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Smart contracts implementation in the allocation of Covid-19 vaccines

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Abstract. The need for a good supply chain distribution of vaccines in disasters is critical in today's world. This paper targets the vaccines' allocation in several periods for various and separated demand zones. To discover and make the allocation network more efficient and help the policymaker decide more wisely, we implement a smart contract to suggest product allocation in different cases taking into account dynamical changes. Our smart contract tries to decrease the uncovered demands and facilitate the governments' prediction of the demands and evolution of a disease in demand zones. In this manner, several reactions of the smart contract are considered through different scenarios that can happen in the pandemics. The cases are sudden increase, sudden decrease, and steady demands. Moreover, we discuss the validity of the proposed smart contract and its benefits. Finally, we discuss the future aspects of our work and other objectives that can be useful in the proposed problem.

Keywords: vaccine supply chain, allocation problem, smart contract.

1 Introduction

Several phenomena lead to significant losses in human beings' lives and damaged nations' economies, environments, and societies. The causes can be earthquakes, flooding, etc. According to World Health Organization, the COVID-19 had several features that make it easier to spray and damage people's lives [1]. According to the statistics, a year and a half after the appearance of Covid-19, the total number of affected cases was 173 million people, with 3.73 million death cases all over the world. After several months, some companies from different countries were able to produce vaccines to protect people from the virus. The problem is that the number of vaccines is not enough for all people. Therefore, an important task is to assign vaccines to priority groups, such as older people, medical staff, and so on [2]. In this manner, proposing a vaccine supply chain (VSC) that can supply vaccines well and help rulers and health organizations for allocating the vaccines more efficiently is crucial. Ozdamar *et al.*, [3] introduced the distribution of various commodities problems in an emergency time. They proposed a multi-period multi-commodity model for material flows from supply centers towards distribution centers. They tried to minimize unsatisfied demands.

Several papers exist in the context of the uncertain and changing environment. In most cases, demand is an uncertain and changeable parameter. Abazari *et al*, [4] introduced a humanitarian supply chain (SC) for distributing relief items. They tried to minimize distance traveled by the reliefs' item, minimizing costs, traveling time and total perished items quantity. More information about the uncertainty in the VSC exist in [5]. One of the other important aspects of the demand is that it cannot stay fixed over time. Sarkar *et al*, [6] considered the cost of the products as the most important factor in changing demand over time. Pramanik *et al*, [7] considered the demand as a changeable parameter that is dependent on the selling price for the customers, credit period offers by the retailer, and credit amount.

It is necessary to discretize time into different periods, to take into account these potential changes and consider an uncertain demand of the humanitarian SC, which make the decision-making more challenging [8]. Therefore, it is vital to distribute vaccines optimally and predict the critical and dynamical demands more wisely. The distribution of vaccines could be complex since countries' strategy is different, and the different types of vaccines have various constraints. These problems brought the idea to propose a VSC that can well distribute vaccines and help the decision-maker to better allocate the limited vaccines quantities by a dynamic protocol based on smart contracts.

One of the first definitions of the smart contract by Szabo¹, which came long before Bitcoin and blockchain technology, is "a computerized transaction protocol that executes the terms of a contract." The other definition of smart contracts by Delmolino *et al*, [9] is "Smart contracts as computer protocols designed to oversee, enforce, or verify performances or negotiations of contracts." Regarding that, there will be no third party during all transactions. In addition to the irreversibility and documentation of all records, these protocols can prove their reliability and credibility [10]. Considering SC, smart contracts may be useful in several aspects and we can cite Dolgui *et al*, [11] who have implemented a smart contract on a SC. The decision-making of the scheduling problem according to the smart contracts has three roles. Rely on the completion time of the operations. Hasan *et al*, [12], considered the usage of smart contracts for shipment tracking and delivery. They consider the multi-echelon and multi-party setting.

In this paper, the proposed smart contract will suggest different vaccine allocations according to the evolution of the disease (which affects the demands) to the policymakers. The propositions are the vaccines' constraints and the real needs in a specific area at a given time. The policymaker will be able to define his allocation strategy according to the smart contract's allocation and other strategic data such as his health security strategy, economy, etc. The main interest of our work is to offer a tool that will allow integrating dynamic evolutions and allow the decision-makers to be more reactive in their strategy. In this paper, we only present the first step of our tool, which concerns the proposal of allocation in a short time. The second step of our work will be more appliances of the smart contract in the proposed SC.

The rest of the paper is as follows: Section 2 defines the problem. Section 3 proposes the mathematical formulation. Section 4 brings the results and discussions. Finally, section 5 gives the conclusion and perspectives to our work.

¹ Szabo, N. (1994). Smart contracts. Unpublished manuscript, 26.

2 Problem description

In this paper, we consider the distribution part of a VSC with two types of main actors: customers who are the representatives of a country (government, decision centers, etc.) and vaccine distributors. The first one is identified by demand zones (denoted DZs, DZs correspond to regional zones defined by the representatives of a country), and warehouses represent the second one (in this paper, we only consider the distribution part of the global VSC). The vaccines are COVID-19 vaccines that are vital to vaccinate all the community and cover all demands in several periods. A period is a time duration defined by a government that will vaccinate special group of people in each one of them. According to the strategy chosen by the government, the objective is to maximize the number of vaccinated people at a given final date (finite time horizon) to reach a collective immunity sufficient to face the virus.

The actors of this SC cooperate to optimize the distribution of products (vaccines). These actors are government and more precisely, policymakers (the customers), the pharmaceutical groups that are marketing the vaccines (suppliers), a 3PL-type service provider that ensures the distribution of the vaccines (the company that defines and manages the smart contract), this provider being able to call upon transport and warehouse suppliers, and finally the DZs in which doctors will carry out the vaccines, nurses, and any person defined in the government's strategy. The cooperation between actors is facilitated by the use of a smart contract that allows modifications to the initial defined contract to consider dynamic changes that may occur.

The products (COVID-19 vaccines) are stored in warehouses. We suppose that the sum of all distributed products for the finite time horizon (i.e. sum of all considered periods) of study is sufficient to cover the sum of all the demands in this finite time horizon (i.e. the objective define by the government to obtain the collective immunity to face the virus). Moreover, not all types of products are guaranteed to be available for all periods (the competition is very strong between the different countries wishing to vaccinate as soon as possible). In addition, the vaccination strategy for a given type of vaccine may change depending on the problems detected during vaccination (the testing phase have been shortened to the maximum). Consequently, products may be missing or not all be usable in the same way in a considered period. In parallel, new vaccines may appear and increase the availability of products. These changes may lead to changes in the vaccine strategy and subsequently the distribution of demand by period (new people could be vaccinated or not). The disease also evolves rapidly according to the mutations of the virus, causing increases in contamination and mortality in certain geographical areas, which can also vary the vaccination strategy. Therefore, the demand for a given period in a DZ could change.

When a country's government defines its initial vaccine strategy, usually defined according to the population's age and its specificities/functions, such as caregivers, the country's government defines pre-allocation of some vaccines to a given DZ at a given period. In this paper, we only propose the model for a country; we do not consider the market nor the competition. The total demand on the time horizon is known. Of course, depending on the evolution of the disease, this total demand may vary a little. Still, if we consider the case of covid-19, the mortality rate does not exceed 0.5% of the total

population for each country in the world². Therefore, the policymaker of a government defines its own vaccine strategy by defining periods and the DZs, and for each DZ i and each period f the demand dem_{pfi} for a given product p ³. However, as described above, these government strategies may change over time depending on the number and characteristics of the products offered by the pharmaceutical groups and on the evolution of the epidemic. Besides, some DZs could have crucial periods and need more or fewer vaccines. The total demand over the finite time horizon is the same, but its distribution at the DZs and periods can change that is uncertain.

In the proposed problem, two types of material flows exist: from warehouses to DZs at the beginning of a considered period, and from a DZ to another DZ. In this case, it depends on the current travel time from a given DZ to another DZ. Indeed, this flow will not exist if the distance is too far (because of transport and storage constraints for some vaccines). These material flows will be allocated with the help of smart contracts, which allow integrating many changes as the demand for a given period, the availability of a product, the arrival of a new product, a change in vaccine strategy, etc. In the first step, the smart contract will propose an optimal allocation according to the changes (this allocation may or may not be retained by the political decision-maker). The second step that is not presented in this paper, the smart contract will propose an optimal location-allocation of the products to the different DZs, taking into account the strong constraints of the products (at the level of transport, storage, and duration of use).

The material flow should be according to the pre-allocated products and demands of the DZs. Regarding the first step, our smart contract must take into consideration the different changes that may occur in a given period and for a DZ. To do the mentioned task, we decompose our time period into sub-periods of the same size (Fig. 1). As it can be seen, each period is divided in several checking points according to some parameters such as the importance of the targeted population in that period, government strategy, etc. The number of checking points for a given period is known that it is the results of the calculations made before the beginning of the period by the organism and gave it as a parameter to the smart contract or directly determined by the smart contract itself, based on contextual parameters and government's strategy. It should not be too large because the policymaker will not want to change strategies too often, nor too small, in order to take into account enough changes. For example, in France, the vaccine strategy is revised every week, so we can define the same number of checkpoints for all periods equals one week (which allows the government to get enough information about the positive or negative evolution of its vaccine strategy). Another country may decide to schedule a different number of checkpoints by period, considering that some population groups are more or less subject to evolutions. The calculation of the allocation happens at the beginning of each period and checkpoints.

After determining the products' optimum material flow, our smart contract will check the differences between the demands (initial demands and real demands) and the existing materials in the DZs at different checking points (Fig. 1). Indeed, the virus can spread and increase the number of the affected people over time. Therefore, it will be

² <https://ourworldindata.org/coronavirus> data base for covid-19

³ <https://covidtracker.fr/> data base for covid-19 in France and in the world

necessary to cover the new and unpredicted demands at each checking point during each period. On the other hand, some communities will need fewer vaccines after injecting the vaccines. Then we can send the vaccines to other DZs to save more lives. According to the mentioned reasons, our smart contract will calculate the differences between the demands and determine the best possible products' flow in the checking points.

Real demand depends strongly on the evolution of the epidemic. It can be estimated from the rates (incidence rate, positivity rate and reproductively rate) and hospital tension (these data could be obtained with database) and from epidemiological models that are good estimators of the spread of the SARS-CoV-2 virus within a population [13].

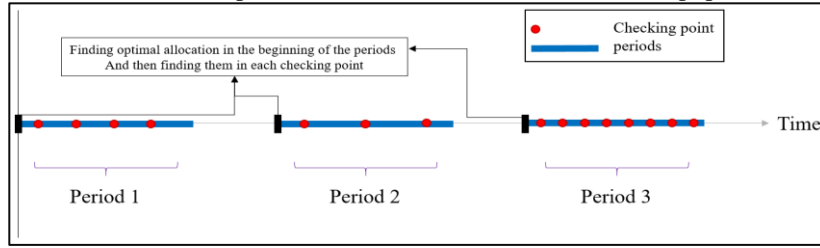


Fig. 1. Smart contract checking points and periods.

Besides, the main difference between the two types of material flows in the first of each period and checking points is that it is only from the warehouses toward the DZs at the beginning of the periods, and at checking points, it could be between DZs to each other and warehouses to DZs.

According to the real worlds' constraints, some DZs cannot send the products to each other because of some limitations such as the far distances and more traveling time. In what follows, we present the mathematical model of this allocation proposal.

3 Mathematical formulation

The model assumptions are as follows:

1. There are multiple vaccines with different characteristics. Because, in some cases, the usage of a product can be more useful than the other at several periods
2. Products carry in special conditions that are well respected without decay and harm
3. Each period includes several checking.
4. The sum of products in the warehouses can answer all the demands
5. Real demand is reported by the organism and Covid-19 tracker at the checking points

The notations, parameters and variables are given below:

i, i'	Set of DZs $\in \{1 \dots I\}$
p	Set of products $\in \{1 \dots P\}$
t	Set of checking points $\in \{1 \dots T\}$
f	Set of periods $\in \{1 \dots F\}$
w	Set of warehouses $\in \{1 \dots W\}$
a_{pfi}	Pre-allocated products p in the period f to the DZ i

$b_{pii'}$	1: if the product p from DZ i can be sent to the other DZ i' 0: otherwise
dem_{pfi}	The demand of the product p in the period f in the DZ i
Δdem_{pti}	The differences of the demands of the product p in the checking point t of the period f in the DZ i from the previous checking point
$Realdem_{pti}^f$	The real demand of the product p in the checking point t which belongs to the period f in the DZ i
θ_{pti}^f	The minimum percentage of uncovered demand of the product p in the checking point t which belongs to the period f in the DZ i
TC_{pwi}	The cost of transferring product p between warehouse w and DZ i
$RDZ_{pii'}$	The cost of sending product p from a DZ i to the other DZ
<hr/>	
Z	The objective function
q_{pfi}	The quantity of product p in the period f that send from the warehouse w to the DZ i
$qp_{ptii'}$	The quantity of product p in the checking point t of the period f that send from the DZ i to the other DZ i'
qt_{ptwi}	The quantity of product p in the checking point t of the period f that send from the warehouse w to the DZ i
s_{pti}	Not covered demand of product p in the checking point t of the period f in the DZ i

The difference between the real demands and predicted demands is given by formula (1). Formula (2) determines not answered demands rely on the real demands.

$$\Delta dem_{pti} = Realdem_{pti}^f - dem_{pfi} \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall f \in \{1...F\}, \forall t \in F \\ \forall i \in \{1...I\} \end{array} \quad (1)$$

$$s_{pti} = Realdem_{pti}^f - \left(\sum_w q_{pfi} + \sum_{i'} b_{pii'} qp_{ptii'} + \sum_w qt_{ptwi} \right) \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall f \in \{1...F\}, \forall t \in F \\ \forall i \in \{1...I\} \end{array} \quad (2)$$

The objective function and constraints are as follows:

$$\min Z = \sum_p \sum_f \sum_w \sum_i TC_{pwi} q_{pfi} + \sum_p \sum_t \sum_i \sum_{i'} RDZ_{pii'} qp_{ptii'} + \sum_p \sum_t \sum_w \sum_i TC_{pwi} qt_{ptwi} \quad (3)$$

Subject to:

$$a_{pfi} \leq \sum_w q_{pfi} \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall f \in \{1...F\} \\ \forall i \in \{1...I\} \end{array} \quad (4)$$

$$dem_{pfi} \leq \sum_w q_{pfi} \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall f \in \{1...F\} \\ \forall i \in \{1...I\} \end{array} \quad (5)$$

$$-\Delta dem_{pti} \leq \sum_{i'} b_{pii'} qp_{ptii'} \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall t \in \{1...T\} \\ \forall i \in \{1...I\} \end{array} \quad (6)$$

$$\Delta dem_{pti} \leq \sum_{i'} b_{pii'} qp_{ptii'} + \sum_w qt_{ptwi} \quad \begin{array}{l} \forall p \in \{1...P\} \\ \forall t \in \{1...T\} \\ \forall i \in \{1...I\} \end{array} \quad (7)$$

$$s_{pti} \leq \theta_{pti}^f \text{Realdem}_{pti}^f \quad \begin{array}{l} \forall p \in \{1 \dots P\} \\ \forall f \in \{1 \dots F\}, \forall t \in F \\ \forall i \in \{1 \dots I\} \end{array} \quad (8)$$

$$q_{pfwi}, qp_{ptii}, qt_{ptwi}, r_{q_{ptiw}} \geq 0 \quad \begin{array}{l} \forall p \in \{1 \dots P\} \\ \forall f \in \{1 \dots F\}, \forall t \in F \\ \forall i \in \{1 \dots I\} \end{array} \quad (9)$$

Equation (3) is the cost function. This cost includes transferring the products at the starting of the periods and checking times between warehouses and DZs. Constraint (4) pre-allocates the products to the DZs according to the governments' point of view. It means that the flow of products should meet at least a considered lower bound. Constraint (5) represents that it is essential to answer all the demands in each period for the DZs. Constraint (6) ensures that if the demand is changed before the checking time and the amount of the products are more than need, the products can be sent to the other DZs that need the products. Constraint (7) depicts that when a DZ needs more products according to the checking time, it is necessary to answer it by other DZs or warehouses. Constraint (8) limits the uncovered demands. Constraint (9) determines the types of variables.

4 Results and discussion

In this section, we will define the procedure of the smart contract and present several possible scenarios. Then we will solve a test problem, and we will discuss the managerial insights.

The proposed smart contract will consider several cases that can happen and bring the results. First, it will calculate the best allocations, and then it will discover allocation in the possibility of several cases. In the end, it will suggest the best decisions in each period. This procedure makes our proposed smart contract dynamic. Fig. 2 shows the procedure of the proposed smart contract.

Several possible scenarios exist according to the virus behavior in different communities. The three most common scenarios are sudden increase, sudden decrease, and normal spray during a period. In the increased scenario, health organisms will inform the smart contract about the need for more products. Therefore, smart contracts try to reduce the shortage as much as possible and satisfy the demands by asking more products from suppliers. In the sudden decrease that mostly happens after the vaccination of most people of the society, the smart contract will try to help other DZs by using the existing products. In the normal situation, it is about supplying well from the warehouses and reducing the shortages.

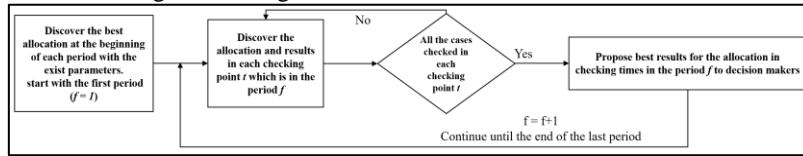


Fig. 2. The procedure of the proposed smart contract

Then, we will try to show the appliance of the smart contract by solving a test problem. Table 1 shows the random parameters.

Table 1. Data generation of the proposed problem.

Parameters	Value	Parameters	Value
a_{pfi}	Uniform-integer (100,200)	Δdem_{pti}	Uniform-integer (-5,+5)
$b_{pii'}$	[0,1]	TC_{pwi}	Uniform(2,8)
dem_{pfi}	Uniform-integer (100,200)	$RDZ_{pii'}$	Uniform(1,15)

For the test problem, we considered two periods ($F=2$). Each period includes two checking points, and the total number of checking points in the problem is four ($T=4$). Number of warehouses, products, and DZs are respectively three, two, and nine ($W=3$, $P=2$, $I=9$). To make the proposed smart contract's innovation clearer, we try to observe its behavior in a checking point through several cases by the numerical results. Table 2 shows the result of the smart contract in the checking point 1 in the period 1 according to the four different cases. All the values in the table are sum of the products.

Table 2. The results of the smart contract (period 1 - checking point 1) through different cases.

	Total Δdem_{pti}	Total S_{pti}	Total $qp_{ptii'}$	Total qt_{ptwi}	Total cost
Case 1	8	10	20	24	17463 \$
Case 2	-10	15	24	26	21350 \$
Case 3	-20	19	16	16	22992 \$
Case 4	24	4	22	30	21502 \$

In case 1, most of the DZs needed are fewer products than the considered from the first of period in the first checking point. Therefore, it was possible to answer most of the new demands in a less costly way. As it can be seen, the total changes of the demands have a positive value, which is 8, which means in more cases, the quantity of products is more than the needed and can send products to the others. Besides, in this case, the DZs had the chance to answer the closer ones' demands. Therefore, the proposed smart contract decided to answer all the less costly DZ by another DZ. Although it was able to be cost-efficient, it could not answer all the demands, and some of the DZs became uncovered that depend on the location and the possibility of sending products. The reason that it is the most cost-effective case exists in our smart contract. For example, in the checking point, DZ 1 needs two products to answer the demands. According to the predictions and answering them, it was unexpected changes too complicated and costly at that moment. Hence, our smart contract decided to send one product from the closest to the DZ 1, DZ 2 and leave one of the products uncovered because it was other priorities to answer other demands.

Case 2 and Case 3 both show the drastic increase in the demands. They can be considered the critical time of a virus. On these occasions, according to the proposed smart contract, the amount of unsatisfied demand will rise, and the cost of the system is high. If the rulers consider predictions and use the proposed smart contract, they can decrease the speed of the spray of the virus in several ways. For example, according to our smart contract, we allocated more pre-allocated products to a DZ that could spread and assign more products to the DZ, less accessible for the warehouses and other DZs. For responding to unpredicted increases, the smart contract tries to balance the warehouses, and DZs material flows to answer the needed demands. For example, it sends products from the DZs that have more products than they wanted to the closest one and from

warehouses to the DZs, which is unreachable for the other DZs. Rely on this point of view; it will be able to respond as fast as possible and be cost-effective. As an example, DZ 5 is the most unreachable for the other DZs. Therefore, the warehouses will cover all the needed demands at the checking point. On the other hand, DZ 3 is accessible to DZ 1 and DZ 2, and the exceeded products of DZ 1 and DZ 2 will be sent to DZ 3.

Case 4 can consider as the quarantine time in the pandemics or the time after several vaccination periods when considerable improvements are achieved. In this case, the lowest amount of unsatisfied demands will happen. The reason is that the total amount of demands is less than the predictions. Therefore, many products to answer other demands exist in this scenario. The smart contract in this section tries to answer all the demands and make the uncovered demands as small as possible by flowing materials from both warehouses and DZs. By studying four different cases, it is possible to have better choices and predict several aspects of the problem by passing times. Besides, all these results and the logical behavior show the validation of the smart contract.

As one of the digital SC enablers, our smart contract can work well and shows its appliances and validity. According to the previous studies in the introduction, other authors tried to use a smart contract appliance to track the vehicles and shipment of the vaccines. However, the main difference of this paper is in introducing a smart contract as a decision-maker tool in the VSC allocation problem in the condition that the demands should be calculated in the checking points and changeable scenarios. Several advantages and novelty exist in the proposed paper from the managerial point of view and remove the global SC barriers. Implementing a decision-making tool like the smart contract in a SC can help the rulers and health care organisms be more responsive and faster during the unpredicted changes. For example, the mentioned smart contract might be able to discover optimum allocation in all situations. Nevertheless, if the policy-maker could not respond well through the changes of the situations, it could cause many deaths for the society, especially during a pandemic like Covid-19. Besides, the implemented smart contract can work when the number of nodes (such as DZs and warehouses) is large. Therefore, it is helpful to manage the real-world problems by implementing the mentioned smart contract in a vaccine distribution system.

5 Conclusion

In this paper, we considered a SC managed with the help of a smart contract that can be useful for COVID-19. The problem proposed the best allocation of the vaccines during several periods to cover all the possible demands. Then, to make the model more dynamic and help the decision-makers, we implemented a smart contract that optimize all the material flows in the checking points and periods. By implementing our smart contract, we discuss about several possible scenarios during periods such as sudden increase and decrease of the demands.

Future research is highly suggested to propose other smart contract structure objectives and bring the results according to the real case data. Data collection is an essential point, and control points are defined to ensure that the smart contract options are correct. A negotiation phase between decision-makers and suppliers must be integrated

into our smart contract to facilitate SC management. The next step will be to define a real-time location-allocation problem considering the different events that can happen.

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