Covid-19 vaccine supply chain: a blockchain-based system for inventory management

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Abstract: Vaccination is a highly effective method for preventing and controlling infectious diseases. Strict supply chain management practices for vaccine production, transport, and storage must be implemented to ensure vaccine efficacy and patient protection. Moreover, it is important to ensure the safety of doses, to prevent counterfeiting or delivering expired doses. During a pandemic, the production and distribution of large quantities of vaccine doses can lead to a significant logistic challenge for governments. It is crucial to design an appropriate network and plan for the rapid and efficient distribution of vaccines to quickly ensure that they are reaching as many people as possible. This study provides an analysis of the organisation of Covid-19 vaccine allocation and distribution in Italy. The main challenges on the management of the vaccine supply chain (VSC) were identified, and the possibilities of using blockchain technology to address these issues were explored. A simulation model was developed to analyse the possible improvements that the introduction of the blockchain technology could bring to the process. A future scenario was assumed in which blockchain technology is used to manage the inventory of the Covid-19 vaccine in Italy. Different inventory policies are implemented, and different lot sizes and order interval are tested. Then, an analysis and comparison of inventory costs using different key performance indicators (KPIs) is performed. The simulation results show that the use of blockchain technology could significantly improve the efficiency of the VSC.

Keywords: Vaccine supply chain, blockchain, cost analysis, simulation, Covid-19.

I. Introduction

The COVID-19 pandemic, caused by the novel coronavirus SARS-CoV-2, has had an unprecedented impact on a global scale. First identified in late 2019, the virus quickly spread across continents, leading to an alarming number of infections and deaths. Governments and health organizations worldwide implemented strict measures such as lockdowns, social distancing, and mask mandates to contain the virus's transmission. The pandemic has not only strained healthcare systems but also disrupted economies, education, and everyday life [1]. To control the effect of Covid-19, an efficient vaccination campaign is necessary to achieve immunisation of citizens quickly and safely. The successful implementation of the recent Covid-19 immunisation programme has been compromised by multiple issues such as: vaccine counterfeiting and expiry, vial security, distribution and patient registration problems, and data processing security issues [2]. To address some of these problems, the recent literature proposes the Blockchain (BC) to improve several aspects related to the distribution of Covid- 19 vaccines [3]. One of the most crucial aspects related to the VSC is to ensure the goodness of the vial reaches the population. In this regard, Kamenivskyy et al., [4] proposed a framework to reduce the problems related to the circulation of counterfeit vaccines and registries. Verma et al., [5] proposed a simulation model which suggests the adoption of drone-assisted vaccine distribution supported by BC technology. The proposal involves the use of drones to deliver vaccines to remote or hard-to-reach areas, ensuring fast and efficient distribution. BC is also suggested as a useful technology to record and track all vaccine-related transactions along the distribution chain. Some authors addressed the problems related to the safe and secure distribution of the vaccine, proposing BC-based solutions to increase the safety and transparency in the traceability of COVID-19 vaccination vials ([6] [7] [8]). Another problem solved with the implementation of BC is linked to data management, and the prevention of possible cyber-attacks and release of sensitive information. Some authors proposed a BC-based solution for managing data related to the distribution and delivery of COVID-19 vaccines, while offering immutable, transparent, and correct data on the registration of vaccination recipients, avoiding identity theft and impersonation ([9],[10]). In this regard, Wang et al., [11] developed a simulation model using BC to create a secure, decentralised register of citizens' health information, guaranteeing the immunity of personal data. This allows health authorities to access the information they need to assess the effectiveness of administered vaccines and make decisions based on reliable data. Shin et al.,[12] instead addressed the problem related to the lack of trust among VSC partners and collaboration between multiple systems, networks, and organisations in different areas. Musamih et al., [13] faced a problem related to the waste of COVID-19 vaccines due to their overproduction and underutilisation. Shan et. al., [14] developed a framework based on BC technology to ensure the secure and timely transmission of operational information related to the distribution of emergency materials in Covid-19 pandemic relief operations. This framework enables the real-time consultation, tracking and recording of the operational status of emergency materials collection, vehicle planning, inventory management, relief materials allocation and other activities. In general, the studies proposed by the literature addressed different aspects, but they show a lack of attention to inventory management along the VSC. To cover this gap, this work presents a simulation model to test different inventory policies to manage the Covid-19 vaccine distribution in Italy including the implementation of BC. The aim is not only to improve the efficiency of the VSC but also to highlight the advances that the BC can bring at each level of a supply chain. Rapid, transparent, and accurate information sharing can strongly influence the VSC's success [15], and BC has been chosen as a suitable technology to exchange information in the network. With a BC-based inventory management system, all information related to vaccine production, logistics and distribution is stored in encrypted blocks and shared securely between authorised participants. This means that every transaction is permanently recorded and verifiable, eliminating the need for intermediaries and increasing the transparency and efficiency of the entire supply chain [16]. In addition, Inventory management is a crucial aspect of the Covid-19 VSC and requires an appropriate policy to ensure that sufficient stock is always available. However, choosing the right inventory management policy depends on many factors, such as the expected demand for the vaccines, their shelf life, and the risk of obsolete stocks [17]. BC technology can provide valuable information on inventory levels, enabling suppliers to adopt more effective inventory management policies and improve supply chain efficiency. However, the role of BC would not be limited to information sharing, which can be achieved with any other data storage and sharing system. In fact, BC uses smart contracts, which allow it to place orders automatically based on what is needed. In this regard, it should be noted that one of the main critical issues in the management of the VSC is the occurrence of late orders, which leads to an increase in procurement lead times with consequences in vaccination rescheduling. Therefore, better information sharing, and the automation of requests were the basis of the BC-based simulation model proposed. The focus of the study is on testing different lot sizes and order intervals and the research question is: how can different inventory management policies affect the success of the Covid-19 VSC?

The rest of the document is organised as follows: Section 2 defines the logic and structure of the simulation model; Section 3 introduces the Italian cases study. The simulation results are presented in Sect. 4 and the last section concludes with the main findings of the study.

II. SIMULATION MODEL

The study was carried out in four main phases. First, data on the Italian vaccination campaign were analysed to understand the criteria and logic behind the real distribution strategy. Second, a discrete-event simulation model was developed using Microsoft Excel and was designed to replicate the existing VSC. Then, the simulation model was validated by comparing its results with the real situation. Finally, a to-be scenario was modelled where the BC mechanism was introduced to reflect its use and test its impact on the system's behaviour. A three-level supply network was considered to simulate the allocation and distribution of doses from the National Hub (NH) to the 21 regional sub-hubs (RH) and test the impact of adopting different inventory management policies on the efficiency of the Covid-19 vaccine distribution system. The flow of material and information was designed starting from a framework developed by Rinaldi et al. [18]. In particular, the logic adopted in practice by the NH to distribute doses to RH was first considered (AS-IS MODEL). The NH assigns doses to the RH considering both the doses' availability and the characteristics of the population (e.g., number of the healthcare personnel or old people). Then, this first assignation enters the BC MODULE to be changed according to the daily stock levels of each RH and the selected inventory policy. Thus, the information flow is revised with the help of BC technology and the use of smart contracts, which allowed the monitoring of RH stocks and the definition of the lot size based on requests of citizens (final demand).

Thus, the simulation model can plan the deliveries from the NH to the RH and is able to assess how different inventory management policies may affect the efficiency of the distribution system.

Figure 1 shows the flow chart of the working mechanisms of this model.

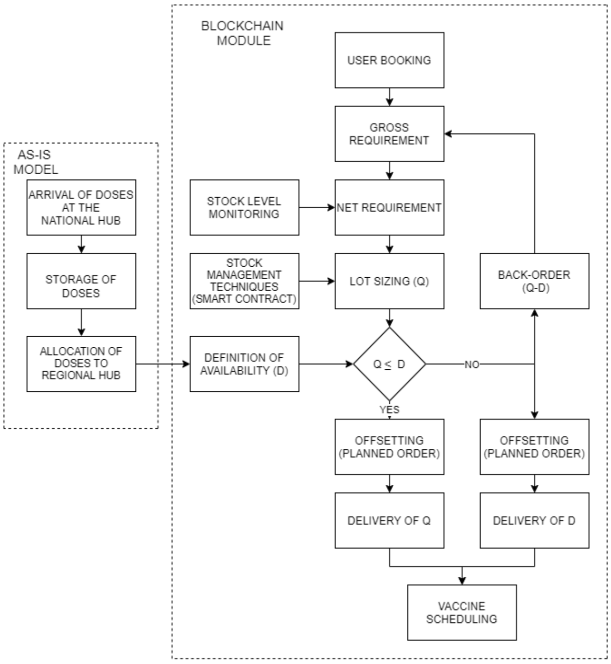

Figure 1. Simulation model flowchart

The starting point is the AS-IS model: vaccine doses are delivered from the supplier to the NH and allocated to the RH. However, unlike in the real system, in the proposed model there is no immediate delivery of allocated doses, but only the definition of the availability D for each RH. Meantime, the vaccination booked by citizens (User booking), together with any back orders (Back-Order), determine the gross requirement of each RH. The real-time monitoring of RH stock levels makes possible the calculation of the RH net requirement. Then, the lot-size (Q) is defined simulating the use of the smart contracts which calculate Q by replicating the logic of a defined inventory management policy. To simulate the role of smart contracts, a proper module has been programmed and automatically launched any time the system needed to take a decision about the amount to assign and deliver to a RH. Thus, if Q is less than or equal to the availability D at the NH for that RH, then it can be fulfilled. Otherwise, only the quantity available D will be delivered, while the rest of doses whose demand has not been satisfied is classified as a backorder and, therefore, sent as soon as available. It is only at this point, based on the quantities delivered, that vaccinations can be scheduled. Note that the availability D of doses at the NH for each RH is cumulative in nature. Therefore, the utilization of the simulation model enhances the efficiency of delivery planning by aligning it with the final demand, while ensuring that the established allocation criteria set by the responsible authorities remain unaffected.

A. Key Performance Indicators

A set of key performance indicators (KPIs) were defined to assess the efficiency of different inventory policies and compare it with the real distribution system. In particular, the KPIs quantify the main factors related to lot sizes and different order interval and their effects on the costs of the VSC. A brief description of the KPIs is presented below; each KPI refers to the whole simulated period:

Number of stock-outs N_{SO}: number of times in which the demand is greater than the number of doses available.

Maximum stock-out level SO_{MAX} [units]: maximum stock-out value.

Maximum quantity delivered Q_{MAX} [units]: maximum number of doses delivered per single order. This KPI allows us to assess the fleet size, thus determining the number and capacity of vehicles needed to guarantee the deliveries, with an impact on transport and total cost.

Medium quantity delivery Q_{MED} [units]: average number of doses delivered per single order. This KPI allows us to assess the efficiency of the procurement process, which has an impact on transport and total cost.

Total number of deliveries N_D: number of deliveries.

Average of administration rate A_{AVG} [%]: percentage of the administration of vaccines considering all the periods (average value). It is given by the number of doses administered with respect to the number of doses delivered.

Total order cost OC [€]: cost incurred each time an order is placed, and it is defined as the product between the unitary cost of order C_o [€/unit] and the number of orders placed N_o:

$$OC = C_o \cdot N_o$$

Total holding cost HC [€]: it is determined by considering the average stock S_{AVG} [unit], and the unitary cost of holding stock (C_{HS}), which is calculated based on the purchase cost:

$$HC = S_{AVG} \cdot C_{HS}$$

Transport cost TC [€]: it was defined as the sum of the daily transport costs $C_{t,i}$ [€/day] incurred during the simulated period. It consists of two rates, a fixed part $C^{FIX}_{t,i}$ and a variable part $C^{VAR}_{t,i}$ that is linked to the vehicle distance and consumption, then multiplied by the number of vehicles required to fulfil the order N_V.

$$TC = \Sigma^{N}_{i=1} C_{t,i} = \Sigma^{N}_{i=1} (C^{FIX}_{t,i} + C^{VAR}_{t,i}) \cdot N_V$$

Total cost C_{tot} [€]: the total cost was defined as the sum of holding cost HC, order cost OC and transport cost C_t:

$$C_{tot}=HC+OC+TC$$

III. Numerical Application

A VSC consisting of one NH and 21 RH was modelled. For each level, the described logic was implemented. The simulated period matches with the most critical phase of the vaccine procurement process, and it has been set at 30 weeks, running from the end of December 2020 to the end of July 2021. To simulate NH availabilities and requests from citizens in the different regions, real data were used.

The main objective of the study is to evaluate how the performance of the VSC varies with the implementation of BC combined with different inventory management policies in terms of cost minimisation and distribution system efficiency. To this end, six scenarios were tested. The scenarios differ in terms of the stock management policy adopted, i.e., lot sizes and order intervals.

The six scenarios are described below:

Scenario 1 (S1): the real distribution of vaccines in Italy was reproduced. Each RH has its own booking system for vaccination, and therefore the allocation and distribution plan considers only the AS-IS MODEL shown in Figure 1.

All the remaining scenarios also consider the BC MODULE.

Scenario 2 (S2): the *fixed period policy* is adopted. Orders are periodically placed (every 3 days), and the order quantity is equal to the amount needed to satisfy the exact demand of the next 3 days.

Scenario 3 (S3): the *lot for lot* technique is modelled. Orders are placed every day and the exact quantity of vaccines needed to meet the daily demand is ordered. This policy aims to minimise the stock holding costs and reduce the risk of obsolescence by ordering only what is needed for a specific period (1 day in this case).

Scenario 4 (S4): the *Silver-Meal* policy was simulated. It requires determining the total cost per period as a function of the number of periods the current order is to cover and stopping the computation when this function first increases. In this way, it is possible to determine and change step-by-step lot size and order interval, which are both variables.

Scenario 5 (S5): the *least unit cost technique* is implemented. It's a variant of the Silver-Meal policy, thus the aim is to minimize the total cost, but the stopping condition is regulated by calculating the total cost per unit and not the total cost per period.

Scenario 6 (S6): The part period balancing is applied. The procedure to calculate lot size and order interval is equal to the Silver-Meal policy. The difference lies in the aim, which is to balance the order costs and the holding costs. Thus, their difference is calculated to determine the stopping condition.

IV. Results and Discussion

The results report the comparison among the 6 scenarios tested. All KPIs are presented considering the sum of all the 21 RH and, as already mentioned, a 30-week observation period.

Starting from the analysis of the number of stock-outs (figure 2), it is possible to observe that while the Fixed-Period (S2) and Lot-For-Lot (S3) techniques show almost the same performance as the AS-IS model (S1), the other policies (Silver-Meal, least unit cost, and part period balancing) report a higher number of stock-outs. However, considering the simulation period of over 30 weeks and the KPI definition as the sum of stock-outs in all 21 RH, this result seems acceptable when considering the improvements brought by these techniques following described.

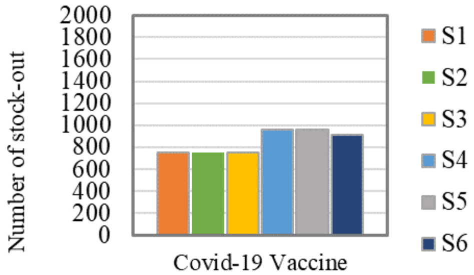

Figure 2. Comparison among scenarios: number of stock-outs.

Regarding the maximum amount of stock-outs, figure 3 underlines that although some techniques have a higher quantity of stock-outs than the AS-IS model, this does not influence the maximum amount registered, which probably depends on the NH availability.

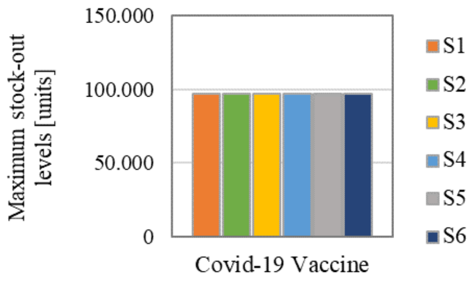

Figure 3. Comparison among scenarios: maximum stock-out levels.

Figure 4 shows the maximum quantities delivered for a single day to the RHs. This result is particularly useful for dimensioning the fleet of vehicles and thus determining the number and capacity required to guarantee all the deliveries of a day. All the inventory management policies provide a better result, i.e., a lower maximum quantity of units shipped per day compared to the AS-IS model (S1).

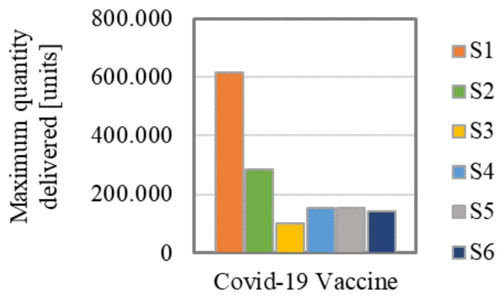

Figure 4. Comparison among scenarios: maximum quantity delivered.

In line with previous results, in Figure 5 we can see that the medium quantities delivered in a single delivery have improved. The BC technology, which provides real-time information about final demand and current stock level, leads to more efficient inventory management by closely aligning the doses on stocks with the real needs, avoiding oversizing.

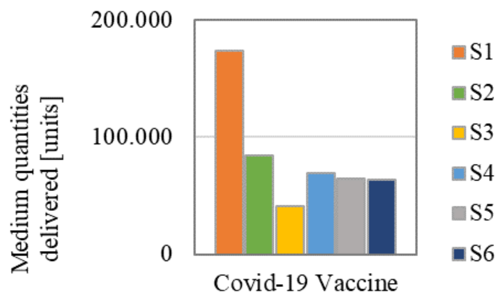

Figure 5. Comparison among scenarios: medium quantity delivered.

Figure 6 presents the total number of deliveries to the RHs. If excluding the lot-for-lot method (S3), which presents the highest rate as it provides the exact quantity required every day, the other policies show similar values. The AS-IS model and the fixed-period inventory policy (S1 and S2) are characterized by a fixed order interval of 3 days while the order interval is variable and calculated step by step for the other techniques (S4-S6), having similar performances means that 3 days seems to be a proper interval which allows to minimise and balance costs.

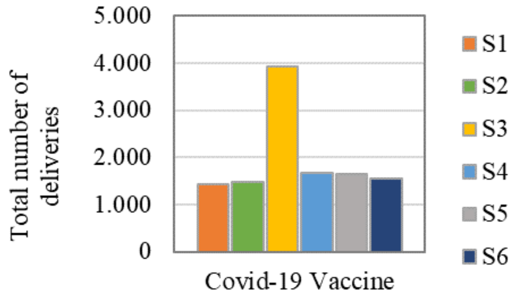

Figure 6. Comparison among scenarios: total number of deliveries.

Looking at the averages of the administration rate the results from Figure 7 highlight the improvement that BC technology could bring to the distribution system. Indeed, the BC module returns higher average administration rates for all the inventory management policies compared to the AS-IS scenario. In particular, the lot-for-lot technique (S3) has the highest average, despite being more expensive.

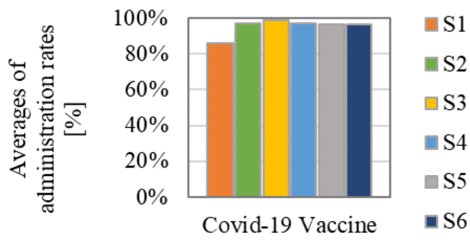

Figure 7. Comparison among scenarios: averages of administration rate.

Figure 8 shows the total order cost for different scenarios. Under its definition, is directly proportional to Figure 6.

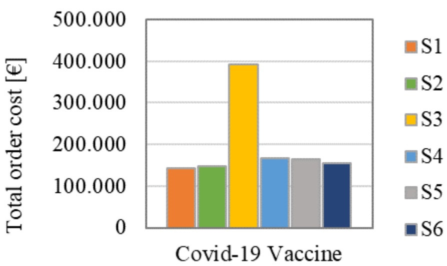

Figure 8. Comparison among scenarios: total order cost.

Regarding the total holding cost, (figure 9) since the BC technology allows for managing and coordinating the inventory based on the real demand and the number of doses in stock, it is possible to minimise stocks, and consequently, the related costs. This is particularly relevant for the stock of Covid-19 vaccines, which are particularly sensitive to temperature and require special storage conditions, which require to be stored at ultra-low temperatures and, therefore, to be equipped with ultra-freezers, particularly expensive. It should be noted that the lot-for-lot method (S3) doesn't incur any holding costs as it delivers the required quantity every day. As expected, the cost-minimization techniques, i.e., S4 (Silver-Meal) and S5 (least unit cost) result in lower costs compared to the AS-IS model and fixed-period, techniques (S1 and S2). However, it's important to underline that these techniques minimise the total cost for a specific period, and not for the entire period considered in this analysis. The part period balancing technique (S6) which aims to minimise the difference between order and holding costs, is the best policy if considering holding costs.

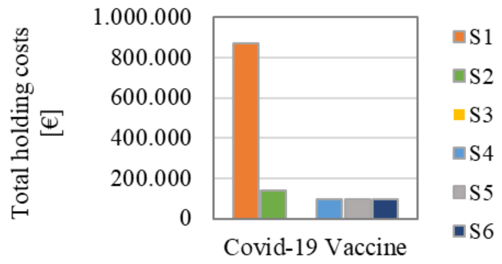

Figure 9. Comparison among scenarios: total holding cost.

Figure 10 presents costs related to transport. It is possible to see that the inventory management technique with the highest cost is the lot-for-lot technique (S3), as it involves deliveries when needed (every day) without considering the impact on costs. On the other hand, the other techniques return lower costs by reducing the number of deliveries, thus trying to consolidate orders and, therefore, ensure full-load shipments.

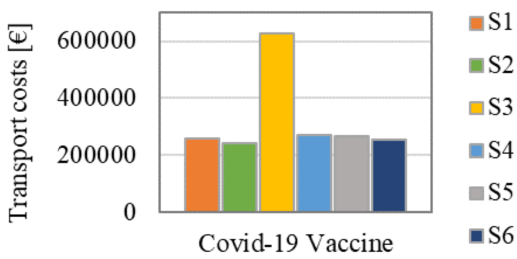

Figure 10. Comparison among scenarios: transport cost.

In conclusion, considering the total cost (figure 11), it can be deduced that adopting daily deliveries allows to slightly increase the administration rate but also result in excessive costs. Instead, a policy that aims at minimising or balancing costs cancan ensures efficiency in terms of both administration and cost, improving performance compared to the AS-IS scenario.

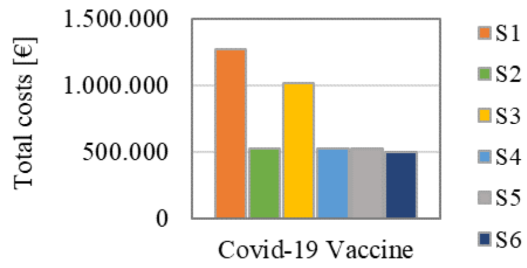

Figure 11. Comparison among scenarios: total cost.

V. CONCLUSION

The supply chain management of Covid-19 vaccines faced several challenges, including the need to transport and store units at specific temperatures, to ensure effective traceability operations, avoid expired or falsified vaccines, and solve interoperability problems in health IT systems. In Italy, the VSC had followed specific government guidelines to guarantee priority to different population groups. Some critical issues were identified in the way doses were allocated and distributed. To assess the benefits of a unified data-sharing system that automates inventory management, a simulation model has been developed to reproduce the vaccine allocation and distribution based on BC technology. The use of this innovative technology can increase trust, security, and communication between the various actors in the supply chain, ensuring data immutability, encryption, and transparency. In addition, the use of smart contracts allows to automate the processes and develop autonomous systems, reducing dependence on the human factor. To develop the vaccine allocation and distribution model based on BC technology, delivery and administration data in Italy were analysed, and the real system was modelled and simulated to develop the base for the BC model. The results of the analysis showed that transparent and unified data sharing along the entire supply chain, can reduce the stocks and, consequently, the possibility of some doses expiring and subsequently being turned into waste, improve system efficiency, and reduce inventory management costs. However, other critical issues such as delays in the delivery of vaccines or inadequate storage systems cannot be solved with BC technology. Moreover, although the use of the discrete event simulation can provide a realistic and detailed view of interactions in the supply chain, future research could explore agent-based models or develop the simulation using specific simulation tools. These tools could better capture the dynamic and adaptive nature of the supply chain and enable a more accurate representation of the behaviour of the actors involved. In addition, the investment required to use BC technology and the high amount of energy required to validate transactions can result in high economic and environmental costs and they should be investigated in future research.

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