Vaccinet: Immunization and Public Health using Blockchain*

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Abstract

Each year, millions of deaths could be prevented solely by vaccinating a greater number of people in developing countries. We identified three main obstacles to overcome in order to solve the problem. There are not enough funds to pay for medicine, a lack of trust in the system due to corruption and a missing incentive to make it lucrative for people to get vaccinated despite not being able to work in the meantime and missing out on much needed income. We attempted to solve these problems by introducing a Health-Token to be given to each person upon being vaccinated. On a distributed ledger, every vaccination can be tracked ensuring trust in the system and (hopefully) fueling donations. The token on the other hand can be used by the people to compensate for their missed income. Lastly, we identified several challenges to this system which are further discussed in the paper. Nonetheless, we think it is a concept worth exploring since such a system could have far reaching impact in averting deaths due to lack of immunization from preventable diseases.

1 Problem Overview

Around 10% of infants worldwide (12.9 million) did not receive basic vaccinations [1] in 2016. Further, around 6.6 million infants who had received the first of the three doses of vaccines against diphtheria-tetanus-pertussis [2] did not complete the vaccination series, exposing them to serious and potentially fatal diseases. The situation is especially dire in parts of Sub-Saharan Africa and countries affected by wars. In 2016, DTP-coverage of 1-year-olds was at around 45-70% in most Sub-Saharan-countries [2]. In Syria and Ukraine coverage rates have fallen to 42% and

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Disease	**Number of vaccine-preventable disease cases per year**
Hepatitis B	900'000
Measles	888'000
Haemophilus influenzae B	400'000
Pertussis	346'000
Neonatal Tetanus	215'000
Tetanus	195'000
Yellow Fever	30'000
Diphteria	5'000
Poliomyelitis	720
Total	**2'979'720**

Table 1: Estimated impact of improved vaccine accessibility (Source: WHO [3]).

19% respectively. At the same time, it is widely agreed upon that vaccinations provide one of the most cost-effective health interventions and thus offer one of the easiest ways to improve public health in developing countries [4]. The WHO estimates that currently around 2-3 million deaths were averted by timely vaccinations and 1.5 million more lives could be saved by further spreading immunization [1].

A report by the WHO indicates that immunization is in some areas inhibited by logistic rather than economic reasons [5]. National stock-outs of vaccines in developing countries are caused mainly by inaccurate forecasts, funding delays and shortages in supply of vaccines. The forecasts on demand for vaccines often depend upon scarce and unreliable data related to immunization coverage. This lack of transparency naturally results in a lack of trust in the current immunization system possibly holding back a part of the much needed investments from not only public-institutions, but also from local communities and private funding entities.

In many developing countries over eighty percent of the population have encountered corruption in the health care sector [6], resulting in vaccines not reaching those in need. According to [7], countries with high incidences of corruption also exhibit higher infant mortality rates, even after adjusting for income, female education, health expenditure, and urbanization. Displaced, mobile and neglected populations are primarily affected by these logistic issues.

Another problem faced by individuals is a lack of incentive in getting one's vaccines in time, even if it is subsidized or free. People living in remote areas and/or people who are poor may have to sacrifice half a day of work which would further reduce their income; such people may lack the incentives to undertake any necessary effort to obtain vaccinations. As can be expected, most of such people make their living from farming related activities, where every missed hour of work means less money to feed themselves and their family.

Thus the problem we would like to address is twofold: Increase transparency at centers where vaccines are administered, and provide an incentive for people, especially of a lower socio-economic class, to take their vaccines. This problem is especially prevalent in developing countries, where corruption is further facilitated by shortage of staff in health related sectors: when there is a shortage in staff, it leads to staff being overworked, which in turn tends to staff cutting corners in tedious yet crucial verification processes, for example [8].

The rest of the paper is organized as follows: the next section describes our solution with a simple model to trace the vaccination process using a distributed ledger. Section 3 lays out an extended subsidiary model whereas Section 4 presents an overview of the code implementation in Solidity and Web3. Section 5 provides an outlook and discusses some of the challenges and extensions.

2 Proposed Solution

We propose to set up a system using a Distributed Ledger that allows us to track the vaccination process and add transparency to the existing immunization framework; and to create incentive for people to take their vaccines. This way, we can ensure the arrival of vaccines and confirm that donations satisfied their purpose.

2.1 Model Overview

Facing a problem of global scale, our first goal was to identify the involved parties and their relation to each other with respect to spreading immunization. To simplify, we reduced the involved parties to three entities. We started by defining our target group: people with limited access to or interest in receiving vaccinations. Next we considered institutions interested in spreading and funding immunization, such as pharmaceutical companies, health insurance providers, central governments, charities and private donors. We refer to them collectively as the "donor pool". The financial assets in the donor pool are supervised by a trusted entity, for example the WHO. The third party are hospitals, which represent any type of vaccination center.

We assume that donor pool funds can be used to purchase necessary vaccinations and that the state can distribute them to respective hospitals. We further introduce a method to ascertain that a vaccination has taken place using a Token we call HealthCoin. Through the usage of a blockchain, this data is impossible to forge and is accessible to everyone, a feature which is obviously particularly useful for the donors. The simple model including all parties and interactions is depicted in Figure 1.

2.2 Parties and Interactions

One of our main objectives is increasing transparency in the vaccination process, for the purpose of which we introduce HealthCoins, generated upon the registration for each vaccination. The person receiving the vaccine is awarded HealthCoins. This generation of coins is stored in a Decentralised Ledger, ensuring immutability and reinforcing trust that the donations are being put to good use.

There are three main actors involved in the model:

- **The donor pool** is a fund under supervision of the government or an organization such as the WHO anybody can contribute to. The supervising entity should be an organization which can be trusted. In our opinion, the

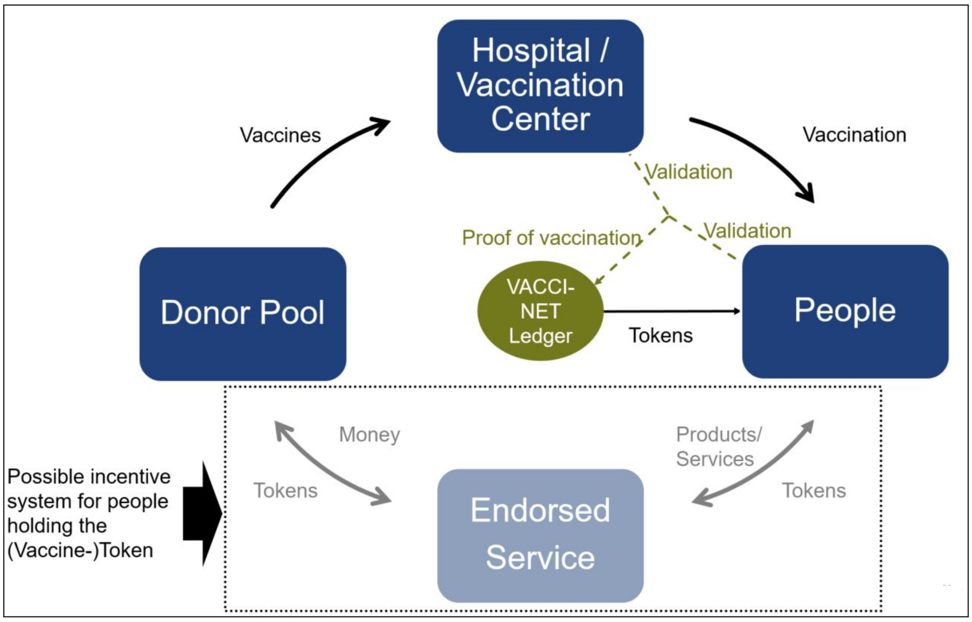

Figure 1: A simple model for the Vaccinet framework.

government of a developing country might not be considered sufficiently trustworthy, so we believe the WHO to be a suitable candidate for executive control over the fund. The government will still need to be involved, as issuing and verifying the digital IDs of centers and citizens alike is a matter of national competence. We expect most contributions to be made by the respective governments, NGOs and charities. This fund will provide for the vaccines and possible incentives.

- **Vaccination centers** are facilities administering vaccinations. They need to be verified by the state in order to guarantee authenticity. This could be hospitals in main cities or simple temporary health stations with the sole goal to vaccinate people in an area where a permanent medical facility is not a feasible option.

- **People to be vaccinated** are the prospective recipients of vaccines.

A medical facility can file a request for vaccines and the body governing the fund is in charge of the supply chain. This entity has to ensure a fair distribution across the country. Since this body has full access to the distributed ledger, they can easily look up if an order is appropriate by checking how many patients were vaccinated and comparing it to the stack of doses the hospital had obtained on an earlier order.

2.2.1 Receipt Verification

Whenever a person registers for a vaccination, a token is generated in the account of the hospital. The tokens are of no immediate use for the hospital, as they are differently registered in the code, leaving them without the option of spending any money. This prevents fraudulent behavior of doctors or the hospital. After the doctor has administered a shot, they can subsequently enter the patient's address in the hospital view of our application, following which the transaction of the previously generated token from the medical center to the patient's account is set to pending.

The patient can thereafter confirm the receipt of the vaccine, which completes the transaction.

As both sides' mutual agreement is needed and the transaction is stored on the immutable distributed ledger, donors get trustworthy insight ensuring them that their donation has been put to good use.

2.2.2 Transfer of Services

This transaction is currently not implemented but could be easily added and used by the overseeing entity to create incentives for the population.

After the token has been transfered to the patient, they can subsequently spend it on an available service of their choice. These services might include food, agricultural goods or public transport. In case the provider is a private institution they can exchange the HealthCoins for fiat currency. Obviously such private service providers would have to be registered differently as well, because otherwise everyone would have access to a cash-out function. Upon reaching the donor fund, the tokens are burnt. The possibility remains to activate a function which allows the client to directly cash-out their token for currency at a reduced rate in case the government wants to specifically endorse certain services.
Should this function be implemented, the fund manager consisting of the government and possibly the WHO would be responsible to pay for the incentives.

2.3 Token

In our system, the usage of the token mainly serves as guarantee for transparency in the vaccination process. Through the blockchain, every shot administered can be tracked. We hope the increased trust fuels contributions into the donor pool, possibly enough to support a fully-fledged incentive system. In this extended system, the token could serve to pay for services provided or endorsed by the donor pool.

3 Extended Subsidiary Model

3.1 Introduction

In this extension of our model, we focus on those people whose absence from work or trip to the vaccination center is a financial burden. Our objective was to compensate them for their lost time and reward them with a token that will support them according to their needs.

3.2 Qualitative Description

Beyond the Donor Pool, Vaccination Centers and people to be vaccinated, we introduce a branch of service providers, whose services we consider beneficial for our target group. These, for example, include health insurance providers, medical institutions or educational facilities. In the following section, we will describe a system that subsidizes these services with the help of a “Health Coin” token. It is visualized in Figure 2.

3.2.1 Involved Tokens

To create a reliable and transparent system, we use a distributed ledger (DL) and cryptocurrencies. We will work with the following currencies:

- The StableCoin ($\mathbb{SC}$). This represents an arbitrary, already established and stable cryptocurrency (e.g., Ethereum). We use this to transfer donors' funds to the recipient of a vaccination. We will also allow recipients to be rewarded directly in $\mathbb{SC}$. This will be described in more detail in the following paragraph.
- HealthCoin ($\mathbb{HC}$). This is a token we introduce to create incentives for people to get vaccinated. Its value depends on the service its owner wants to spend it on. Its value is higher if it is spent on services we consider beneficial, for example ones related to health care. HealthCoin's value is comparatively lower if it is directly exchanged to another cryptocurrency.

  We set the HealthCoin's value such that it is correlated to that of StableCoin $\mathbb{SC}$ in the following manner:

  - For a service we want to subsidize, the owner of the HealthCoin can directly transfer the full value of the $\mathbb{HC}$ to $\mathbb{SC}$ at an exchange rate of $1\mathbb{HC} = 1\mathbb{EC}$.
  - If the owner of the $\mathbb{HC}$ would like to purchase another service, they can directly transfer HealthCoins to StableCoins at an exchange rate of $1\mathbb{HC} = \lambda \cdot \mathbb{SC}$ where we choose $\lambda \in [0, 1]$ dependent on the scale at which a particular service needs to be subsidized.

  We introduce the notion of the HealthCoin Pool. In the vaccine distribution process HealthCoins will be transferred to this pool. If the person receives their vaccination, these will be transferred to the person's HealthCoin account.[1]

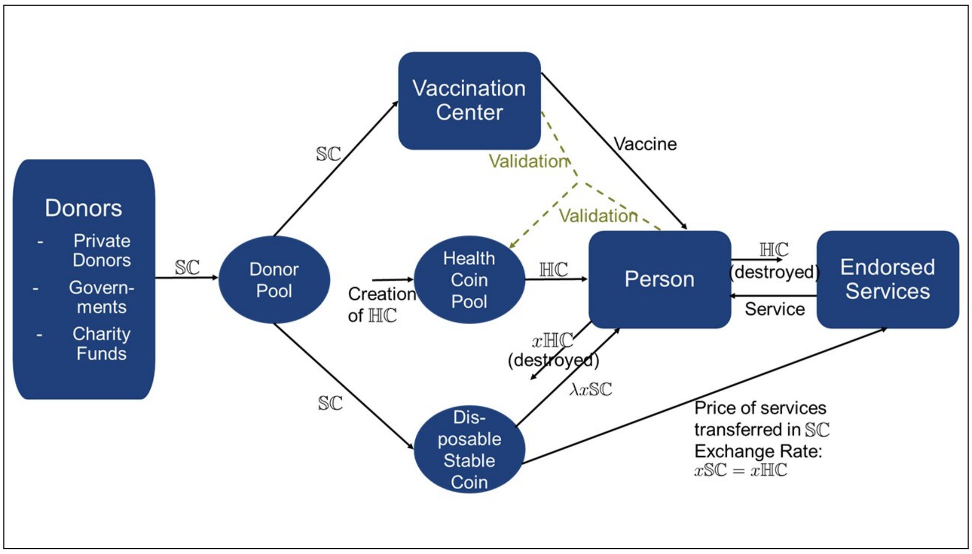

Figure 2: An extended subsidiary model with an inbuilt incentive mechanism.

[1] Note that in the implementation, this does not appear and we only introduce it here to make the model easier to understand.

3.2.2 Interactions

Our program enables the parties to interact in the following manners:

1. **Donate**. Any user account can transfer $\mathbb{SC}$ from their personal account to the Donor Pool.

2. **Delivery**. People who have not received vaccinations yet can apply for a vaccination via our website. If the Donor Pool has sufficient balance (enough to cover the cost of the vaccine and the reward for the recipient), the Vaccination Center receives the amount of $\mathbb{SC}$ needed to purchase vaccine. At the same time, a certain amount of $\mathbb{HC}$ is created in the HealthCoin Pool. This will later be released onto a person's account upon validated vaccination.

3. **Vaccinate**. When a person goes to a vaccination center and the vaccination is validated both by the center and the recipient, the value of the reward in $\mathbb{HC}$ is transferred to their account from the HealthCoin Pool.

4. **Transfer**. In this transaction people exchange $\mathbb{HC}$ for $\mathbb{SC}$ at the rate 1 $\mathbb{HC}$ = $\lambda \cdot \mathbb{SC}$.

   Technically, the $\mathbb{HC}$ the person is trading in, is removed from the system and the person receives $\lambda \cdot \mathbb{SC}$ for every $\mathbb{HC}$ onto their personal account.

5. **Supported Service**. If a person purchases a supported service, they can pay in $\mathbb{HC}$ at the direct exchange rate 1 $\mathbb{SC}$ = 1 $\mathbb{HC}$. Technically, the person's $\mathbb{HC}$ balance is updated (the $\mathbb{HC}$ are removed from the system) and the required amount of $\mathbb{SC}$ is transferred from the Donor Pool to the health service provider.

3.3 More General Subsidiary Systems

One of the goals of this system is to subsidize health services to improve health care in developing countries. We believe that the idea could be transferred to other subsidiary systems.

By replacing the donor pool with an entity interested in funding a certain cause, the people to be vaccinated by the entity's target group and supported services according to the objective, the system could be implemented in a similar fashion.

3.3.1 Example: Plastic Bottle Recycling

We will consider the recycling of plastic bottles as an example of a subsidiary system that follows the same idea.

When we purchase a plastic bottle, we currently have few incentives to recycle it. Since plastic pollution poses a great threat to ocean wildlife, supporters of recycling might include wildlife foundations, governments, or environmental activists. To increase the financial leverage, lawmakers could introduce a deposit on plastic bottles. The idea is the following: When someone returns their plastic bottle to a recycling station, they receive a certain amount of tokens $\mathbb{T}$. If they decide to transfer these directly to an existing currency, they can do that at an exchange rate $1\,\mathbb{T} = \lambda \cdot \mathbb{EC}$ for $\lambda \in [0, 1]$. Our donor pool might be interested in subsidizing products or services that reduce a person's carbon footprint, such as local, seasonal food, public transportation or products that can easily be recycled. For these services, the token can be exchanged at $1\mathbb{T} = 1\mathbb{EC}$.

4 Code Solution

4.1 Overview

The design of the solution is fairly straightforward: We provide a Website powered by Javascript- and Jquery code. Through a Web3-based interface the user interacts with a smart contract which functions as the back-end. Depending on the user interacting with the interface, its layout and functionality changes. Currently there are three categories - the people, the health centers and the vendors - with different implementations.

4.2 Backend - Solidity

The smart contract assigns each user several properties such as `uint256 balanceOf`, `int typeId` and `int beenVac`. The first integer value keeps track of the coins a user has accumulated. This number is bound by the different number of vaccines and how often a certain vaccine has to be issued before it fully protects against the respective disease. The `int typeId` records whether a user is a "Vendor", "Center" or a "Person". The second type determines the status of vaccination which can be either "Unregistered", "Registered" or "Vaccinated". This function only serves a purpose if the user belongs to type "Person". A function `isKnown()` checks whether the user is already known to the contract and has thus been initialized. If this is not the case, the initialization function `init()` is called by the website to initialize the user. A user is then allowed to register for a vaccination by entering a valid center `address` and clicking the *Register* button. Upon calling this function, the person's `beenVac` status is set from 0 to 1, representing "unregistered" and "registered", respectively. If a person's address has been registered for a vaccination, a center-type user can click the *Confirm* button to confirm that a vaccination has taken place and allowing the user to confirm the same. When both parties have confirmed the reception, a token is transferred to the user and his `beenVac` status is set to 2, meaning "vaccinated". Though this process is somewhat lengthy and complex we consider this the optimal solution to reduce corruption and prevent abuse of the system.

4.3 Frontend - Web3

The website consists basically of one html page. All information is centralized in a semi-transparent and round-edged div on the screen. Depending on the current user, which is determined by their ID, some elements are hidden or shown using javascript. A regular user, which is the case for vaccination-patients, can register for a vaccination. To do so, they have to enter the ID-address of the hospital offering the vaccination. A hospital, on the other hand, is provided with different options; namely, it has a vaccination balance which is defined by the number of vaccination doses available to the hospital. The confirmation process will then continue as described in the previous section. After finishing this process, the current balance of the patient is increased by one HealthCoin. To support some of our variations and ideas that allow HealthCoins to be transfered directly to goods and services rather than physical or digital money, a user can make use of the *buy service* feature. This feature is implemented as a small Jquery Dialog, where users can agree to a transaction. Further implementation of this protocol was omitted due to a lack of time. For an extended and more dense implementation we provide a *donator* button, which can be used by any regular user to make a donation to the Donor Pool and therefor support Vaccinet. To use this function a fourth user type would have to be implemented with the only option of donating money. It should be possible to get such a user address using a simple email registration and confirmation process, while for example the registration of a hospital is much more cumbersome.

Figure 3: The Vaccinet frontend.

Figure 3 shows the website as seen by a customer. The design is kept clean and intuitive. Some CSS was used for general issues whereas most of the control elements are based on a Twitter Bootstrap. As a background image a photo of rural fields and villages is used, adorned with our Logo.

4.4 Extensions

The current contract allows for most of the functions called for in the initial concept, as well as some of the functions that would be required for Section 3. There are however numerous small features that could be designed to further improve the look of our website. One example would be a counter that increases every time a vaccination has taken place and thus visualize for potential donors what impact they have and further enhance the trust in our system. However, since this was meant mostly as a proof of concept, we are generally satisfied with the final result.

5 Outlook and Challenges

5.1 Further Extending the Model

Assuming the citizens have been provided with digital IDs, it would not be difficult to associate medical data obtained after medical procedures with their ID and thus

replacing paper-based medical records, reducing and automating bureaucratic procedures. One could also imagine automatic registration for required vaccines when traveling to countries where a specific disease is more prevalent. So when a person passes a border an immigration officer could scan his digital ID and if all necessary vaccinations were taken, the person would be allowed to enter the country and otherwise entry could be refused.
In our project, we applied our model on the distribution of vaccines in developing countries; however, it is a model easily generalized to other behavior an entity would like to support. Such examples could include, but are not limited to, the following:

- **Education:** Households might be awarded for sending their children to educational institutions instead of keeping them at home for farm work.
- **Insurance:** Insurance companies could employ wearables or other IoT devices to reward their clients for a healthy lifestyle by lowering their premium.
- **Recycling:** An example discussing the recycling of bottles was already mentioned in Section 3, but also this idea could be scaled up.
- **E-Voting:** Governments are interested in the voting participation of its population and by giving even small incentive a lot of people could be motivated to vote in elections. Especially in Switzerland, where mobile phone penetration lies above one hundred percent [10] and the use of digital ID's is already tested in some parts, most of the difficulties that were limiting for the vaccination system do not occur here.

One can see that the general concept is not limited to developing countries but can also be implemented in first world countries.

5.2 Further Challenges

5.2.1 Funding Issues

The primary obstacle a reader might notice would be the funding of such an enterprise. We assumed above that the body governing the donor pool would issue the vaccines and possible incentives to take them to its population without demand for recompense. Is it realistic for funds of this magnitude to be raised?
A possible starting point to accumulate the necessary capital could be the combined efforts of the respective government and NGOs such as GAVI, mentioned above, UNICEF, or other charities. GAVI is a global Vaccine Alliance with an objective similar to that addressed in this paper. They bring together many of the organizations that were mentioned, such as the WHO, charities and governments of first world countries interested in donating, with the main goal of spreading immunization in developing countries worldwide. However, we are aware that it is unreasonable to expect this to suffice for every case. Nonetheless, we are confident in the positive potential impact even a partial implementation of this project could have.

5.2.2 Corruption in the Vaccination Process

One might also consider the following scenario in case we allow the tokens to be traded for incentives: The doctor responsible for administering the vaccine might find it more profitable to sell it to a third party off-blockchain than to give it to the patient. The patient's interest, on the other hand, might lie exclusively on the promised incentives instead of the vaccines, so both parties might profit from undermining the blockchain by mutually agreeing on the smart contract despite the vaccine having been sold elsewhere.

Presently, we see no way to effectively prevent this behavior, except perhaps by a more technically involved solution described in the next section. However, we also consider this scenario to have at most a negligible effect on the total efficacy of our system, for the following reasons:

- Demand for vaccines to be bought illicitly ought to be low, as most vaccines have no psychoactive effects and are thus not suitable as drugs. We could not find any evidence of a sizable vaccine black market, which is no surprise since people have no big interest in getting this type of medicine and especially no money to finance it, as previously discussed.
- Probably few people would accept a deal with the doctor to receive only the incentives when they could have the vaccine, too. We believe they would file complaints in order for the doctor to be punished or replaced.

5.2.3 Digital ID

So far, our project also relies on every citizen possessing both a smart phone and a unique digital ID. The latter is an undertaking already being implemented in many countries and communities, even in developing countries, so it is not unreasonable for this to be given in the foreseeable future. A perfect example is Nigeria which stared an eID program back in 2014 and could be a perfect example for other African nations [11]. Regarding smart phone penetration in developing countries, we find that it is rapidly growing, as well [9]. At least in the near future, the base conditions for implementing this project should be met.

5.2.4 Privacy Issues and Price Corruption

Along with the distribution of digital IDs, there are critics concerned by the open nature of the blockchain exposing sensible data to everyone. This problem has been observed in many pilot projects all around the world. While the public key alone does not suffice to identify individuals, the major concern is that once a person is identified with a certain key, their whole medical history lays open for everyone to see. Possible solutions could be the usage of a private blockchain, controlled by the government and a third party organization, because otherwise the corruption problem remains unresolved. One might also argue that personal data concerning solely vaccinations is not sensible. The public accessibility of the distributed ledger could also, however, lead to pharmaceutical companies gaining valuable insight into the amounts of a certain vaccine that is administered and therefore adjusting their prices to maximize their profits.

5.2.5 Informing People

Perhaps it is also necessary to ensure the population is sufficiently informed about the project. We see this as a burden mainly affecting the initiation phase of implementation. A PR campaign may help to get people interested, who could then inform their friends and relatives about the promised incentives.

5.2.6 Additional workload from the Confirmation Process

The whole confirmation process might result in additional workload for the hospitals. We can identify mainly two cases where this could arise: One must be sure on one hand to implement the system properly to avoid technical problems which are often time consuming to fix, and on the other hand, the digitalized administrative process may be too cumbersome for (especially older) people unfamiliar with today's technology.

We tried to address the second problem by designing an interface that is as simplified as possible. The first problem can, from our side, only be solved to the point of delivering a perfectly functioning program, but blackouts, malfunctioning hardware and improper installations remain factors to be considered, albeit outside of our influence.

5.3 Proof of Receipt

In the implementation of the receipt verification above, we used an application requiring mutual confirmation from both the doctor and the patient, triggering the transaction of HealthCoins. However, this might still allow fraudulent behavior, as discussed in Section 5.2.2. A more robust, albeit more expensive, solution to ensure that a vaccination dose has been *actually* injected could make use of a sensor based device called SmartShot. This approach is briefly presented below.

Using a system as described by Ambrosus, the individual syringes should be equipped with an identification tag. Then, the vaccination centers must use a cylindrical reading device in which the syringe is inserted. The device subsequently checks the ID tag of the syringe and the proximity of the ID of the citizen to receive the shot, as well as triggering the token transaction upon verifying that the syringe has been emptied. Proximity sensing might be carried out using a platform such as SmartAgora.

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