Vaccine 39 (2021) 495–504

Contents lists available at ScienceDirect

Vaccine

journal homepage: www.elsevier.com/locate/vaccine

An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic

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ARTICLE INFO

Article history:
Received 5 October 2020
Received in revised form 23 November 2020
Accepted 7 December 2020
Available online 9 December 2020

Keywords:
Vaccine supply chain
Healthcare equitability
Inventory-location problem
Mixed-integer linear programming
Influenza virus

ABSTRACT

The addition of other respiratory illnesses such as flu could cripple the healthcare system during the coronavirus disease 2019 (COVID-19) pandemic. An annual seasonal influenza vaccine is the best way to help protect against flu. Fears of coronavirus have intensified the shortage of influenza shots in developing countries that hope to vaccinate many populations to reduce stress on their health services. We present an inventory-location mixed-integer linear programming model for equitable influenza vaccine distribution in developing countries during the pandemic. The proposed model utilizes an equitable objective function to distribute vaccines to critical healthcare providers and first responders, elderly, pregnant women, and those with underlying health conditions. We present a case study in a developing country to exhibit efficacy and demonstrate the optimization model's applicability.

1. Introduction

The emergence and spread of diseases, such as Middle East Respiratory Syndrome, influenza, and Ebola have threatened people's health and lives. Vaccines increase the likelihood of preventing the spread of these diseases and save the lives of millions of people, including children and the elderly [1]. Unfortunately, many countries, especially developing countries, often encounter a shortage of vaccines [2]. Many factors can cause a vaccine shortage. Production monopoly, complex production processes, increased oversight of manufacturing facilities, unforeseen fluctuations in demand, and reduced producers are the most frequently cited reasons for vaccine shortage [3–6].

There are four components in the vaccine supply chain: product (what type of vaccine is needed?), production (how many vaccines should be produced and when?), allocation (who should receive the vaccine?), and distribution (how should the vaccine be distributed?) [7]. An effective vaccine distribution chain used to distribute vaccines from producers to consumers requires an efficient overall structure, an examination of the demand rate and inventory requirements, and identifying suitable vaccine distribution locations. Jacobson et al. [2] proposed a stochastic inventory model for evaluating pediatric vaccine supply. This model aimed to examine the inventory of pediatric vaccines to combat production interruptions in the United States. Their model showed that if the disruption in production is less than six months, the vaccine's stockpile level would be sufficient; otherwise, some shortages leading to disease spread would occur. Uscher-Pines et al. [8] proposed a systematic analysis for proposing policies to deal with the influenza vaccine shortage in the United States. Using the brainstorming method and Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, they developed a framework for purchasing, producing, and distributing vaccines.

Straetemans et al. [9] investigated the distribution prioritization of influenza vaccine in 27 European Union countries and four non-European Union countries. They utilized experts in the distribution planning department and collected data via telephone, email, and fax. Their findings showed that 26 states had considered at least one high-priority group for vaccination. According to their research, essential service providers, healthcare workers, and high-risk individuals were the most common high-priority groups for

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https://doi.org/10.1016/j.vaccine.2020.12.022
0264-410X/

vaccination. Shrestha et al. [10] studied pediatric vaccine storage and proposed a model for supply shortages, cost, and health impacts. Their model examined the shortage cost of 14 pediatric vaccines and their health impacts using scenario analysis. Samii et al. [11] developed an inventory control model for reserving and allocating the influenza vaccine. Abrahams and Ragsdale [12] presented a decision support system for minimizing total vaccination scheduling costs based on a binary integer programming model and genetic algorithm. Meshkini et al. [13] studied the opportunities and threats associated with vaccine production in Iran required by the world trade organization (WTO). The results showed that the main challenges for joining the WTO were the absence of firm internal intellectual property rules, the use of old equipment, and the lack of cooperation with global vaccine companies. Privett and Gonsalvez [14] identified and prioritized vaccine supply chain challenges in developing countries through interviews and surveys. A multi-objective possibilistic programming model was proposed by Pishvaee et al. [15] to design a sustainable medical supply chain network. They considered the economic, social, and environmental aspects of the needle and syringe supply chain in Iran to validate their model. Lydon et al. [16] analyzed vaccine outsourcing by analyzing data from a vaccine supply chain in South Africa. The results showed that the outsourcing of some parts of the vaccine supply chain could reduce costs and increase supply chain efficiency.

A mixed-integer linear programming (MILP) model was developed by Saif and Elhedhli [17] to design a vaccine supply chain by including environmental considerations. They used a novel hybrid simulation–optimization approach to solve and validate their model. Cernuschi et al. [18] studied the balance between supply and demand for the Bacillus Calmette-Guérin vaccine by examining global demand, global supply, product registration, vaccine shortage, and global demand–supply balance. Gooding et al. [19] conducted a study to investigate vaccine stockouts' effect on immunization. They presented a conceptual model that showed the relationship between routine immunization and vaccine availability. Their model considered economic status, ethnicity, cultural and religious belief by examining the national immunization supply chain data. Vaccines are highly sensitive to temperature, and their transportation at unfavorable temperatures significantly affects their quality. Lin et al. [20] developed a vaccine transportation model by utilizing a cold supply chain network. Their model analyzed how the inspection policy of the retailer influences the distributor's decision. Zandkarimkhani et al. [21] proposed a bi-objective MILP model for distributing Avonex (prefilled syringe for multiple sclerosis disease) under uncertainty. Their distribution model simultaneously minimizes total costs and lost demands. They used a fuzzy goal programming approach to solve and validate their model with data collected from Iran's Avonex distribution chain. Enayati and Özaltın [22] introduced a mathematical programming model for equitable influenza vaccine distribution in a heterogeneous population. Their model minimizes the vaccine doses allocated to subgroups for preventing the disease outbreak at the early stages of the epidemic. They divided the population into different subgroups and distributed the vaccine justifiably to varying subgroups according to an equity constraint.

This study proposes a mathematical model for equitable influenza vaccine distribution, similar to Enayati and Özaltın [22]. However, we go one step further and introduce a new concept for equitable vaccine distribution using a customizable objective function applicable to the COVID-19 vaccine. In addition, unlike the Enayati and Özaltın's [22] model, we consider the location of distribution centers and storage facilities, vaccine shortage, and budget constraints in the proposed model. In summary, this study addresses the following questions:

- How can an optimization model address the need for an equitable influenza vaccine distribution to a heterogeneous population?
- Which distribution centers should be included in an equitable vaccine distribution model?
- How many vaccine doses should be stored in each distribution center?
- How many vaccine doses should be made available to each group?

The contributions of this study are threefold. We (i) propose an equitable model to classify heterogeneous populations for influenza vaccine distribution during the COVID-19 pandemic; (ii) propose a novel MILP model for equitable influenza vaccine distribution considering inventory-location problems; and (iii) demonstrate the applicability and efficacy of the proposed vaccine distribution model with real-world data.

The remainder of the paper is organized as follows. In Section 2, we define the problem and formulate the model. In Section 3, we present a case study to demonstrate the applicability of the method proposed in this study. In Sections 4 and 5, we propose sensitivity analysis and managerial implications, respectively. In Section 6, we conclude with our conclusions and future research directions.

2. Problem definition and proposed model

The prevalence of the seasonal flu virus starts every year with the arrival of the year's cold seasons (i.e., fall and winter) and the spread of infectious diseases. The seasonal flue affects over five million people annually and leads to 290,000–650,000 deaths annually [23]. Due to the outbreak of coronavirus disease 2019 (COVID-19), the world's population will experience difficult fall and winter this year (i.e., 2020) since the seasonal flu virus will spread in parallel with COVID-19. Although the flu virus has many mutations, and the mutated virus's vaccine is produced and distributed each year [24], one of the problems is accessibility to this vaccine as it is produced and distributed by a limited number of countries.

On the other hand, many countries cannot supply the flu vaccine to the entire population due to seasonal shortages. Therefore, it is crucial to develop a practical approach to equitable distribution of vaccines in these countries. Equitable distribution does not always mean equal distribution among individuals, but rather a distribution in which more needy people have a higher priority than less needy people. Accordingly, this paper presents a mixed-integer linear programming model for equitable distribution of the influenza vaccine among different groups of people with varying priorities. The prioritization model requires a balance between helping society and protecting an individual's health. The supply chain consists of two levels: a supply point (i.e., distribution center) and multiple demand points (i.e., city, state, province, etc.). The health experts group residents in each demand point according to pre-determined criteria. This grouping will determine the need for vaccination in each demand point. The proposed model is used to distribute the vaccines equitably among the demand points according to the following assumptions:

- The proposed model is a single product multi-period distribution model.
- The model determines the optimal location for the distribution center.
- The distribution center is capacitated.
- The demand point (warehouse) has storage facilities for future periods.
- The model considers the possibility of a shortage.

3. Mathematical model

3.1. Indices

p	Demand point (Province)
i	Group type
k	Distribution center
t	Time-period

3.1.1. Parameters

POP_{ip}	The total demand of group i for influenza vaccine in province p
ST_k	Cost of setting up the distribution center k
PR	The per-dose purchasing cost of the influenza vaccine
TR_{kp}	The per-dose transportation cost of the influenza vaccine from distribution center k to province p
HL_p	The per-dose holding cost of the influenza vaccine in province p warehouse for each time-period
θ_i	The minimum percentage of group i to be covered (coverage rate)
β_{kt}	The maximum capacity of distribution center k for supplying influenza vaccine in time-period t
BG	Budget
M	A big number

3.1.2. Variables

$\omega_k \begin{cases} 1 \\ 0 \end{cases}$	Binary	If distribution center k is set up Otherwise
y_{ipt}	Integer	Number of influenza vaccines allocated to group i in province p in time-period t
w_{pt}	Integer	Number of influenza vaccines stored in province p warehouse in time-period t
x_{kpt}	Integer	Number of influenza vaccines shipped from distribution center k to province p warehouse in time-period t

3.1.3. Objective function

$$Max\ Z = Min\left\{\frac{y_{ipt}}{POP_{ip}}\right\} \tag{1}$$

s.t.

$$\sum_t y_{ipt} \geqslant \theta_i \times POP_{ip} \quad \forall i,p \tag{2}$$

$$w_{pt} = \sum_k x_{kpt} - \sum_i y_{ipt} \quad \forall p, t = 1 \tag{3}$$

$$w_{pt} = w_{p(t-1)} + \sum_k x_{kpt} - \sum_i y_{ipt} \quad \forall p, t > 1 \tag{4}$$

$$\sum_p x_{kpt} \leqslant \beta_{kt} \quad \forall k,t \tag{5}$$

$$x_{kpt} \leqslant M \times \omega_k \quad \forall k,p,t \tag{6}$$

$$\sum_k ST_k \times \omega_k + \sum_{k,p,t} PR \times x_{kpt} + \sum_{k,p,t} TR_p \times x_{kpt} + \sum_{p,t} HL_p \times w_{pt} \leqslant BG \tag{7}$$

The objective function distributes vaccines equitably by maximizing the minimum delivery-to-demand ratio per group in each province and each time-period. This objective function is a novel and new concept for equitable vaccine distribution. The objective function's underlying premise is the demand at each node, and the trade-off between the nodes, are established according to a delivery-to-demand ratio. To this end, equitability is enforced at each node by maximizing the minimum delivery-to-demand ratio.

Constraint (2) guarantees that vaccines are assigned to each group, at least at the coverage rate. The inventory balance in the provinces' warehouses is given in Constraints (3) and (4) for the first and the subsequent periods. Constraint (5) ensures the capacity of distribution centers is not violated. Constraint (6) ensures the distribution center is already set up and ready to receive vaccines from the distribution center. Constraint (7) ensures that the total cost of the vaccine supply chain, including setting up cost, purchasing cost, and transportation cost, do not exceed the budget.

3.2. Linearization process

The objective function of the proposed model is nonlinear and requires linearization. This linearization is accomplished by introducing a new free variable (μ) to replace $Min\left\{\frac{y_{ipt}}{POP_{ip}}\right\}$ in the objective function. Therefore, the following holds true:

$$\mu = Min\left\{\frac{y_{ipt}}{POP_{ip}}\right\} \tag{8}$$

Based on Eq. (8), the following formula always holds true:

$$\mu \leqslant \frac{y_{ipt}}{POP_{ip}} \quad \forall i,p,t \tag{9}$$

Therefore, according to Eqs. (8) and (9), the proposed nonlinear model is converted into a linear model as follows:

$$Max\, Z = \mu \tag{10}$$

s.t.

$$\mu \leqslant \frac{y_{ipt}}{POP_{ip}} \quad \forall i,p,t \tag{11}$$

Constraints (2) to (7)

4. Case study

Every year, the seasonal flu virus spreads in Iran and other parts of the world with the arrival of cold seasons. The Iranian government annually buys the flu vaccine from the producing countries in limited quantities, proportional to the population. In 2020, the country's demand for influenza vaccine has increased sharply due to the outbreak of COVID-19. According to the statistics released by the Iran Ministry of Health and Medical Education (MOHME), this amount has increased ten times compared to that in the last year (http://ird.behdasht.gov.ir). The rising demand, on the one hand, and sanctions, on the other hand, has resulted in a shortage of flu vaccine in Iran. Consequently, MOHME needed an efficient and effective vaccine distribution model to cope with the flu vaccine shortage during the cold season and the COVID-19 pandemic. In this case study, we present a prototype model developed for the MOHME for an equitable and fair distribution of the flu vaccine during the fall and winter flu season. Vaccines are generally distributed according to factors such as medical risks, ethics, public health, equity, economic impact, and logistics, among others. The MOHME considers age, pre-existing medical conditions, pregnancy, and healthcare-related jobs to group potential vaccine recipients into the following eight categories:

- Group 1: Infants and toddlers aged 6 to 35 months
- Group 2: Pregnant women with pre-existing medical conditions
- Group 3: Adults aged 65 years and older with pre-existing medical conditions
- Group 4: Critical healthcare providers and first responders
- Group 5: Pregnant women without pre-existing conditions
- Group 6: Adults aged 65 years and older without pre-existing medical conditions
- Group 7: People with pre-existing medical conditions
- Group 8: Other people

The demand for each group in each province and each group's coverage rate are presented in Tables 1 and 2, respectively. The MOHME has selected Tehran, Isfahan, East Azerbaijan, and Kerman (among the 31 available ones) suitable for distribution centers, as shown in Fig. 1. The transportation cost for each vaccine dose from the four potential distribution centers to the 31 warehouses (provinces) is shown in Table 3. Each vaccine dose costs the government $14.86, and the total available budget of MOHME for this year is $270,000,000.

Table 3 presents the transportation cost from a distribution center to a demand point for each vaccine dose. This cost is proportional to the distance between the two points. For example, $0.61 in the first row of this table asserts if Tehran is used as a distribution center, the cost of transporting each dose of vaccine from Tehran to East Azarbaijan is $0.61. This cost is considered as a function of distance due to the lack of actual transportation costs data in the planning phase.

The GAMS software with BARON solver is used to run the proposed model. The optimal values of the objective function and decision variables are calculated as follows:

- The optimal value of the objective function is equal to 0.029.
- Distribution center 1 (Tehran) was selected among the four potential distribution centers.
- A total of 15,398,713 influenza vaccines were purchased with the available budget of $270,000,000.
- The number of vaccine doses shipped from the Tehran distribution center to other provinces is presented in Table 4.

The value 121,686 in the first row and the first column of Table 4 represents that number of flu vaccine doses shipped from distribution center 1 in Tehran to province 1 in East Azarbaijan in time-period 1. Similarly, this table shows the number of vaccine doses shipped to each province in each time-period.

- The optimal number of vaccine doses assigned to Group 1 and each province in each time-period is presented in Table 5. Similarly, the optimal number of vaccine doses assigned to groups 2–8 in each province for each time-period is presented in the Appendix (See Table A).

The value 8678 in the first row and the first column of Table 5 indicates that 8678 flu vaccine doses have been allocated to Group 1 (Infants and toddlers aged 6 to 35 months) in Province 1 (i.e., East Azarbaijan) in time-period 1. The remaining number of vaccine doses are determined accordingly and presented in Table 5.

Table 1
The demand for each group in the provinces.

Province	p	Group							
		1	2	3	4	5	6	7	8
East Azerbaijan	1	285,487	2250	19,557	19,157	20,252	36,324	10,040	3,516,585
West Azerbaijan	2	209,236	842	8678	13,061	15,889	42,596	4657	2,970,260
Ardabil	3	96,045	396	7059	4955	5482	21,125	2275	1,133,083
Isfahan	4	543,628	2436	18,826	28,165	26,241	86,471	10,745	4,404,338
Alborz	5	444,378	1129	8504	15,732	8662	32,469	4360	2,197,166
Ilam	6	50,992	99	1744	1740	2086	7171	1264	515,062
Bushehr	7	92,676	543	2366	3490	4962	12,693	3585	1,043,085
Tehran	8	1,112,514	4598	18,135	79,606	73,328	192,077	35,476	11,751,903
Chaharmahal and Bakhtiari	9	80,727	345	4360	2749	3068	14,210	2709	839,592
South Khorasan	10	91,541	416	1747	2922	4373	10,038	1653	656,208
Khorasan Razavi	11	555,165	1477	9157	32,173	34,646	77,489	15,706	5,708,688
North Khorasan	12	70,181	423	1830	3884	4974	13,524	1615	766,661
Khuzestan	13	461,497	1286	19,525	16,958	30,037	50,966	8352	4,121,888
Zanjan	14	66,876	296	2684	4230	5103	12,473	2630	963,169
Semnan	15	59,558	385	710	2388	4214	11,302	1399	622,408
Sistan and baluchestan	16	348,982	1449	16,537	7770	18,719	39,422	5316	2,336,819
Fars	17	467,381	1066	17,138	24,256	20,367	60,885	10,672	4,249,508
Qazvin	18	97,577	379	6997	5095	6727	18,116	3773	1,135,098
Qom	19	74,038	481	2939	5815	8002	14,176	3328	1,183,505
Sanandaj	20	140,126	1059	2123	4809	5664	19,047	4993	1,425,195
Kerman	21	295,505	796	4290	14,241	11,478	33,045	7671	2,797,687
Kermanshah	22	116,921	851	2222	5272	7752	21,035	2369	1,796,012
Kohgiluyeh va Buyer Ahmad	23	57,172	377	3845	2068	2955	7176	1350	638,116
Golestan	24	166,553	1242	8662	6915	8929	19,549	3770	1,653,194
Gilan	25	268,028	1671	12,551	10,123	7828	33,173	7962	2,189,354
Lorestan	26	123,254	385	9020	5282	11,349	17,077	5613	1,588,669
Mazandaran	27	266,866	1129	9352	14,119	21,881	32,984	10,038	2,927,211
Markazi	28	95,074	226	3773	6433	8111	22,186	3320	1,290,355
Hormozgan	29	150,240	845	7141	5329	7426	23,181	2560	1,579,688
Hamedan	30	156,808	258	1993	6953	7755	17,034	5286	1,542,147
Yazd	31	72,962	494	3263	5123	7948	11,166	2923	1,034,656

Table 2
The coverage rate for each group.

	Group							
	1	2	3	4	5	6	7	8
Coverage rate(θ_i)	0.7	0.9	0.9	1	0.7	0.6	0.7	0.1

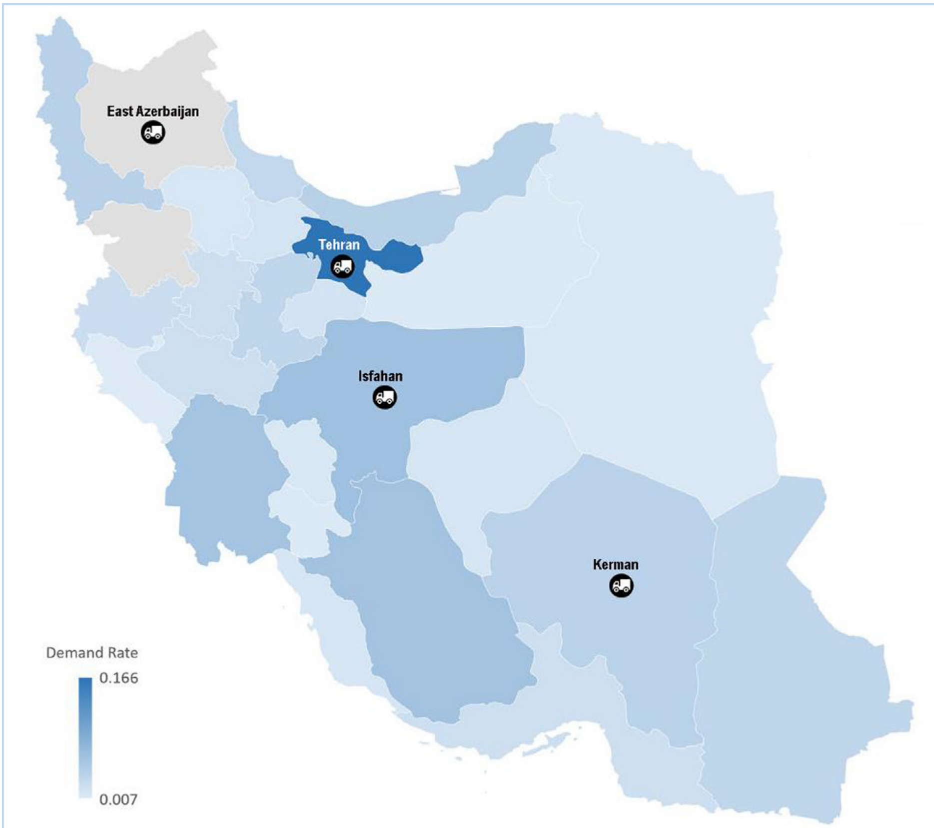

Fig. 1. The geographical location of the potential distribution center.

- The number of flu vaccine doses stored in the warehouses at provinces in each time-period is reported in Table 6.

The proposed model equitably distributes the vaccine doses to all provinces. Fig. 2 presents the vaccine distribution from the Tehran distribution center to East Azarbaijan province for all four time-period.

As shown in Figure 2, 121686, 479059, and 121,801 vaccine doses are shipped from the Tehran distribution center to the East Azarbaijan warehouse in time-periods 1, 2, and 4, respectively. However, no vaccine doses are shipped in time-period 3 since the need for vaccine in this time-period is covered by the available vaccines from time-period 2. Among the 121,686 flue vaccine doses shipped in the first time-period, 8678 doses have been assigned to Group 1 (Infants and toddlers aged 6 to 35 months), 70 doses to Group 2 (Pregnant women with pre-existing medical conditions), 601 doses to Group 3 (Adults aged 65 years and older with pre-existing medical conditions), 594 doses to Group 4 (Critical healthcare providers and first responders), 612 doses to Group 5 (Pregnant women without pre-existing conditions), 1116 doses to Group 6 (Adults aged 65 years and older without pre-existing medical conditions), 311 doses to Group 7 (People with pre-existing medical conditions), and 109,704 doses have been assigned to Group 8 (Other people).

In summary, the optimal solution selected Tehran as a distribution center considering a total budget of $270,000,000) and purchased 15,398,713 doses of the vaccines. The remaining question is the number of vaccine doses that should be bought and distributed if other centers were set up? If the Isfahan distribution center is set up, 15,301,903 doses of vaccine can be purchased and distributed considering the available budget. If the East Azarbaijan is set up, the number of vaccine doses will be reduced to 14,882,527. Finally, if the Kerman is selected as the distribution center, 14,771,554 vaccine doses are purchased and distributed. Therefore, the results show that Tehran is the optimal distribution center. Besides, suppose the decision-makers' policy is to use the maximum capacity of the distribution center. In that case, the question is how much budget is needed to set up a network with the maximum capacity? This distribution center's capacity is equal to 18,000,000 vaccine doses for a total of four time-periods, where the amount of $309,933,087 is required for a chain with this capacity. Thus, for an additional $40,000 budget, it is possible to distribute 2,601,287 more vaccine doses in the chain. It is noteworthy that the value of the objective function changes from 0.029 to 0.03 in this case.

Table 3
The transportation cost for each vaccine dose from the potential distribution centers to the warehouses (provinces).

Province	p	Potential distribution center			
		Tehran	Isfahan	East Azerbaijan	Kerman
East Azerbaijan	1	0.61	0.99	0.08	1.46
West Azerbaijan	2	0.68	1.02	0.31	1.76
Ardabil	3	0.59	0.95	0.21	1.56
Isfahan	4	0.45	0.08	0.99	0.68
Alborz	5	0.12	0.40	0.60	0.96
Ilam	6	0.66	0.75	0.76	1.35
Bushehr	7	0.98	0.79	1.53	1.01
Tehran	8	0.09	0.39	0.61	0.96
Chaharmahal and Bakhtiari	9	0.53	0.12	0.99	0.78
South Khorasan	10	1.01	1.21	1.39	0.81
Khorasan Razavi	11	0.87	1.13	1.34	0.90
North Khorasan	12	0.72	1.15	1.31	0.94
Khuzestan	13	0.81	0.74	0.98	1.28
Zanjan	14	0.33	0.72	0.29	1.17
Semnan	15	0.24	0.61	0.82	1.18
Sistan and baluchestan	16	1.14	1.08	2.05	0.49
Fars	17	0.88	0.46	1.48	0.77
Qazvin	18	0.17	0.53	0.46	1.20
Qom	19	0.22	0.32	0.51	0.98
Sanandaj	20	0.47	0.63	0.43	1.38
Kerman	21	0.96	0.68	1.46	0.08
Kermanshah	22	0.48	0.64	0.56	1.20
Kohgiluyeh va Buyer Ahmad	23	0.74	0.70	1.43	1.00
Golestan	24	0.45	0.80	0.96	1.18
Gilan	25	0.32	0.71	0.46	1.19
Lorestan	26	0.50	0.35	0.75	0.95
Mazandaran	27	0.30	0.64	0.85	1.21
Markazi	28	0.26	0.29	0.78	0.97
Hormozgan	29	1.09	0.95	1.91	0.48
Hamedan	30	0.32	0.45	0.58	1.07
Yazd	31	0.61	0.30	0.96	0.36

Table 4
The optimal number of vaccines shipped from the Tehran distribution center to other provinces.

Province	p	t = 1	t = 2	t = 3	t = 4
East Azerbaijan	1	121,686	479,059	0	121,801
West Azerbaijan	2	101,452	101,452	273,385	101,608
Ardabil	3	39,553	39,551	119,452	39,550
Isfahan	4	472,270	263,003	159,432	159,432
Alborz	5	84,448	374,367	84,442	94,426
Ilam	6	72,957	0	18,063	18,995
Bushehr	7	177,843	0	0	36,642
Tehran	8	654,387	564,517	413,071	901,950
Chaharmahal and Bakhtiari	9	31,914	86,313	32,889	29,507
South Khorasan	10	28,712	81,766	26,497	23,936
Khorasan Razavi	11	916,739	0	0	306,312
North Khorasan	12	26,871	81,371	26,871	28,130
Khuzestan	13	412,221	370,629	0	146,667
Zanjan	14	32,797	32,576	32,587	87,805
Semnan	15	21,866	65,262	24,292	21,857
Sistan and baluchestan	16	172,794	0	426,946	0
Fars	17	420,040	151,039	151,039	233,203
Qazvin	18	39,656	49,247	149,679	0
Qom	19	40,161	40,161	145,715	0
Sanandaj	20	50,211	202,320	0	48,319
Kerman	21	98,530	98,530	311,728	98,530
Kermanshah	22	121,574	0	150,898	62,360
Kohgiluyeh va Buyer Ahmad	23	22,201	22,201	22,201	66,077
Golestan	24	58,184	182,198	118,882	0
Gilan	25	78,790	78,790	78,790	277,783
Lorestan	26	54,813	145,970	65,939	54,813
Mazandaran	27	358,033	0	258,006	0
Markazi	28	88,692	0	44,503	125,678
Hormozgan	29	110,611	0	55,308	169,390
Hamedan	30	54,118	53,800	54,116	167,794
Yazd	31	35,876	89,860	0	77,435

Table 5
The optimal number of vaccine doses assigned to Group 1 and each province in each time-period.

Province (p)	t = 1	t = 2	t = 3	t = 4
1	8678	174,503	8330	8330
2	6343	6343	127,276	6504
3	2983	2983	58,463	2803
4	329,904	16,939	16,852	16,845
5	13,395	270,444	13,395	13,831
6	30,986	1536	1581	1592
7	56,340	2794	2848	2892
8	34,004	184,479	34,709	525,568
9	2508	48,989	2513	2499
10	2816	55,580	2784	2899
11	231,679	17,380	16,196	123,361
12	2195	42,560	2191	2181
13	280,303	15,003	13,871	13,871
14	2233	2017	2028	40,536
15	1858	36,146	1846	1841
16	11,004	10,525	212,026	10,733
17	283,820	14,537	14,537	14,273
18	3027	3014	59,273	2990
19	2283	2284	44,977	2283
20	4233	85,279	4355	4222
21	9237	9117	179,405	9095
22	3746	3545	71,010	3544
23	1786	1789	1789	34,657
24	5119	101,156	5006	5307
25	8459	8082	8450	162,629
26	3841	74,835	3802	3800
27	162,536	8044	8135	8092
28	3006	2969	2969	57,608
29	4647	4384	4685	91,452
30	4846	4852	4852	95,216
31	2193	2198	2257	44,426

Table 6
The number of vaccines stored in warehouses at provinces in each time-period.

Province (p)	t = 1	t = 2	t = 3
1	0	121,205	0
3	0	0	1978
6	18,003	0	0
7	72,011	35,766	0
11	399,411	199,112	0
13	0	145,980	0
16	85,260	0	86,408
18	0	0	39,501
19	0	0	42,388
20	0	50,063	0
22	60,442	0	0
24	0	0	61,179
27	101,315	0	101,635
28	44,318	0	0
29	57,069	0	0
31	0	35,229	0

5. Sensitivity analysis

In this section, budgeting scenarios are used to evaluate the performance and behavior of the proposed model. The total vaccine doses are expected to increase by increasing the budget. Similarly, the total vaccine doses are expected to decrease by decreasing the budget. Seven scenarios are considered for sensitivity analysis. Scenarios 1 to 3 consider possible budget decreases, and scenarios 5 to 7 consider possible budget increases. The seven scenarios' results are presented tabularly in Table 7 and depicted graphically in Fig. 3.

As shown in Table 7 and Fig. 3, the total vaccine doses increase with the increase in budget, and the total vaccine doses decrease with the decrease in budget. This sensitivity analysis confirms the expected behavior of the model proposed in this study.

6. Managerial implications

This study proposes a practical model for equitable influenza vaccine distribution in developing countries. Most developing countries, such as Iran, cannot provide the influenza vaccine to the entire population due to the unavailability of production technology, budgetary constraints, and lack of distribution infrastructure. Therefore, developing an equitable vaccine distribution system and providing vaccines to vulnerable groups is a high priority in developing countries. The model proposed in this study is not only applicable to equitable influenza vaccine distribution; it could be modified for other vaccines (e.g., COVID-19 vaccine) where classification and prioritization are pre-requisites for equitable vaccine distribution. For example, the transportation, storage, and application requirements for the COVID-19 vaccine are similar to those of the influenza vaccine. First, both vaccines belong to the cold supply chain, and storing them at an unsuitable temperature affects their quality and can lead to their perishability. Second, both vaccines are used to kill highly contagious viruses with high outbreak rates. Third, disregard for vulnerable groups in the population can lead to catastrophic events. Fourth, the vaccine's transportation is an important concern in designing a cold supply chain since improper transportation can impact vaccine quality and perishability. Fifth, the transportation cost in the cold supply chain is strongly influenced by the distance between the distribution point and the demand point. In this study, an attempt is made to develop a comprehensive and equitable vaccine distribution model that is easily adaptable to various vaccine distribution and application requirements in developing countries.

7. Conclusion

Influenza and COVID-19 are both respiratory viruses requiring similar supplies and equipment. Hospitals currently accommodating COVID-19 patients may not be able to manage additional flu patients during the flu season [24]. The flu vaccine supply chain's

Table 7
Sensitivity analysis on budget variations.

Scenario	Budget	Total doses of the vaccine purchased
S1	240,000,000	13,504,374
S2	250,000,000	14,135,925
S3	260,000,000	14,749,295
S4 (main problem)	270,000,000	15,398,713
S5	280,000,000	15,951,946
S6	290,000,000	16,687,774
S7	300,000,000	17,425,952

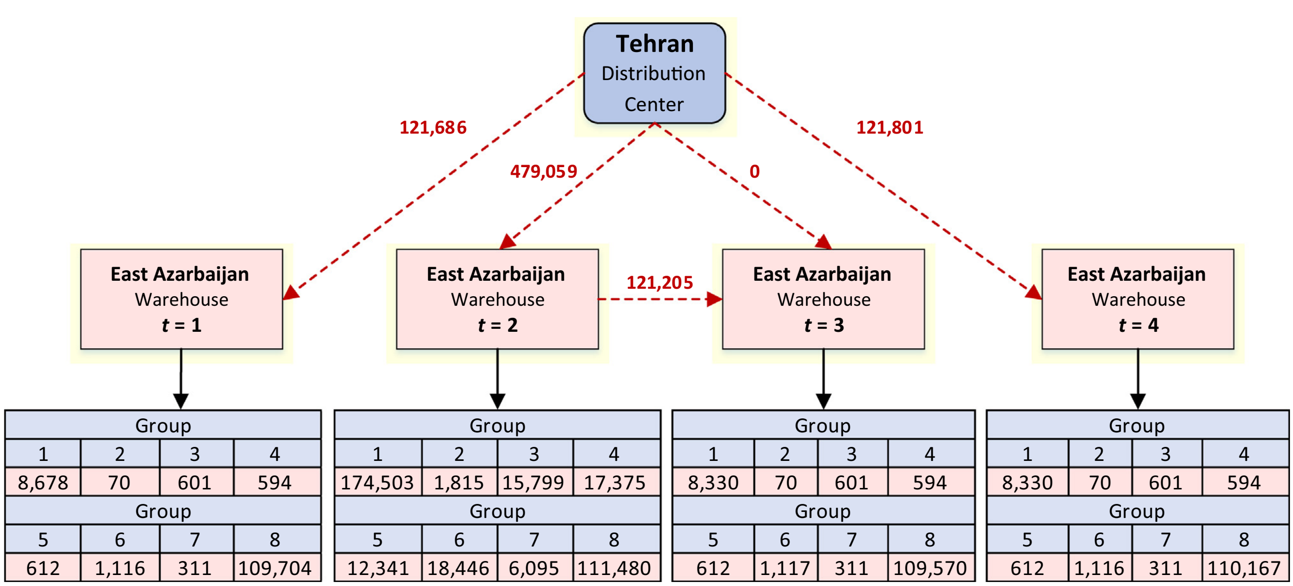

Fig. 2. The assigned vaccines to groups in each time-period in East Azarbaijan Province.

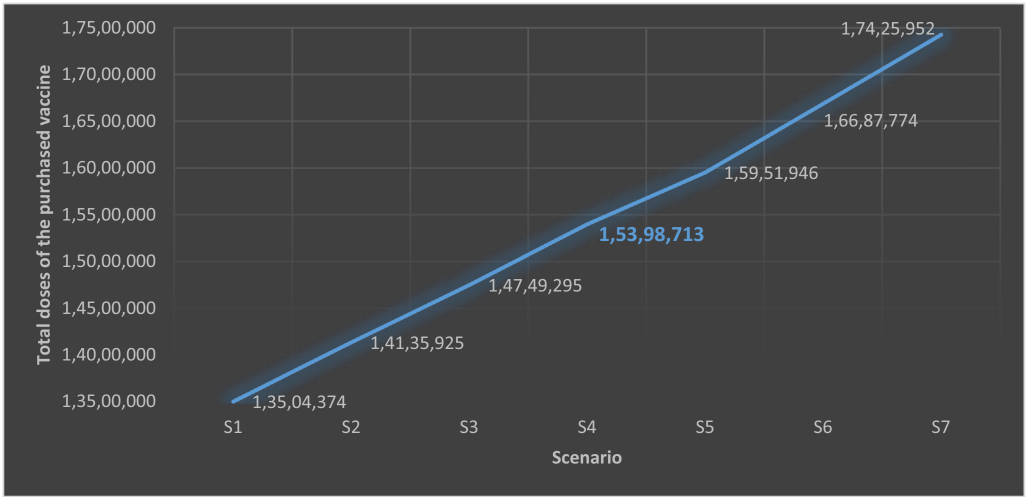

Fig. 3. Total doses of the purchased vaccine for each scenario.

role is to ensure that the right product, in the right quantity, is distributed to the right place, at the right time. The risks of inefficient and ineffective flu vaccine supply chains are detrimental to the healthcare sector [25]. In this paper, we proposed a MILP model for the equitable distribution of influenza vaccine doses during the COVID-19 outbreak. The proposed model is a single product multi-period model with distribution centers, storage capabilities, possible shortage, and capacitated distribution centers. According to the MOHME requirements, the population was divided into eight groups according to age, pre-existing medical conditions, pregnancy, and healthcare-related jobs. Each group was allocated an equitable number of vaccine doses according to their coverage rate. The results demonstrate the applicability of the inventory-location optimization model proposed in this study for equitable influenza vaccine distribution During the COVID-19 Pandemic.

The storage and distribution of the influenza vaccine are similar to that of the COVID-19 vaccine. Future research is needed to develop a cold supply chain network for equitable COVID-19 vaccine distribution by considering uncertain, unavailable, or incomplete demand data in developing countries. Moreover, vehicle r-outing considerations can improve the model's performance and applicability in rural areas with little or no transportation infrastructure. Finally, the inclusion of other objectives, such as the number of healthcare workers and vaccination stations, may enhance the model's efficacy in urban areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Dr. Madjid Tavana is grateful for the partial support he received from the Czech Science Foundation (GAČR19-13946S) for this research.

Appendix Table A. The optimal number of vaccine doses assigned to groups 2–8 and each province in each time-period

p	Group 2				Group 3				Group 4				Group 5				Group 6				Group 7				Group 8			
	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4	t = 1	t = 2	t = 3	t = 4
1	70	1815	70	70	601	15,799	601	601	594	17,375	594	594	612	12,341	612	612	1116	18,446	1117	1116	311	6095	311	311	109,704	111,480	109,570	110,167
2	26	26	680	26	263	263	7022	263	405	405	11,846	405	479	479	9686	479	1326	1326	21,580	1326	145	145	2830	140	92,465	92,465	92,465	92,465
3	12	12	320	13	218	218	5695	223	153	153	4495	154	170	170	3326	172	649	649	10,728	649	69	69	1386	69	35,299	35,297	33,061	37,445
4	74	1973	73	73	603	15,200	567	574	882	25,545	869	869	813	15,932	812	812	2692	43,807	2692	2692	326	6548	324	324	136,976	137,059	137,243	137,243
5	35	35	35	912	257	259	257	6881	487	14,264	494	487	268	5255	273	268	979	16,545	979	979	134	134	134	2650	68,893	67,431	68,875	68,418
6	3	3	3	90	1408	54	54	54	1583	52	52	53	1272	63	63	63	3637	222	222	222	39	39	39	885	16,026	16,034	16,049	16,036
7	18	16	16	439	1911	73	73	73	3166	108	108	108	3011	156	158	149	6431	395	395	395	2177	111	111	111	32,778	32,592	32,057	32,475
8	3710	143	143	143	14,642	560	560	560	72,209	2570	2323	2504	44,520	2270	2270	2270	97,835	5804	5804	5804	21,522	1104	1104	1104	365,945	367,587	366,158	363,997
9	11	279	10	11	134	134	3522	134	2499	85	80	85	95	1863	95	95	442	7200	442	442	85	1644	84	84	26,140	26,119	26,143	26,157
10	12	339	12	12	53	1410	53	57	88	88	2658	88	136	2654	136	136	5113	310	293	307	51	1005	51	51	20,443	20,380	20,510	20,386
11	1192	46	46	46	7398	279	276	289	29,185	996	996	996	21,046	1069	1069	1069	39,485	2329	2329	2351	9534	487	487	487	177,809	177,713	177,713	177,713
12	13	13	13	342	55	1482	55	55	124	3526	117	117	154	3020	154	154	421	6852	421	421	50	50	50	981	23,859	23,868	23,870	23,879
13	40	1038	40	40	595	15,798	590	590	521	15,395	521	521	902	18,320	902	902	1586	25,820	1588	1586	260	5067	260	260	128,014	128,208	128,208	128,897
14	9	9	9	240	83	83	83	2167	131	131	131	3837	155	153	153	3112	387	386	386	6325	81	79	79	1602	29,718	29,718	29,718	29,986
15	12	311	12	12	22	573	22	22	72	2165	72	79	130	130	2558	132	349	5735	349	349	44	850	43	43	19,379	19,352	19,390	19,379
16	44	42	1174	45	498	498	13,390	498	251	234	7048	237	578	578	11,370	578	1185	1185	20,064	1220	164	164	3230	164	73,810	72,034	72,236	72,933
17	33	33	33	861	559	516	516	13,834	754	749	749	22,004	614	614	614	12,415	1845	1845	1845	30,996	328	328	328	6487	132,087	132,417	132,417	132,333
18	12	308	11	11	215	5653	215	215	158	158	4621	158	202	4081	202	224	564	564	9178	564	117	117	2291	117	35,361	35,352	34,387	35,222
19	15	14	390	14	91	91	2373	91	181	181	5272	181	249	249	4855	249	427	427	8506	428	103	103	103	2330	36,812	36,812	36,851	36,812
20	32	856	34	32	64	1718	65	64	145	4374	145	145	174	3436	181	174	573	9708	576	572	151	3045	150	150	44,839	43,841	44,557	42,960
21	24	24	645	24	130	130	3471	130	455	429	12,911	446	358	357	6963	357	1088	996	16,742	1001	245	231	4663	231	86,993	87,246	86,928	87,246
22	28	25	687	26	68	67	1798	67	164	164	4780	164	240	240	4703	244	651	651	10,668	651	78	71	1439	71	56,157	55,679	55,813	57,593
23	13	11	11	305	119	119	119	3104	64	64	64	1876	92	92	92	1793	217	216	216	3657	42	42	42	819	19,868	19,868	19,868	19,866
24	38	1002	41	37	268	6987	273	268	214	6273	214	214	278	5422	269	282	605	9915	605	605	114	114	113	2639	51,548	51,329	51,182	51,827
25	52	52	52	1348	385	378	378	10,155	315	315	315	9178	246	236	245	4753	1000	1000	1000	16,904	257	240	240	4837	68,076	68,487	68,110	67,979
26	12	12	311	12	276	7298	272	272	163	5282	163	163	353	353	7945	353	539	8673	516	519	175	179	3406	170	49,454	49,338	49,524	49,524
27	35	35	912	35	290	290	7547	290	436	436	12,811	436	701	663	13,290	663	1001	1027	16,801	962	307	293	6117	310	91,412	90,527	90,758	90,847
28	7	7	7	183	117	117	117	3045	195	195	195	6433	251	251	251	4925	685	666	666	11,295	102	102	102	2018	40,011	40,011	40,196	40,171
29	26	26	26	683	221	221	221	5764	161	161	161	4846	231	231	231	4506	723	721	721	11,744	81	79	79	1553	47,452	51,246	49,184	48,842
30	8	8	8	209	62	62	62	1608	214	209	209	6321	240	244	240	4705	526	526	526	8643	160	159	159	3223	48,062	47,740	48,060	47,869
31	15	400	15	15	101	2634	101	101	154	4661	154	154	246	4822	250	246	348	5663	343	346	91	1774	91	91	32,728	32,479	32,018	32,056

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