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Global Supply Chain Optimization for COVID-19 Vaccine under COVAX initiative

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Abstract

After the onset of the COVID-19 pandemic, World Health Organization (WHO) launched COVAX in April 2020 to bring together countries and vaccine manufacturers and provide innovative and equitable access to COVID-19 vaccines. We developed a global supply chain model to optimize the production of the vaccines and allocation to different countries worldwide. The global COVID-19 vaccine supply chain of COVAX should be resilient to various disruptions and risks. In this work, we develop an optimization model with risk mitigation strategies to determine the procurement of vaccines from production centers and distribution to different countries when the supply chain is subjected to various disruptions. Our case study demonstrates how different risk mitigation strategies would enable COVAX to meet the demand amid multiple disruptions. It indicates that it is feasible to meet the vaccine demand and help participating countries overcome the global pandemic.

Keywords: add three to five keywords here.

1. Introduction

The only way to overcome the ongoing pandemic and achieve herd immunity is to vaccinate people worldwide. After the accelerated vaccine development, several vaccines have been approved globally. However, to overcome the challenge of coordinating the procurement and distribution of vaccines globally, the COVAX initiative was set up. It is co-led by WHO, Gavi (an organization that works towards getting people from developing countries vaccinated), and Coalition for Epidemic Preparedness Innovations (CEPI), a Gates Foundation-funded project that aims to make more vaccines available during an outbreak, was setup. Under the COVAX initiative, funding from rich countries was supposed to pool to invest in multiple vaccine development to increase the chances of effective vaccine development and approval. In addition, the funding was intended to provide vaccines for poorer countries. COVAX initiative handles the procurement and distribution of COVID-19 vaccines without discriminating between participating countries based on income \cite{1} (Figure 1). However, after the approval of several COVID-19 vaccines, the global delivery has been successful but limited to rich countries. Due to unprecedented demand for vaccines, there has been a shortage of vaccines to the COVAX initiative as the rich countries procured vaccines through bilateral deals. \cite{2}. COVAX deliveries have been hindered but slowly accelerating. COVAX has been making efforts to address and mitigate various risks. Therefore, optimizing the supply chain under
various uncertain disruptions is crucial to minimize the overall cost and utilize the resources best.

Stochastic supply chain optimization has been studied to optimize the supply chains of vaccines in the past. However, a recent study [3] reported a lack of existing academic publications on vaccine supply chain resilience. Few papers have been published partially addressing the challenges for the COVID-19 vaccine supply chain [4,5]. To account for the potential disruptions of vaccine production and delivery, we establish a stochastic model to capture different scenarios and minimize the overall cost. The objective function also has a term quantifying the supply chain's resilience. This work first provides insights into various setbacks faced by the COVAX facility in section 2. Section 3 describes the mathematical model in detail, and the solution for optimistic deterministic cases and scenarios with various disruptions are presented in section 4. Finally, the conclusion and future work is mentioned in Section 5.

Figure 1. The schematic of the COVAX facility involves vaccine procurement and global distribution.

2. Challenges faced by COVAX

To achieve the objectives of COVAX, they made investments for the development of several vaccines during the development phase and then signed deals with various manufacturers to deliver vaccines once approved. Once the vaccines are procured, COVAX is responsible for transporting the vaccines from the manufacturing center to the Countries' central hub. However, even after the successful approval of the vaccines, COVAX has failed to meet its objectives. Since its launch, it has been subjected to various setbacks, and the most crucial ones are as follows: 1) Production facilities are not adhering to the promised doses. For example, COVAX depended mainly on the Serum Institute in India for vaccines for 2021 (~50%). The second wave of COVID-19 in India resulted in a halt in the supply of doses to COVAX [6], 2) Lack of transportation capacity and various transportation disruptions: With the unprecedented demand for vaccines, available transportation capacity is not enough. In addition, when the rich countries came forward for donation, the freight and storage had to be taken care of by the COVAX [7], 3) Vaccine nationalism: Rich countries have procured the vaccines, and none are left for the low- and middle-income countries under the COVAX facility. After 18 months of the
launch of the COVAX initiative, 98% of people in low-income countries remain unvaccinated [8].

3. Problem Statement
This paper considers a two-echelon production-distribution network for vaccine distribution under COVAX. The COVID-19 vaccine delivery from the manufacturer to the country's central hub is carried through direct shipment to the point of use without any distribution centers in the middle. As part of the initiative, there are various manufacturers $m$, manufacturing set of vaccines $v$ and delivering them to different countries $c$ in the world through transportation links (TLs) using storage containers type $s$ based on the storage requirements of vaccines. The risk mitigation strategies for different disruptions are as follows: 1) In case of a risk involved with the production facility, we employ two mitigation strategies: a) More investment should be made in scaling up the production capacity. If the production capacity is reduced, investment should be made to restore the capacity for the next round of allocation. In addition, instead of ordering the exact amount initially, COVAX should have a deal for extra doses as a buffer, b) Streamline the donation process: Coordinate with rich countries and plan the delivery of the vaccines. Rich countries are wasting several million unused doses. COVAX should tap into these countries and sign deals for donations. In other words, putting efforts to connect donating countries (backup nodes) when the primary manufacturer is not available. These mitigation strategies will help deal with the above-mentioned (Section 2) challenges with the procurement of doses. During the disruption in the cold chain transportation of the vaccines or sudden requirement of transportation fleet when a country agrees to donate, the COVAX facility should employ backup, i.e., 3PL, to take care of the vaccine distribution. This would ensure that the facility is prepared for the transportation of vaccines without any capacity constraints, would also enable that no vaccines are damaged during transport, and ensure that the donations are well-received.

4. Supply chain optimization
Decision-making in vaccine production and allocation is formulated as a mixed-integer linear programming (MILP) model. The objective functions and constraints are mentioned in table 1. The objective function is divided into two parts: one corresponding to minimizing the design costs based on pre-disruption decisions, and the second is the cost during expected worst-case after the realization of the disruptions. The worst case is incorporated in our model via the conditional Value at Risk (cVaR) measure. Stochastic optimization aims to minimize the total cost. Pre-disruptions design costs include establishing transportation links with the fleet and investment in procurement, such as signing more deals with donors to scale up the production capacity and contracting 3PL as backup transportation. The second part of the objective function is the expected worst-case cost, including transportation costs, storage costs, vaccine procurement costs, and recovery costs for restoring production and transportation capacities after disruptions. The optimization constraint includes capacity constraints, supply-demand balance, and other logical constraints. (Eq 6 – 9, Table 1).
5. Case study

We have considered the demand for nine countries (India, Pakistan, Nigeria, Mexico, Ethiopia, Egypt, DRC, Iran, and Thailand), 50% of COVAX demand. The vaccine portfolio of 9 vaccines is also considered. These vaccines broadly fall into four categories (Figure 1). The vaccines differ in price per dose, the number of doses per person, storage requirement, and production sites where each vaccine is produced. The production centers are fixed based on the deals with the vaccine manufacturers. Various costs such as storage cost, transportation per unit distance, and selling price of vaccines are fixed and taken from literature. However, few costs such as contracting 3PL, cost of restoration of production capacity, and setting up a contract between a production center and a country for vaccine delivery are assumed. Through our case study, we want to demonstrate the effectiveness of our model over the basic model employed by the COVAX facility currently. The production and transportation capacities are subjected to various disruptions and are expressed in the percentage of available capacity. We define four independent scenarios for production and transportation disruptions each i.e., 100%, 80%, 60% and 40% capacities. Therefore, we have a total of $4^4 = 64$ scenarios, each with an equal probability of occurrence. The demand for each country is fixed at 20% of its population, which was the goal of COVAX in 2021 [1].

6. Results

Evaluating the deterministic base supply chain model without any risk mitigation strategies: First, we optimized the base supply chain model without risk mitigation strategies. We have solved the problem for the ideal (optimistic) scenario which COVAX had expected. Under the ideal scenario, all the deals with the manufacturers are delivered without any delay and the transportation is not subjected to any disruptions. Then we optimized the model for the actual situation faced by the COVAX facility, accounting for all the production and transportation disruptions. Results demonstrate how the supply
chain model failed when subjected to disruptions. This is validated by the fact that COVAX is far behind in fulfilling its objectives. Based on the results, it was found that these disruptions have led to around 64% of the unmet demand (Figure 2b). Based on the deals made by the facility, the allocation results indicate that countries are served by more than one production center. The allocation is not only based on the transportation and storage cost but based on the selling price of the vaccines. Vaccines provided to the AMC-funded countries are cheaper than the ones provided to the self-funding countries. On the other hand, the cost distribution indicates that vaccine cost is the main contributing factor compared to other costs (Figure 2a).

Figure 2. a) Cost distribution for basic supply chain model for optimistic scenario and actual case, b) The demand satisfied under each scenario.

5.2 Evaluating the performance of our model for the 2021 case study: We have successfully demonstrated the performance of our model as 100% demand is met and the cost is optimized (Table 2). Results support the claim that the vaccine demand can be met by having well-coordinated donations as backup production centers, restoring the production capacity after disruption, and having deals for buffer doses. We also studied the effect of disruption on different costs and found out that disruptions lead to an increase in the overall cost (Table 2). However, which cost factors will increase is not certain and is subjected to the nature of disruption. The cost distribution is illustrated in Figure 3. As we see that the major cost driver is the cost of vaccines, followed by the 3PL transportation cost. This is because 3PL handles the transportation of donations from various countries. Surprisingly, the results also demonstrate that the optimized cost for our model is only 13% higher than the ideal scenario. This proves that the COVAX facility does not have to spend a lot of extra money to meet the demand, rather should focus on coordinating and procuring donations effectively.

Figure 3. Cost distribution for our supply chain model for actual scenario of 2021 case study
Table 1. Optimization results of scenarios considering various disruptions.

| Scenario                        | Total Cost (USD in billions) | Demand Satisfied |
|---------------------------------|------------------------------|------------------|
| Optimistic scenario (Base model)| 3.13                         | 100%             |
| Actual (Base model)             | 1.48                         | 35.7%            |
| Actual (Our model)              | 3.54                         | 100%             |

7. Conclusions

The case study of 2021 has been used to study the performance of our supply chain model. Through our proposed model, we demonstrated that different risk mitigation strategies are crucial in order to successfully deliver the vaccines worldwide. In the absence of such measures, it is observed that the demand is not met, and the low- and middle-income countries are suffering the most. To handle various disruptions, a two-stage scenario-based MILP s programming model is presented. Scaling up the production facilities, coordinating donations, contracting 3PL to manage sudden transportation requirements are considered as the mitigation (i.e., resilience-enhancing) strategies. Furthermore, the COVAX facility also should invest in restoring the disrupted capacitates. The model demonstrates how COVAX could have battled various challenges it faced during 2021, and these strategies should be employed for 2022 to effectively deliver the vaccines to all the countries. Future work is to use this model and determine the strategies that COVAX should adopt for 2022 to meet the delivery promises. The future work is to forecast the dynamics of the virus in different countries through compartmental modeling and determine the vaccine demand to attain herd immunity and use our model to plan the production and distribution of the vaccines.

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