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A bi-objective mathematical model to respond to COVID-19 pandemic

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Abstract

COVID-19 has infected more than 543 million people and killed more than 6 million people since it was first diagnosed in Wuhan, China, on December 1, 2019. Vaccines were needed to combat the epidemic from the start of the pandemic due to the high incidence of morbidity and mortality. After the development of vaccines, due to the need for extensive vaccination to stop the spread of the disease, the supply chain of COVID-19 vaccines and the need to develop mathematical optimization models became vital. Lack of admission capacity at vaccination centers is one of the main problems facing vaccination, which slows down the process and increases infection risk. For this purpose, this paper proposes a mathematical optimization model for the COVID-19 vaccine supply chain network design, considering two objectives: maximizing the minimum demand coverage and minimizing the total time. With its equitable approach, the first objective function increases demand coverage. A second objective function accelerates vaccination by optimizing activities like allocating vaccines from storage centers to distribution centers and reducing the risk of spreading diseases by reducing transportation times to vaccination centers. According to this model, temporary vaccination centers can enhance or maintain vaccination rates by supplementing existing vaccination centers' admission capacity. Two numerical examples were used to validate the proposed mathematical model. The model's performance was then assessed using sensitivity analysis on its key parameters, demonstrating the effectiveness of temporary vaccination centers.

Keywords: Supply chain network design, COVID-19 vaccine, optimization, temporary vaccination centers

1- Introduction

As of this writing, the COVID-19 disease had infected over 490 million people and killed over 6 million (World Health Organization, 2022). Different vaccines have been developed and approved through clinical trials and used by countries. The high demand for manufactured vaccines has created many challenges in their supply chain, which indicates the need to examine the network design supply chain for vaccines of COVID-19 (Alam et al., 2021).

Some of the main difficulties that should be addressed are long distances between vaccine storage centers and vaccination centers, a lack of efficient planning, and ineffective cooperation between organizations (Antal et al., 2021). The current situation, which has endangered many lives, can be made far more complex and dangerous due to the COVID-19 vaccine supply chain's inefficiency, which indicates the need to examine the vaccine supply chain of this disease (Chakraborty and Mali, 2021).

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The lack of planning at different levels of the COVID-19 vaccine supply chain is one of the main issues. As a result, vaccine storage centers allocate existing vaccines to distribution centers without planning and considering the influential parameters. Such an approach is also observed in the allocation of vaccines from distribution centers to vaccination centers. Also, inadequate allocation of demand to vaccination facilities may result in overcrowding of some vaccination centers, increasing the time of vaccination and increasing the chance of infecting people with the COVID-19 virus due to overpopulation (Patel *et al.*, 2020). Inefficient planning also imposes significant expenses on the supply chain and might divert it from its ultimate purpose of serving demand to the greatest extent possible. Furthermore, given the significance of vaccinating the majority of a community as quickly as possible, a suboptimal supply chain can stymie the vaccination process.

Distributing the vaccine fairly, referred to as "equitable," means that different people access the vaccine according to their needs and necessity while considering prioritized needs. However, equal vaccine distribution means that all people (regardless of priorities) get the same access to the vaccine. The equitable distribution of COVID-19 vaccines should be considered because different groups of people in society, such as health workers, and people with a history of previous diseases such as cancers, are more at risk of virus infection (Abila et al., 2020). The vaccine will not only protect those who receive it but also aid in developing herd immunity, which will assist prevent transmission once 70 percent of the world's population has received the shot. However, getting people vaccinated without planning will not ensure the end of the pandemic if the vaccine distribution doesn't do equitably. Therefore, A fair vaccination policy is essential to creating herd immunity (Binagwaho, Mathewos and Davis, 2022).

Because of overwhelming demand at the start of mass vaccination, it was discovered that the capacity of vaccination sites was insufficient, resulting in long queues; also, due to these centers' low vaccine capacity, many individuals waiting could not receive the COVID-19 vaccine. The limited capacity of vaccination centers might cause vaccination to be delayed, resulting in various dangers and obstacles. To tackle these concerns, considering temporary vaccination centers, which have been employed in many countries, can alleviate these difficulties considerably (Gianfredi et al., 2021). Another challenge posed by the high demand for the COVID-19 vaccine is the consideration of equitable access to vaccines for all demand areas. Unfair access can have social consequences, such as public discontent, and, more importantly, diminish the effectiveness of mass vaccination and ultimately lead to a lack of mass immunization (Forman et al., 2021).

The COVID-19 virus is highly contagious, and exposure to it for a short period of time makes a person infected with it (Zaki and Mohamed, 2021). Therefore, the fewer people exposed to this virus, the lower the risk of infection. Considering an objective function to minimize the total time can help to allocate people to their nearby vaccination centers if there is capacity in these centers, which can lead to less exposure to this virus. On the contrary, considering the objective function of minimizing the total time, the allocations in the supply chain network are more optimal in terms of time and increase the speed of vaccination operations. By reducing network times, the possibility of vaccine spoilage in transportation between facilities is also reduced.

For this purpose, a supply chain network design (SCND) for the COVID-19 vaccine is proposed in this article. In this network, vaccine storage centers, distribution centers, and vaccination centers have been considered to plan vaccine distribution operations. Temporary vaccination centers are also being considered to mitigate the consequences of the extremely high demand for the COVID-19 vaccine. The demand of different regions is allocated with the two objectives of maximizing the minimum demand coverage and minimizing the supply chain total time.

In the continuation of the article, in section 2, the literature on the subject will be reviewed, and the gaps will be discussed. Then, section 3 will deal with the mathematical modeling of the SCND for the COVID-19 vaccine. Finally, section 4 will discuss the results obtained from the mathematical model, and Section 5 will conclude the paper.

2- Literature review

Due to the global effect of the COVID-19 pandemic, essential resources were suddenly in high demand, necessitating resource allocation and distribution optimization to maximize patient survival. The distribution of important items needed by COVID-19 patients is one of the topics researched to date due to its importance. We will review some of these studies that focus on COVID-19 disease in the following.

Considering that Drive-Through vaccination centers are one of the effective ways for mass vaccination and such centers can be used as temporary vaccination centers, using artificial intelligence and machine learning algorithms and training on a large dataset, Asgary proposed a model that could predict the outcomes of different methods of drive-through vaccination centers, and then turned it into an online application for broader use (Asgary et al., 2021). To answer how vaccines should be distributed to reduce the effects of COVID-19 on the community, Bertsimas proposed a data-driven model for the distribution of COVID-19 vaccines. They first used the augmented DELPHI method to capture the effects of vaccinations and mortality rates of different groups of people; then, they developed a mathematical model to locate the vaccination centers and the allocation of vaccines (Bertsimas et al., 2022). Matrajt optimized the vaccine allocation of COVID-19 vaccines considering both single-dose and two-dose vaccination. According to the findings, combining single-dose and two-dose vaccination efforts might be a key differentiator in controlling the pandemic (Matrajt et al., 2021).

Consideration of the priority of some groups in the distribution of vaccines has been investigated in several studies (Hogan *et al.*, 2021; Jadidi *et al.*, 2021). To mention, Libotte suggested two optimal control problems to distribute vaccines using the real-time data from China. The first problem's objective was to minimize the number of infected individuals using a differential evolution (DE) algorithm. The second model's objectives were to minimize both the number of infected individuals and the quantity of vaccine concentrate administered (Libotte et al., 2020). In this regard, by considering three metrics of death, symptomatic infections, and hospitalizations, Matrajt, Eaton, Leung and Brown proposed an optimal plan for vaccine allocations (Matrajt, Eaton, Leung, & Brown, 2021).

Equity in vaccine distribution is another crucial aspect that several studies have considered. Two critical issues in vaccine distribution are the availability of resources and limited access to resources, the former complicating the operation of the vaccine distribution and the latter causing inequality in distribution. For this purpose, Rastegar, proposed an inventory-location model that would equitably distribute the influenza vaccine under the COVID-19 pandemic conditions. This model has set a lower limit for vaccination for different groups. Also, this group has suggested that the proposed model can be used for COVID-19 vaccine distribution (Rastegar et al., 2021).

Due to the high demand for COVID-19 vaccines, a shortage of vaccines is another problem. For this purpose, Liu and Lou analyzed different models under different situations and constraints to cope with this issue. Their analysis has considered priority vaccination strategies, time-varying prioritization, dose stretching (delaying the second dose), and dose sparing (fractional dosing strategy). Finally, they proposed different strategies depending on the vaccines' effectiveness, limitations, and constraints (Liu & Lou, 2022). Similarly, Shim proposed a model for the optimal allocation of the COVID-19 vaccine considering age-specific contact rates and vaccine efficacy when the supply is limited (Shim, 2021).

Considering foreign and domestic manufacturers of COVID-19 vaccine, packaging centers, distribution centers, and central health centers, Gilani and Sahebi proposed a sustainable data-driven optimization model for the COVID-19 vaccine supply chain network (Gilani & Sahebi, 2022). In a relatively similar study, Asadi proposed a closed-loop SCND for the ventilator (essential medical equipment during the COVID-19 pandemic), aiming to minimize the carbon emissions and total costs and maximize the total responsiveness of their proposed system (Asadi et al., 2022). Noting that the allocation and distribution of the COVID-19 vaccine on a large scale is a complicated task, Abbasi proposed a mathematical model to aid vaccine allocation decisions based on exposure risk, susceptibility rate, and operational restrictions such as medical center capacity, vaccine stock, and transshipment capacity (Abbasi et al., 2020).

2-1- Research gaps

As seen in the literature review, not much research has been done on the supply chain of the COVID-19 vaccine. The need for various studies considering the different features of this pandemic is clearly felt.

Temporary vaccination centers are suitable for a fast and effective way of mass vaccination and have been used in the past for several reasons such as not gathering people in one place which lowers the risk of spreading the disease, while establishing these centers is convenient, it reduces costs and transportation (Prosser *et al.*, 2008; Hannings *et al.*, 2019; Abdul-Mutakabbir et al., 2021). Further, vaccinations in temporary centers have been shown to increase vaccination satisfaction and make vaccination easier for the vaccinated. (Hannings et al., 2019)

One of the gaps observed in the literature review is the lack of attention to temporary vaccination centers. Temporary vaccination centers are widely used in countries' vaccination programs, but the planning for locating these centers and allocating vaccines to these centers has received less attention. Failure to pay attention to such temporary centers can waste a lot of resources and delay the vaccination of people in the community, which increases the number of patients and deaths of patients. Also, in addition to temporary vaccination centers, the existing centers for vaccination and allocating people to all vaccination centers have great importance, which has been less considered in previous studies.

3- Mathematical model

Currently, there are many problems with the COVID-19 vaccine supply chain network. Due to the particular storage and shipment conditions of the vaccines (such as the specific temperature conditions for shipping the vaccines), the need to plan for the number of vaccines available in the vaccine storage centers and the number of vaccines allocated to the vaccine distribution centers have become very important. For manufacturing, distribution, storage, and administration of COVID-19 vaccines to guarantee potency, effectiveness, and ultimately population safety, a specific "cold chain" process is required, starting with temperature control at the manufacturing plant and continuing through transportation and administration to the patient. Since many of the vaccines provided by governments are ordered in high volumes, and it takes time until they are used, vaccine storage facilities are vital to maintaining their quality and effectiveness. Since many of the vaccines provided by governments are ordered in high volumes, and it takes time until they are used, vaccine storage facilities are vital to maintaining their quality and effectiveness. Furthermore, paying attention to the location of these facilities and planning for their location can help reduce costs and increase the efficiency of mass vaccination. On the other hand, due to the enormous changes in the demand for vaccines (extreme changes caused by the spreading of the disease), the rate of use of vaccines becomes unpredictable, and it becomes more crucial to maintain them properly.

On the other hand, another major problem of this supply chain is the limited number of vaccination centers. The lack of vaccination centers can cause long queues for vaccination, more difficult storage conditions for COVID-19 vaccines due to the forced increase in the number of vaccines in vaccination centers, and many other problems. These problems can have consequences such as increasing the risk of people getting infected with COVID-19 disease and reducing the number of people who tend to get vaccinated due to dissatisfaction with the vaccination conditions.

For this purpose, a bi-objective mathematical model for the supply chain of the COVID-19 vaccine is presented in this research. As shown in figure 1, in this model, patients are assigned to existing and temporary vaccination centers by locating temporary vaccination centers. Vaccines required in vaccination centers are also planned so that the vaccines are allocated from the storage centers to the distribution centers. Then the distribution centers distribute the vaccines to the vaccination centers. The storage centers in the modeling are considered because storing high volumes of vaccines, along with the very complicated conditions of their storage, is very expensive and requires a facility that specifically takes on the task of storing and maintaining them. The proposed model will make decisions on the followings:

- The location and number of temporary vaccination centers
- The number of people allocated to the vaccination centers

- The number of shipped vaccines from storage centers to distribution centers
- The number of shipped vaccines from distribution centers to the vaccination centers

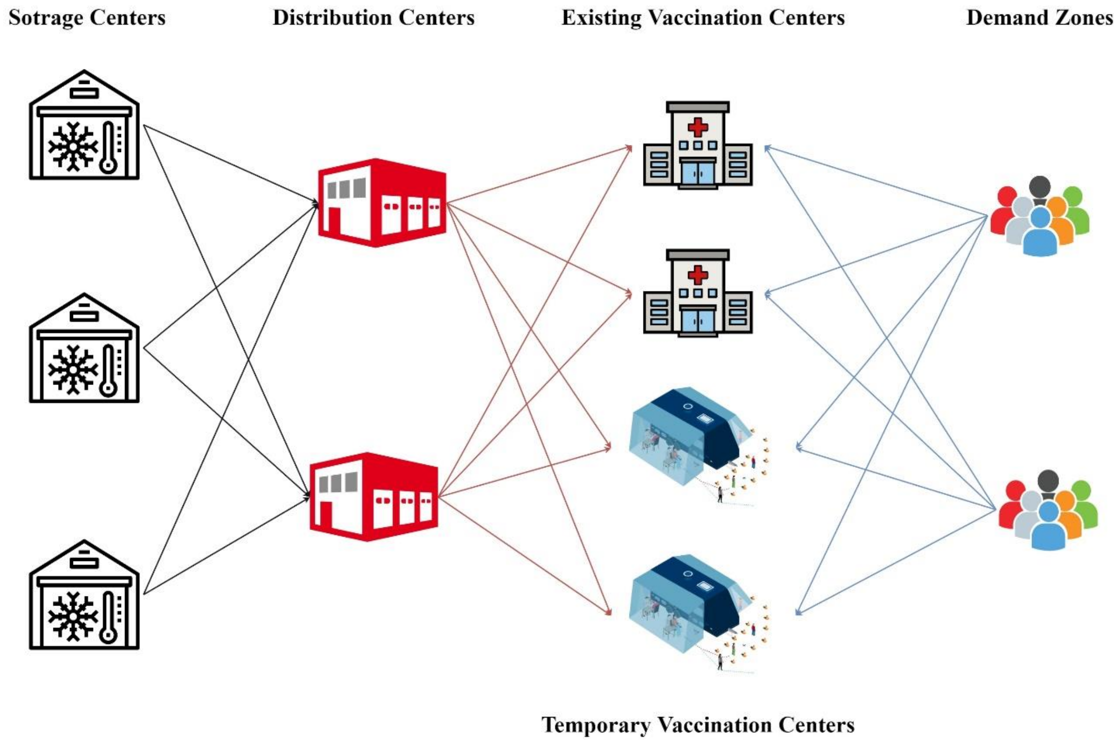

Fig1. The proposed supply chain network

The developed model has two objectives: (1) maximizing the minimum patient allocation to vaccination centers among all demand zones and (2) minimizing total transportation and shipping time. The following section introduces the sets, parameters, and decision variables, followed by the mathematical model.

3-1- Sets and indices

S Set of vaccine storage centers, $s \in S$

C Set of distribution centers, $c \in C$

E Set of existing vaccine centers, $e \in E$

T Set of candidate locations for temporary vaccine centers, $t \in T$

A Set of all vaccination centers, $a \in A$

D Set of demand points, $d \in D$

V Set of types of vaccines, $v \in V$

3-2- Parameters

ts_{sc}	Shipping time from vaccine storage center s ∈ S to distribution center c ∈ C
tc_{ca}	Shipping time from distribution center c ∈ C to vaccination center a ∈ A
ta_{da}	Transportation time between demand point d ∈ D and vaccination center a ∈ A
de_{dv}	Demand for vaccine-type v ∈ V in demand point d ∈ D
$scap_{sv}$	The capacity of vaccine storage center s ∈ S for vaccine-type v ∈ V
$dcap_{cv}$	The capacity of the distribution center c ∈ C for vaccine-type v ∈ V
$vcap_{av}$	The capacity of vaccination center a ∈ A for vaccine-type v ∈ V
$acap_{a}$	The admission capacity of the vaccine center a ∈ A

3-3- Decision variables

x_v^{da}	Number of people allocated to vaccination center a ∈ a who want vaccine type v ∈ V in demand point d ∈ D
y_t	1 if temporary vaccine center t ∈ T is set up, 0 otherwise
z_v^{sc}	Amount of vaccine-type v ∈ V shipped from vaccine storage center s ∈ S to distribution center c ∈ C
l_v^{ca}	Amount of vaccine-type v ∈ V shipped from distribution center c ∈ C to vaccination center a ∈ A

3-4- Mathematical model

Objective functions:

$$Max\ Z_1 = \left\{ \min_{d} \left(\frac{\sum_{a \in A, v \in V} x_v^{da}}{\sum_{v \in V} de_{dv}} \right) \right\} \tag{1}$$

$$Min\ Z_2 = \sum_{d,a,v} x_v^{da} \times ta_{da} + \sum_{s,c,v} z_v^{sc} \times ts_{sc} + \sum_{c,a,v} l_v^{ca} \times tc_{ca} \tag{2}$$

The first objective function maximizes the minimum demand allocation to vaccination centers ratio. The second objective function seeks to minimize the total transport and shipping times, including the total vaccine shipping times from storage centers to distribution centers, total vaccine shipping times from distribution centers to vaccination centers, and transportation times of individuals from demand zones to vaccination centers.

Constraints:

$$\sum_{c \in C} z_{sc}^{v} \leq scap_{sv} \qquad \forall s, v \qquad (3)$$

$$\sum_{s \in S} z_{sc}^{v} \leq dcap_{cv} \qquad \forall c, v \qquad (4)$$

$$\sum_{c \in C} l_{ca}^{v} \leq vcap_{av} \qquad \forall a, v \qquad (5)$$

Equation (2) ensures that the total allocation from vaccine storage centers to distribution centers does not exceed the capacity of vaccine storage centers. Equation (3) ensures that the sum of the allocations to each distribution center does not exceed its capacity. Equation (4) does not allow vaccines to be allocated more than the capacity of vaccination centers from distribution centers.

$$\sum_{c \in C} \sum_{v \in V} l_{ct}^{v} \leq \sum_{v \in V} vcap_{tv} \times y_{t} \qquad \forall t \qquad (6)$$

According to equation (6), vaccines will only be distributed from distribution centers to temporary vaccination centers if temporary vaccination centers are established.

$$\sum_{a \in A} l_{ca}^{v} \leq \sum_{s \in S} z_{sc}^{v} \qquad \forall v, c \qquad (7)$$

$$\sum_{d \in D} x_{v}^{da} \leq \sum_{c \in C} l_{v}^{ca} \qquad \forall v, a \qquad (8)$$

Equation (7) ensures that the vaccine allocated from each distribution center to the vaccination centers is less than the vaccines shipped from storage centers to the distribution center. Similarly, Equation (8) ensures that the number of people allocated to vaccination centers (the demand for vaccines allocated to vaccination centers) is less than the number of vaccines allocated to the vaccination centers.

$$\sum_{a \in A} x_{v}^{da} \leq de_{dv} \qquad \forall v, d \qquad (9)$$

$$\sum_{d \in D} \sum_{v \in V} x_{v}^{da} \leq acap_{a} \qquad \forall a \qquad (10)$$

Equation (9) ensures that the allocation of individuals from points of demand to vaccination centers does not exceed each region's demand. Equation (9) does not allow the allocation of demand to vaccination centers beyond the capacity of vaccination centers.

$$x_v^{da}, z_v^{sc}, l_v^{ca} \geq 0 \qquad \forall d, a, s, c, v \qquad (11)$$

$$y_t \in \{0,1\} \qquad \forall t \qquad (12)$$

Equations (11) and (12) depicts the properties of the decision variables.

3-5- Linearization method

In this section, the proposed nonlinear mathematical model is linearized by introducing a new free variable of β and replacing the $\underset{d}{min}\left(\frac{\sum_{a\in A,v\in V} x_v^{da}}{\sum_{v\in V} de_{dv}}\right)$ with it in the objective function (1) Due to its nonlinearity. As a result, the following holds true:

$$\beta = Min\left(\frac{\sum_{a\in A,v\in V} x_v^{da}}{\sum_{v\in V} de_{dv}}\right) \qquad \forall d \in D \qquad (13)$$

The linear model obtained from Equation (13), therefore, is as follows:

$$Max\ Z_1 = \beta \qquad \forall d \in D \qquad (14)$$

Objective function (2)

$s.t.$

$$\beta \leq Min\ \left(\frac{\sum_{a\in A,v\in V} x_v^{da}}{\sum_{v\in V} de_{dv}}\right) \qquad \forall d \in D \qquad (15)$$

Equations (3) – (12)

3-6- Multi-objective solution technique

Among the most widely used multi-objective programming methodologies are ε-constraints. To find the exact Pareto set of the suggested multi-objective problem, an enhanced version of the augmented ε-constraint approach, named AUGMECON, was applied (Mavrotas, 2009). In the ε-constraint technique, one of the objective functions will be used as the primary objective function, and the remaining objectives will be used as constraints using an epsilon value as the bound. By adjusting the bounds and solving the single-objective model, efficient solutions can be obtained. The AUGMECON2 technique is detailed below:

$$max\ f_1(x) + \epsilon \times (S_2 + \cdots + S_p) \tag{16}$$

$$s.t.$$

$$f_2(x) - S_2 = e_2 \tag{17}$$

$$\vdots$$

$$f_p(x) - S_p = e_p \tag{18}$$

$$x \in S, S_i \in R^+ \tag{19}$$

Constrained objective functions can be parametrically varied by modifying the right hand side (e_p) to obtain the efficient solutions of the problem. Additionally, $\varepsilon \in [10^{-6}, 10^{-3}]$. As a result, the mathematical model presented using the AUGMECON approach will be as follows:

$$Max\ \beta + \epsilon \times S_2 \tag{20}$$

$$s.t.$$

$$\left\{\sum_{d,a,v} x_v^{da} \times ta_{da} + \sum_{s,c,v} z_v^{sc} \times ts_{sc} + \sum_{c,a,v} l_v^{ca} \times tc_{ca}\right\} + S_2 = e_2 \tag{21}$$

$$\text{Equations } (3) - (12)$$

$$\text{Equation } (15)$$

4- Computational results

This section proposes and solves several sample problems using the proposed mathematical model to evaluate the performance and validate the presented model. Two types of sample problems were used to do the mention: medium size and large size. Next, the sensitivity analysis is performed on the main parameters of the model. GAMS software with CPLEX solver has been used on a computer with an Intel Core-i7 processor with 2.42 GHz speed and 16 GB of Ram to solve the proposed model.

4-1- Medium test problem

For the medium test problem, four vaccine storage centers, three distribution centers, seven vaccine injection centers, including five existing and two temporary centers, five demand zones, and two vaccine types have been considered. The parameters used in the medium test problem are exhibited in table 1.

Table 1. The values of the input parameters for the medium test problem

Parameter	Value
ts_{sc}	$ts_{sc} \sim U(10,20)$
tc_{ca}	$tc_{ca} \sim U(5,10)$
ta_{da}	$ta_{da} \sim U(5,15)$
de_{dv}	$de_{dv} \sim U(200,350)$
$scap_{sv}$	$scap_{sv} \sim U(350,400)$
$dcap_{cv}$	$dcap_{cv} \sim U(300,400)$
$vcap_{av}$	$vcap_{av} \sim U(200,300)$
$acap_{a}$	$acap_{a} \sim U(350,450)$

The Pareto front obtained from solving the medium test problem is shown in figure 2. As can be seen, the two objective functions conflict with each other. In cases where the first objective function has achieved better and higher demand coverage, the second objective function shows longer shipping times. Similarly, as shipping and delivery times decrease, the smallest allocation to demand ratio decreases, suggesting that demand coverage has generally declined.

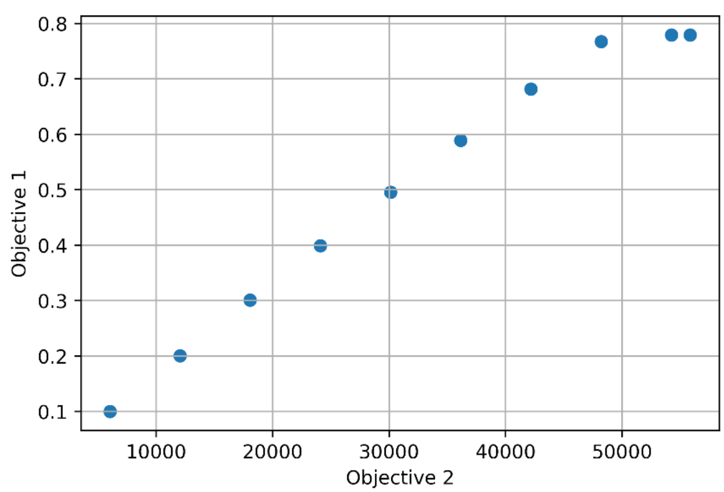

Fig 2. Pareto solution of solving the medium test problem

Table 2 shows the number of people allocated to vaccination centers in each Pareto solution. By moving from the optimal solution of the first objective function (maximizing the minimum coverage) to the optimal value of the second objective function (minimizing the total time), the sum of the allocation of demands to vaccination centers has decreased.

Table 2. Allocation of demands to vaccination centers in each Pareto solution

# Pareto Solution	Number of people allocated
1	2131
2	2103
3	1992
4	1764
5	1528
6	1283
7	1036
8	782
9	522
10	261

4-2- Large test problem

For the large test problem, twelve vaccine storage centers, eight distribution centers, twenty vaccine injection centers, including fifteen existing and five temporary centers, ten demand zones, and four vaccine types have been considered. The parameters used in the large test problem are the same as the medium test problem, which is shown in table 1. According to the figure 3, as the first objective function decreases, the second objective function also decreases, indicating a contradiction between the objective function.

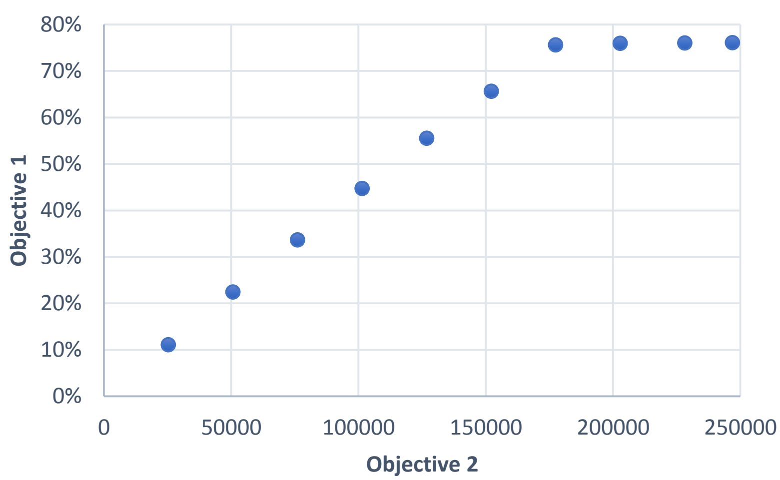

Fig 3. Pareto solution of solving the medium test problem

As in the medium-sized problem, as shown in figure 4, moving from the optimality of the first objective function to the optimality of the second objective function, the total number of people allocated to the vaccination centers decreases. Also, Pareto's first four solutions clearly show that the policy of temporary vaccination centers can reduce total times and increase vaccination rates by keeping demand coverage high, thereby reducing the risks of slow vaccination rates.

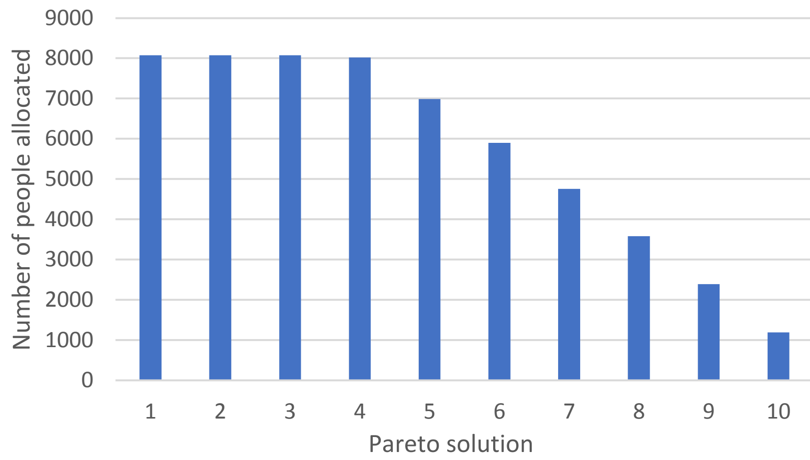

Fig 4. Allocation of demands to vaccination centers in each Pareto solution

4-2- Sensitivity analyses

The sensitivity analysis has been conducted on some of the most important parameters of the proposed mathematical model in this section to measure the model's performance. All sensitivity analyzes have been performed on a large test problem. Foremost, sensitivity analysis is performed on the demand parameter. Figure 5 illustrates that with an increase in demand parameter, the model has experienced a very small decrease in people allocated to vaccination centers, which clearly shows that establishing temporary vaccination centers can cope well with changes in demand.

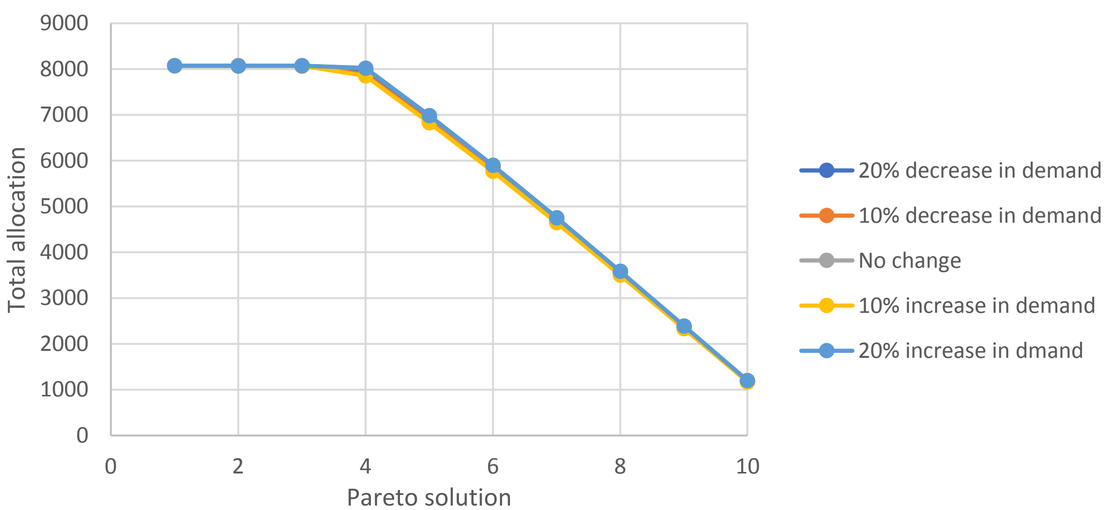

Fig 5. Sensitivity analysis of the demand parameter on total allocation

The next important parameter selected for sensitivity analysis is the admission capacity of patients in vaccination centers. As shown in figure 6, with the reduction of the capacity of existing vaccination centers, the demand coverage has decreased significantly. Furthermore, with increased capacity, the demand coverage has significantly increased. Additionally, according to the values of the second objective function, the total time decreases as demand coverage decreases and increases as demand coverage increases.

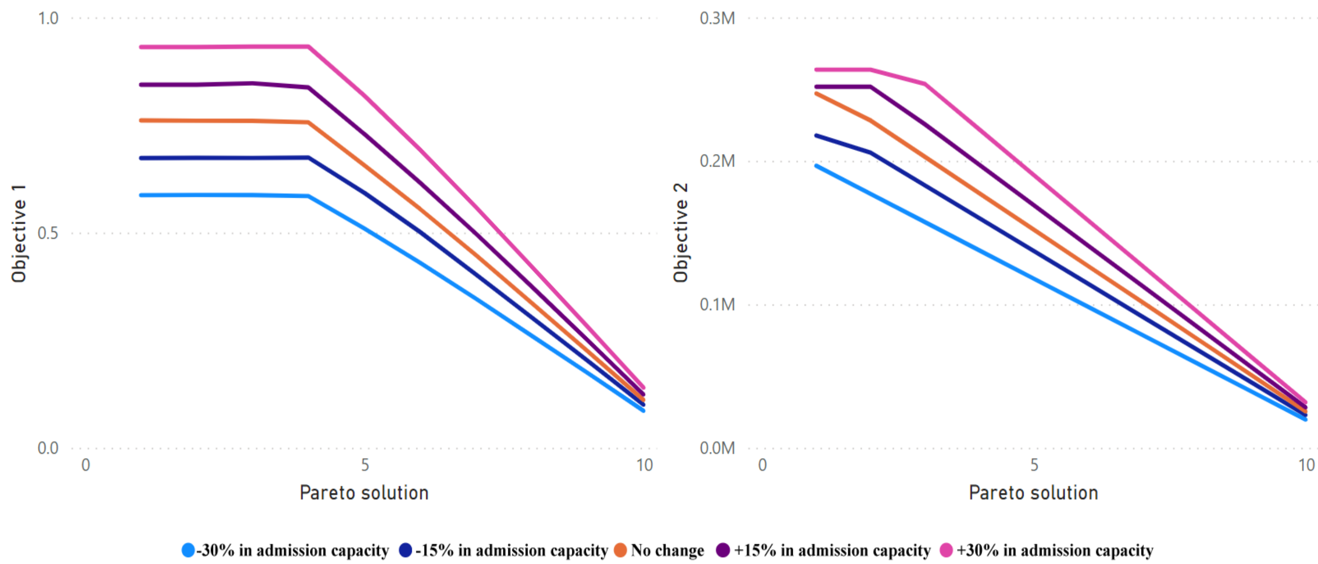

Fig 6. Sensitivity analysis of existing vaccination centers' admission capacity on objective functions

Figure 7 shows the sensitivity analysis of the admission capacity parameter of existing vaccination centers on the total demand allocations. As it is known, the allocation of demand to vaccination centers has a very strong relationship with the admission capacity of these centers; as the capacity of these centers decreases, the total allocation decreases, and with increasing this parameter, the total allocation experience increases.

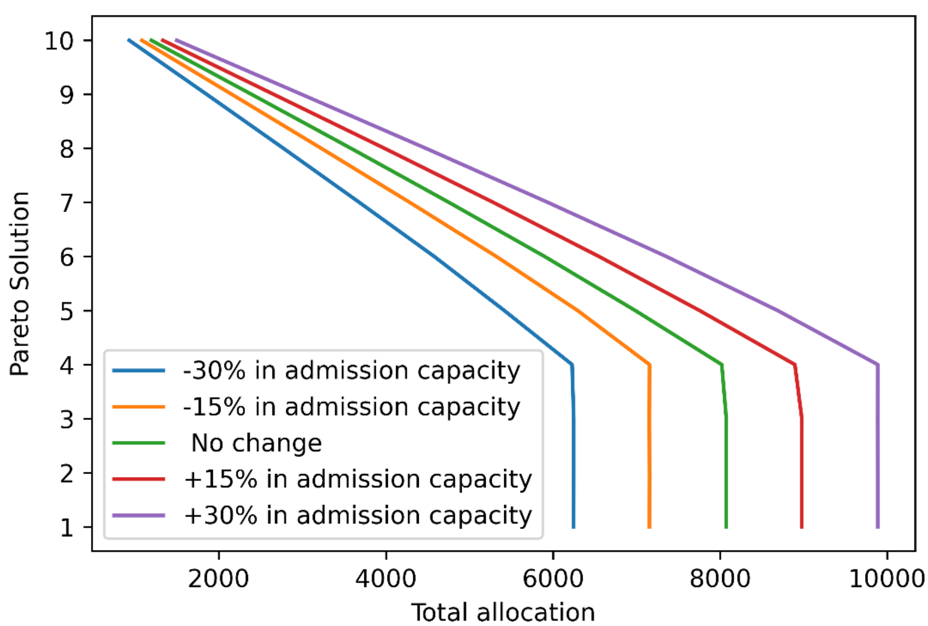

Fig 7. Sensitivity analysis of existing vaccination centers' admission capacity on total allocation

5- Conclusion and managerial insights

The COVID-19 disease has claimed the lives of many people worldwide and made the lives of many people difficult. Due to the many problems that this disease has brought, various vaccines have been developed to immunize people against it. Since the COVID-19 virus has caused a global pandemic, rapid vaccination and vaccination of many people in the community have become very important. At a low rate, vaccinating people in the community can infect more people with the COVID-19 virus and greatly increase the risk of infection and death. For this reason, the COVID-19 vaccine SCND is extremely important.

This paper presents a mathematical model of the COVID-19 vaccine supply chain network, considering vaccine storage centers, distribution centers, and vaccination centers. In this model, temporary vaccination centers were also considered due to the high importance of vaccination of individuals. If the admission capacity in the existing vaccination centers is completed, these temporary centers will be located and provide services. The proposed mathematical model has two objective functions: maximizing the minimum demand coverage percentage of areas and minimizing the total time, including vaccine delivery times between different supply chain levels and transportation times to vaccination centers.

In order to validate the proposed model, two numerical examples (medium and large size) were presented, which were solved by the proposed mathematical model, and the results confirmed the validity of the suggested approach. Also, to measure the performance of the proposed mathematical model, sensitivity analysis was performed on the two main parameters of the model, which are the demand and the admission capacity of vaccination centers. The proposed mathematical model in this research makes the following decisions:

- Number of vaccines allocated from vaccine storage centers to distribution centers
- Number and location of the temporary vaccination centers
- Number of vaccines allocated from distribution centers to existing and temporary vaccination centers
- Allocation of people from demand areas to vaccination centers

Managerial insights could be summarized as follows:

- Considering places for temporary vaccination centers will accelerate the vaccination of people in the community and can reduce the risk of infection and death.
- Temporary vaccination centers can play an important role in times when the demand for vaccines suddenly increases dramatically, and existing vaccination centers cannot meet this high demand.
- Increasing the capacity of centers such as vaccine storage centers and vaccine distribution centers can improve the COVID-19 supply chain and can cause faster establishment of temporary vaccination centers.

The findings of this study can be used in other similar cases (such as vaccination of another pandemic). Future research could consider different demand groups in mathematical modeling, different scenarios and stochastic modeling, machine learning tools for data-driven decision-making, considering multi-period in modeling and vaccine spoilage.

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