3: vaccination: Inoculation/Push Vaccine - TX

```

Input: Authority ID, Vaccine ID, Holder ID, Vaccine Name;
Vaccine Provider Checker();
j=0, k=0;
while j < 8 do
  if HighPriorityNo[j] != 0 then
    [HighPriorityNo[j] - The number of holders in j-th priority who have
    not taken the first dose]
    break;
  end if
  j++;
end while
if j < 8 then
  if Holder belongs to the running priority then
    Push Vaccine; Vaccine Storage -=1;
    Dose Number (Holder) +=1;
    HighPriorityNo[j] -=1;
  end if
end if
else if j ≥ 8 then
  while j < 16 do
    if LowPriorityNo[k] != 0 then
      break;
    end if
    j++; k++;
  end while
  if j < 16 then
    if Holder belongs to the running priority then
      Push Vaccine; Vaccine Storage -=1;
      Dose Number (Holder) +=1;
      LowPriorityNo[j] -=1;
    end if
  end if
end if

```

The owner of the Holder wallet is the only authorized entity that generates his/her test certificate. Following the initial check (e.g. checking the address of the function caller), it generates a QR code containing necessary information (**holder's name, age, photo, location, test result, the name of the issuer**) about the covid-19 test. Since it is just a query, it will not cost any ether.

Algorithm 4: vaccination: Inoculation/Push Vaccine - TX

```

Input: Authority ID, Vaccine ID, Holder ID, Vaccine NameContinued from
algorithm 3...;
else if  $j \geq 16$  then
   $k=0$ ;
  while  $k < 8$  do
    if  $HighPriorityComp[k] \neq 0$  then
      [ $HighPriorityComp[k]$  - The number of holders in k-th priority
      who haven't completed the dose]
      break;
    end if
     $k++$ ;
  end while
  if  $k < 8$  then
    if Holder belongs to the running priority then
      Push Vaccine;
      Vaccine Storage  $--1$ ;
      Dose Number (Holder)  $+=1$ ;
       $HighPriorityComp[k] --1$ ;
      if  $Dose\ Number == Dose\ Limit$  then
        | Eliminate the Holder's name from the vaccination list;
      end if
    end if
  end if
else if  $k \geq 8$  then
   $j=0$ ;
  while  $k < 16$  do
    if  $LowPriorityComp[j] \neq 0$  then
      [ $LowPriorityComp[j]$  - The number of holders in j-th
      priority who haven't completed the dose]
      break;
    end if
     $j++$ ;
     $k++$ ;
  end while
  if  $k < 16$  then
    if Holder belongs to the running priority Push Vaccine;
    Vaccine Storage  $--1$ ;
    Dose Number (Holder)  $+=1$ ;
     $LowPriorityComp[k] --1$ ;
    if  $Dose\ Number == Dose\ Limit$  then
      | Eliminate the Holder's name from the vaccination list;
    end if
  end if
end if
end if

```

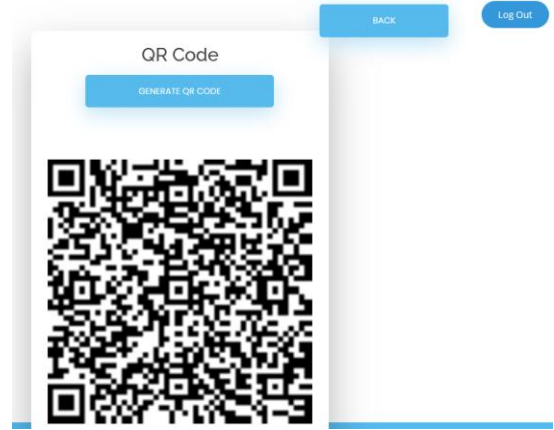


Figure 9: QR code of Test Certificate.

This cost is charged only once while the system is being initialized for the first time. More than half of the total cost estimation is consumed by it. Moreover, setting a priority list also consumes the one-fourth portion of the total gas cost which is also executed only once during the prioritization process. The rest of the methods which are frequently executed require comparatively less ether. Since the gas cost is relatively low, it indicates the lower complexity of code which refers to high-performance stability.

The bar chart provides a clearer view of the estimated gas cost (Figure 11). The x-axis represents the method names and y-axis represents their corresponding gas cost in ether. At a glance, it is evident that contract deployments consume the highest gas price compared to others. It is to be noted that if we utilize a Ethereum consortium blockchain, it can eradicate all the existing gas cost complexities. This is because in a consortium blockchain we can restrict the gas price or it can be completely removed, therefore, it is not an issue to worry about.

Cost Analysis: The deployment and transaction cost of all interfaces have been presented below in Table 1.

Table 1: Gas Cost in USD on March 6, 2021

Category	Gas Cost	Doller
Contract Deploy(3)	0.210641	314.89
Set Priority(300 people)	0.127718	190.93
Authority Sign Up	0.00429	6.41
System Initialization	0.0209	31.24
Update Storage	0.001269	1.90
Set Vaccine	0.004362	6.52
Issuer Sign Up	0.008051	12.28
Issue Result	0.002292	3.50
Push Vaccine (2 Dose)	0.010489	16.00
Vaccine Provider Sign Up	0.007475	11.40
Holder Sign Up	0.011652	17.78
Holder Permission	0.00147	2.24

Due to the fluctuation of ether cost the overall transaction cost might become a matter of concern. This is because the

5.1.10. *dhp*: Vaccination Passport (Holder)

A holder can generate a QR code which has the information of his/her covid-19 vaccination, similar to Figure 9. Like the previous activities, the owner of the Holder wallet is the only authorized entity that generates his/her vaccination passport. That is, following the initial check (e.g. checking the address of the function caller), it generates a QR code containing necessary information (**holder's name, vaccine taken, vaccine name, dose number, priority**) about the covid-19 Vaccination. Since it is just a query, it will not cost any ether.

6. Performance Evolution

In this section, we present the performance evaluation of the developed system with respect to gas cost incurred for different operations in the system.

The pie chart depicts the estimated gas cost for each operation (Figure 10). As we have three smart contracts which containing all the methods, it costs 0.210641 ether while deploying.

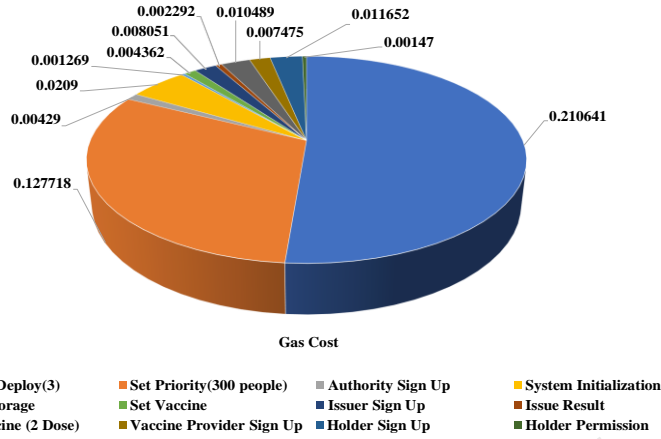


Figure 10: Gas Cost Analysis (Pie Chart).

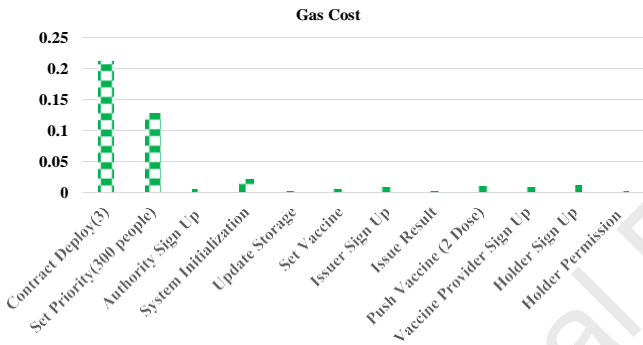


Figure 11: Gas Cost Analysis (Bar Chart).

price of the public crypto-currencies like bitcoin and ether are unpredictable. However this issue can be easily tackled by introducing a private blockchain system where the mining cost can be reduced or removed. The Hyperledger Fabric [35] will be a good alternative solution for that.

7. Discussion

Our proposed system has successfully achieved the requirements as stated earlier. Here we discuss the four distinguishing factors of our system to analyze how the requirements have been satisfied.

1. **Seamless Integration:** This system can successfully integrate both test certificates and vaccine passports, along with the prioritization for vaccination according to the mentioned criteria. It will reduce the complexity and the possibility of chaos.
2. **Fairness and Transparency:** A certain criteria is being followed to reach a hypothetical solution towards the prioritization process for vaccination. The covid-19 negative candidates of the highly infected areas will receive the top priority when the vaccination process starts. The whole system is transparent with a view to ensuring the fairness.

3. **Tackling Corruption:** Since it is a decentralized and open system, it is fully transparent and there is no scope of any monopoly.
4. **Cyber Attack Resilient:** It is immune from the cyber attacks as the platform is developed under Ethereum environment which is considered a robust system because of its secure and distributed consensus algorithm.

The difference between our system and some state of art blockchain system has been discussed in below in a tabular form in table 2.

8. Conclusion

It has been almost two years that the world is suffering with the invisible enemy sars-cov2 (covid-19). It is difficult to fight or create antibodies against viruses. In the past we have seen that the vaccines against viruses like influenza, Ebola and so on took several years to achieve a suitable vaccine. Fortunately, due to the massive advancement in technology we have now lots of approved vaccines within just one year. However, due to production limitations, it is impossible to cover all people under vaccination within a very short period of time. So the possibility of chaos in vaccination raises. Countries like Bangladesh with huge populations need an authentic prioritization based system, where proper vaccination will be assured without any chaos. Recently, we have seen lots of scams recently related to false covid test certificates. Our implemented system handles all these criteria in a combined fashion. Also, an authentic test report certification has been implemented to ensure biased and counterfeit certificates cannot be produced without being noted by the authority. Recently, we have seen lots of scams related to false covid test certificates. Our blockchain-enabled deployed system mitigates the tampering possibilities and creates transparency. We have shown the cost efficiency of our system and analyzed how our system will provide all these services conveniently. Prioritization offers the most unique but significant feature which will ensure an optimized vaccination process. With

Table 2: Comparison among the COVID-19 certificate approaches

Approach	No Third Party	Prioritization	Benchmarked	Seamless Integration of TC and VC	Implementation Details	Objective
Vaccify [36]	●	○	○	○	●	Vaccination Passporting
Hygiea [37]	○	○	○	○	●	Issue and Verify Covid Certificates
QDX HealthID [38] Immunization Passports	●	○	○	●	○	Testing and Immunization Passport
Covi-Pass [39]	●	○	○	○	○	Digital Health Certificate
SecureABC [40]	○	○	●	○	●	Immunity Passport
DigiLocker [41]	●	○	○	○	○	Vaccine Certificate (VC)
VaccineGaurd [42] [43]	●	○	○	○	○	Aid Vaccine Distribution
CATCApp [44]	○	○	●	○	●	Test Certificate
VitalPass [45]	●	○	●	○	●	Aid Vaccination and Upgrading Vaccine Passport
Digital Health Pass [46]	●	○	●	○	●	Standardization of Vaccine Passport
NovidChain [47]	●	○	●	○	●	Self Sovereign Identity and Ensuring W3C Verifiable Credentials Standard
Our System	●	●	●	●	●	Seamless Integration of Covid-19 Testing, Management and Distribution

all these features, we believe that our system can be an effective tool to fight against covid-19.

The proposed system offers a wide range of features which can ease the way of overall vaccination process which will mitigate any kind of perfidy. However still there are some issues that could be solved in a future work.

- If public blockchain is used (e.g., Ethereum), the transaction cost can be a cause of concern. This can be solved by shifting the network to a private setting where the miners will be under control and thus the incentive also. By introducing private blockchain i.e. “Hyperledger Fabric” the cost efficiency can be increased.
- We are now calculating the higher positive ratio of a specific location to prioritize. But during the vaccination process the negative tested people of those area with higher ratio, a profession or health quota wise prioritization could make the vaccination process more acceptable and fair.
- A hybrid machine learning algorithm did well for suggesting an individual about which vaccine should be taken according to his/her health condition. [48]. It can be integrated to our proposed system for further improvement.
- Currently, we have a web interface to deal with the overall process. But a mobile app can ensure to reach more people as smart phone is available in every one’s hand.

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Dear Professor,

On behalf of all the authors, I declare that we do not have any conflict of interest.

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Yours sincerely,

Dr. MJM Chowdhury (on behalf of all authors)

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