Fair allocation of potential COVID-19 vaccines using an optimization-based strategy

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Abstract

The fair allocation of resources among multiple stakeholders in any area is a complex challenge for decision-making. This paper presents an optimization strategy for the allocation of COVID-19 vaccines, when these are available, through different fairness schemes (social welfare, Nash, Rawlsian justice, and social welfare II scheme). The applicability of the proposed model is illustrated using the case study of Mexico, including the states of the country as stakeholders. We involve several parameters to guide the allocation, such as the size, risk profiles, and fraction of vulnerable groups in the population. Furthermore, different scenarios of the availability of potential COVID-19 vaccines were evaluated. The social welfare approach is the most used scheme for the allocation of resources. However, we demonstrate that this scheme yields non-unique or multiple solutions (through the social welfare II approach). These social welfare approaches provide inequalities in the allocations that become critical when the resources are scarce. Specifically, the social welfare scheme favors large stakeholders (greater population) in all scenarios. We also observe how the complexity of the allocation increases with the higher availability of vaccines. Hence, the importance of considering allocation schemes to identify fair solutions.

Keywords: Optimization, COVID-19, vaccines, allocation schemes, mathematical modeling.

Introduction

The first outbreak of severe acute respiratory syndrome (SARS) was 18 years ago. Since then, several SARS-related coronaviruses (SARSr-CoVs) have been discovered in their natural reservoir host: bats (Li et al. 2005). Also, serological evidence related to the potential of bat SARSr-CoVs to infect humans has been presented (Wang et al. 2018). Recently, the identification and characterization of the new coronavirus, which caused the epidemic that started on 12 December 2019 in Wuhan, China has been reported (Zhou et al. 2020). The World Health Organization informed about the official name of the infectious disease caused by this new virus: COVID-19 (WHO 2020a). COVID-19 is now a pandemic affecting many countries worldwide.

According to WHO (WHO 2020b), most people recover from the disease without hospital treatment. However, 1 out of 5 patients becomes seriously ill and develop difficulty breathing. Furthermore, it has been reported that the COVID-19 case fatality rates are higher for vulnerable groups. These populations include the elderly and those with comorbid conditions, such as diabetes and hypertension (Wu and McGoogan 2020). Unfortunately, for elderly patients with COVID-19, the probability of progressing to severe disease is higher, as well as mortality. The main cause of this is that elderly patients are more prone to multi-system organ dysfunction or even failure (Liu et al. 2020). Also, patients with pre-existing comorbidities are at higher risk of developing severe coronavirus infections than patients with healthy medical history (Garg et al. 2020).

Problems in the allocation of medical resources have arisen worldwide due to the COVID-19 pandemic. For instance, a shortage of N-95 masks for health workers in the United States occurred. This led to reuse these masks that are designed for single use. Also, in Italy physicians have proposed giving priority of intensive care beds and ventilators to patients that can benefit more. Strategies for the allocation of resources in pandemics have been proposed previously. These strategies include four ethical values: 1) maximizing the benefits, 2) treating inhabitants equally, 3) promoting and rewarding instrumental value, and 4) giving priority to the worst-off. Overall, fair allocation needs a multivalue ethical framework that may vary depending on the context (Emanuel et al. 2020). On the other hand, the allocation of resources is not typically considered in the decision-making process of medical cases, until there is a shortage of healthcare resources. Therefore, when evaluating the allocation of scarce resources, it is important to consider the proportionality of care and distributive justice (Vergano et al. 2020). Similarly, human resource allocation for crisis conditions has been studied by Aviso et al. (2017). Here, a P-graph model for the optimal allocation of workforce during natural disasters or new disease outbreaks was proposed.

The global allocation of potential COVID-19 vaccines is an important concern that is being currently analyzed. The main goal would be to achieve an equitable distribution among all countries. However, this represents a great challenge. Researchers have been warning about the barriers to making vaccines to everyone and the possibilities that wealthy countries might hoard supplies. Even if enough vaccines were made, there is no law to force countries to share them. The Coalition for Epidemic Preparedness Innovations mentioned that there are no contracts yet on the principles for a fair allocation system. Furthermore, there is no global entity responsible for the logistics of the manufacturing of vaccines on a global scale (including orders and payments) (Khamsi 2020). Recently, the European Commission–backed Access to COVID-19 Tools Accelerator was launched. This initiative is devoted to the development and equitable allocation of potential vaccines and others. Several countries and philanthropies are willing to give financial support. Nevertheless, G20 states still need to join the initiative. The global allocation of vaccines and therapeutics should be fair but also health-driven. A health-driven allocation includes considering the size, distribution, and risk profiles of populations. Specifically, governments must develop strategies to ensure that, when vaccines become available, they are distributed equitably and fairly among all their populations (including vulnerable groups) (Bollyky et al. 2020). Moreover, when the COVID-19 vaccine is approved, new manufacturing sites would need to be built. These sites should be distributed worldwide to ensure equitable allocation (Mahase 2020). Besides this, promptly availability in an efficient way that can be accessible or affordable to all must be a priority (Bassi and Hwenda 2020).

The landscape of the COVID-19 vaccine research and development is as follows. Till April 8, 2020, there are 115 vaccine candidates. From these, 78 have been confirmed as active. Of the 78 projects, 73 are at exploratory or preclinical stages, while the most advanced candidates have moved into clinical development (phase 1). 72 % of the confirmed active vaccine candidates are being developed by private or industry developers. The rest are projects developed by the academic, public sector, and other non-profit organizations. Most vaccine developments have been made in North America, followed by China, Asia (excluding China) and Australia, and Europe. There is no current public information about vaccine development in Africa or Latin America. Given the global effort and the urgency for speed, there is an indication that vaccines can be available by early 2021 (under emergency use) (Le et al. 2020).

In the meantime, of the COVID-19 vaccine being approved, some governments (including Chile, Germany, Italy, the UK, and the USA) have suggested an alternative. Their proposal consists of using immunity passports which are documents that certify an individual has been infected and is presumably immune to COVID-19. However, this implies important equitable and legal challenges. Moreover, at this point in the pandemic, there is not enough evidence that people who have recovered from COVID-19 are protected from a second infection. Regarding fairness, there is no guarantee that the access to antibody testing would be equal for all (including vulnerable populations) (Phelan 2020).

The allocation of resources among multiple stakeholders is an important problem for decision-making. Recently, an axiomatic approach including different allocation schemes has been reported (Sampat and Zavala 2019). Here, the deficiencies and desirable properties of these fairness allocation approaches are analyzed. The allocation of resources is often done by maximizing the sum of individual utilities (total utility). This approach is known as the social welfare scheme. Some deficiencies of this scheme include obtaining multiple allocations that yield unfair solutions. Also, the allocations might not capture stakeholder scales properly. On the other hand, the Rawlsian justice scheme was proposed by Rawls (Rawls 1971). This approach allocates resources by maximizing the utility of the smallest stakeholder, which means providing the greatest benefit to the least well-off members of society. However, this scheme might identify non-unique solutions. Alternatively, Nash (Nash 1950) proposed an approach where the allocation is guided by maximizing the product of individual utilities. This is equivalent to maximizing the sum of the logarithms of the utilities. This formulation identifies unique solutions and captures stakeholder scales. Furthermore, a scheme to illustrate the multiple allocations that can be obtained by the social welfare approach was recently proposed (Munguía-López et al. 2019). This scheme is denoted as social welfare II and it helps to identify the degenerate nature of the standard social welfare scheme.

These schemes have been previously used through mathematical models to allocate resources in agricultural (water) and industrial systems (raw materials) (Munguía-López et al. 2019; Juárez-García et al. 2020). Furthermore, the social welfare approach has been used to allocate supply and demand in electricity markets (Zavala et al. 2017). On the other hand, in the allocation of scarce medical interventions, the concepts of some allocation schemes including the Rawlsian justice and the social welfare approach (also called utilitarianism) have been analyzed from an ethical point of view (Persad et al. 2009). Moreover, the Nash approach has been used to compare care delivery settings for older adults (Mendoza-Alonso et al. 2020). Here, a multi-objective integer programming formulation was proposed.

Regarding healthcare allocation, the allocation of ambulances considering fairness elements through optimization models has been studied (Acuna et al. 2019). Here, the min-max strategy and the Nash scheme are compared and new insights for policy regulations are given. Previously for the influenza pandemics, a simulation optimization model to distribute mitigation resources was proposed by Savachkin and Uribe (2012). Their model seeks to support dynamic resource distribution by minimizing the impact of ongoing and potential outbreaks. However, fairness measures have not been considered here. Moreover, a mathematical approach to predict the number of ICU patients, as well as the mortality rate under the COVID-19 emergency, has been proposed (Manca et al. 2020). Here, regression models were used to predict possible scenarios of the analyzed variables. Furthermore, Sy et al. (2020) recommended using optimization modeling techniques for medical supplies allocation, especially in scarce scenarios.

Therefore, we propose a mathematical modeling approach to find optimal allocations that can be deemed fair according to a set of fundamental axioms. Specifically, we study the allocation of potential COVID-19 vaccines among multiple stakeholders under different availability scenarios. Through the proposed model, it is possible to identify various allocations given by the fairness schemes. Moreover, alternatives for the decision-making of allocations are highlighted. This provides a first approach for the allocation strategy of vaccines so that it can be used when these become available.

Problem Statement

The proposed problem consists of finding the optimal allocation of potential vaccines for COVID-19 among distinct stakeholders. To do so, this work presents an optimization formulation that uses fairness schemes to find such allocations. These schemes include the social welfare, Nash, Rawlsian, and social welfare II approaches. Specifically, we propose to apply the formulation to the case study of Mexico. The 32 states of the country are considered as stakeholders, while distinct scenarios of availability of vaccines are analyzed. Different parameters that are characteristic of each state were included. Some of these parameters involve the population, the rate of cases, the available beds, and the mortality rate due to COVID-19. It is important to account for these values to guide the allocation of vaccines. The resulting model is based on the superstructure depicted in Figure 1. The solution to the problem involves finding the optimum allocated vaccines for each state through different allocation schemes. Note that the model is general and can be applied to any case study by modifying the parameters. Besides considering the states of Mexico for the case study, the municipalities can be involved as well. On the other hand, countries could be included in the analysis to identify the worldwide allocation of potential vaccines.

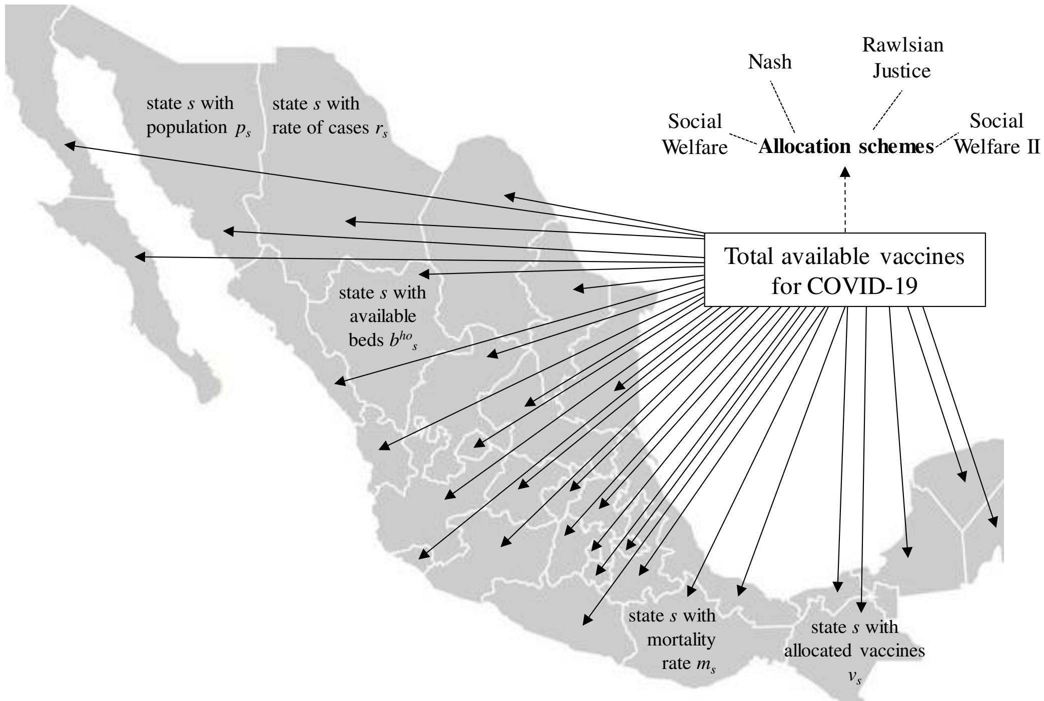

Figure 1. Superstructure proposed for the allocation of potential vaccines among the different states in Mexico.

Regarding the case study, information from the Mexican government, as well as from other references, was used for the different parameters. The data related to COVID-19, such as the rate of cases or the mortality rate, is based on the reported cases till April 29, 2020. Figure 2 presents the fraction of the population of each state that is considered the most vulnerable to COVID-19. These vulnerable groups include the elderly population, adults with hypertension, as well as with diagnosed diabetes mellitus, and obesity. The mortality rate due to COVID-19 in these groups is shown in Table 1. We can see that the highest rate is for the elderly population (m^e), then for adults with hypertension (m^{hy}), diabetes (m^{dm}), and obesity (m^{ob}). The population of the states is significantly different since the least populated state has less than 10% of the population of the most populated state. This data is presented in Table

2. Here, the cases and mortality rates due to COVID-19 for each state are also shown. Besides, the required parameters to estimate the COVID-19 patients that would require hospitalization but will not receive this service due to a lack of medical resources are reported. These parameters include the total available beds per state, as well as the discharged patients (of all diseases) and their average stay in a given year.

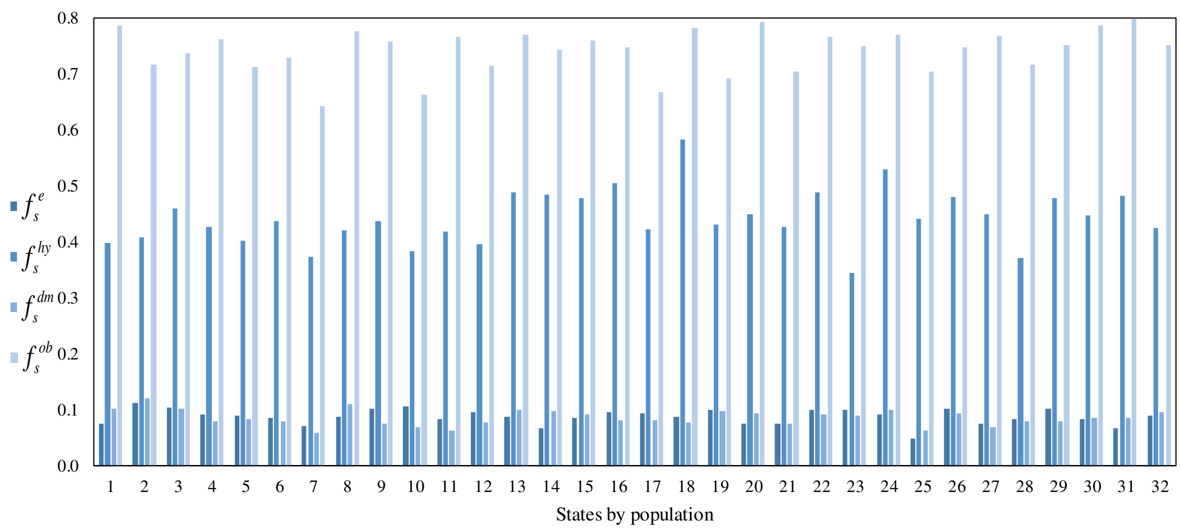

Figure 2. Parameters for each state including the fraction of elderly population (f^e_s), the prevalence of hypertension in adults (f^{hy}_s), the prevalence of diagnosed diabetes mellitus in adults (f^{dm}_s), and the prevalence of obesity in adults (f^{ob}_s) (INEGI 2014; Barquera et al. 2010; Hernández-Ávila et al. 2013; Barquera et al. 2013).

Table 1. Data including the mortality for the vulnerable groups to COVID-19 (m^e, m^{hy}, m^{dm}, m^{ob}) as well as the fraction of COVID-19 patients that require hospitalization (f^h) and the occupancy index in hospitals (i^o) (UISP 2020; DGE 2020; Quesada 2009).

m^e	m^{hy}	m^{dm}	m^{ob}	f^h	i^o
4.81E-01	4.27E-01	3.99E-01	3.00E-01	3.96E-01	8.50E-01

Table 2. Parameters for each state including population (p_s), rate of COVID-19 cases (r_s), and COVID-19 mortality rate (m_s), as well as available beds ($b^{ho}{}_s$), discharged patients ($d^p{}_s$), and average stay of patients in days ($s^a{}_s$) for all diseases. The information related to COVID-19 is based on the reported cases till April 29, 2020 (DGE 2020; SINAISCAP 2020).

States by population		p_s	r_s	m_s	$b^{ho}{}_s$	$d^p{}_s$	$s^a{}_s$
1	Estado de Mexico	17,427,790	1.64E-04	7.33E-02	8,356	303,939	4.3
2	Ciudad de Mexico	9,018,645	5.30E-04	6.71E-02	15,632	249,752	5.7
3	Veracruz	8,539,862	6.02E-05	8.56E-02	4,999	163,327	3.5
4	Jalisco	8,409,693	3.88E-05	7.66E-02	6,460	176,843	4.1
5	Puebla	6,604,451	9.40E-05	1.35E-01	4,012	118,039	4.4
6	Guanajuato	6,228,175	3.84E-05	9.20E-02	3,657	158,514	3.7
7	Chiapas	5,730,367	2.88E-05	4.24E-02	2,260	108,258	3.3
8	Nuevo Leon	5,610,153	5.58E-05	3.83E-02	4,077	54,699	3.7
9	Michoacán	4,825,401	5.76E-05	1.30E-01	2,648	100,186	2.6
10	Oaxaca	4,143,593	3.14E-05	1.38E-01	2,352	76,420	3.5
11	Chihuahua	3,801,487	8.55E-05	2.12E-01	2,915	81,911	4.1
12	Guerrero	3,657,048	7.33E-05	1.83E-01	2,075	78,186	3.2
13	Tamaulipas	3,650,602	8.44E-05	5.84E-02	2,977	77,266	3.8
14	Baja California	3,634,868	4.11E-04	1.42E-01	2,153	40,627	4.5
15	Coahuila	3,218,720	1.15E-04	1.11E-01	2,915	39,205	3.7
16	Sinaloa	3,156,674	2.60E-04	1.62E-01	2,382	54,142	3.9
17	Hidalgo	3,086,414	7.84E-05	1.12E-01	1,367	56,521	4.2
18	Sonora	3,074,745	6.57E-05	1.09E-01	2,894	90,264	2.9
19	San Luis Potosi	2,866,142	3.42E-05	7.14E-02	2,021	60,832	4
20	Tabasco	2,572,287	3.66E-04	1.24E-01	1,583	81,367	2.9
21	Queretaro	2,279,637	5.61E-05	7.82E-02	881	51,749	3.2
22	Yucatan	2,259,098	1.79E-04	6.44E-02	1,800	53,173	4.3
23	Morelos	2,044,058	1.36E-04	1.12E-01	1,047	44,348	2.7
24	Durango	1,868,996	3.10E-05	1.04E-01	1,542	48,582	2.6
25	Quintana Roo	1,723,259	4.13E-04	1.53E-01	1,030	40,320	3.6
26	Zacatecas	1,666,426	4.20E-05	1.00E-01	999	38,496	3.4
27	Aguascalientes	1,434,635	1.29E-04	1.08E-02	966	39,160	3.3
28	Tlaxcala	1,380,011	1.30E-04	1.01E-01	714	54,655	2.2
29	Nayarit	1,288,571	5.59E-05	1.67E-01	714	19,665	2.8
30	Campeche	1,000,617	8.69E-05	1.96E-01	790	24,245	3.9
31	Baja California Sur	804,708	3.74E-04	5.32E-02	695	19,639	3.2
32	Colima	785,153	3.31E-05	1.15E-01	649	19,049	3.5

Model Formulation

To find the optimal allocation of potential vaccines among the states, different schemes were evaluated (social welfare, Nash, Rawlsian justice, and social welfare II scheme) through the mathematical model. The objective function of the model depends on the allocation scheme. Therefore, first, we present the equations that are included in every formulation of the schemes. Then, the objectives for each scheme are explained.

As shown in Equation (1), the sum of the allocated vaccines to each state *s* must be lower or equal than the total available vaccines (*VT*). Furthermore, Equations (2) and (3) are used to denote that the vaccines for each state *s* must be lower or equal than the population (p_s) and at least equal to a specific "cost" (c_s). Note that, when constraint (2) is active, the maximum vaccines are allocated to each state. On the other hand, when constraint (3) is active, the minimum vaccines are allocated to each state.

$$\sum_{s \in S} v_s \leq VT \tag{1}$$

$$v_s \leq p_s, \quad s \in S \tag{2}$$

$$v_s \geq c_s, \quad s \in S \tag{3}$$

This "cost" refers to the minimum amount of population that should receive a vaccine. We estimate this cost by considering the COVID-19 patients that would require hospitalization but will not receive this service due to a lack of medical resources (b_s). Also, the COVID-19 mortality rate is considered (m_s) and the most vulnerable groups to COVID-19. These groups include the elderly, as well as the population with an underlying condition such as obesity, hypertension, and diabetes mellitus. The mortality due to COVID-19 in these groups is also involved (m^e, m^{ob}, m^{hy}, m^{dm}). r_s refers to the rate of COVID-19 cases per state. For the rate of cases, we involve a factor based on the sentinel surveillance technique as an attempt to make a closer estimation of the actual number of cases (Torres-Ramirez 2020; Lazcano-Ponce and Alpuche-Aranda 2020). Note that this cost varies depending on the particular parameters of each state.

$$c_s = b_s + p_s r_s \left(m_s + m^e f_s^e + m^{ob} f_s^{ob} + m^{hy} f_s^{hy} + m^{dm} f_s^{dm} \right), \quad s \in S \tag{4}$$

The demand for hospital beds for COVID-19 patients that cannot be satisfied is denoted by b_s. This demand is estimated considering the fraction of COVID-19 patients that required hospitalization (f^h) plus the beds that are required per year in each state for other diseases minus the available beds per state. The beds that are required per year in each state for other diseases were estimated by using the Brigdman formula (Quesada 2009).

$$b_s = p_s r_s f^h + \frac{d_s^p s_s^a}{d^y i^o} - b_s^{ho}, \quad s \in S \tag{5}$$

It is important to note that c_s and b_s are parameters in the model. We specified how they are estimated and the involved data to show the considerations that are taken into account for the proposed formulation.

As mentioned above, the objective function and the type of model vary depending on the allocation scheme that is selected. For the social welfare and Rawlsian justice schemes, the resulting models are linear programs (LP). On the other hand, for the Nash and social welfare II approaches, the models are nonlinear programs (NLP).

For the social welfare scheme, the following objective is used to allocate the vaccines. This scheme seeks to maximize the total vaccines of all states.

$$\max \quad \sigma^{SW} \tag{6}$$

$$\sigma^{SW} = \sum_{s \in S} v_s \tag{7}$$

The objective function of the Nash scheme is modeled by the following formulation:

$$\max \quad \sigma^{N} \tag{8}$$

$$\sigma^{N} = \sum_{s \in S} \log v_s \tag{9}$$

For the Rawlsian justice scheme, the smallest allocated vaccines are maximized as presented in the next equations:

$$\min \quad \sigma^{R} \tag{10}$$

$$-v_s \le \sigma^{R}, \quad s \in S \tag{11}$$

The social welfare II scheme was previously proposed to illustrate the multiple solutions that the social welfare approach has (Munguía-López et al. 2019). We include this formulation as shown in the following. We can see that this scheme seeks an alternative allocation that is equal to the total allocated vaccines by the social welfare approach (${v^{sw}}_s$).

$$\max \quad \sigma^{SII} \tag{12}$$

$$\sigma^{SII} = \sum_{s \in S} \left(v_s - v_s^{SW} \right)^2 \tag{13}$$

$$\sum_{s \in S} v_s = \sum_{s \in S} v_s^{SW} \tag{14}$$

Results

Several scenarios for the total available vaccines (*VT*) were considered: (a) 0.1%, (b) 4%, (c) 8%, (d) 12%, (e) 16%, and (f) 32% of the total population of Mexico. First, we observe that when the total available vaccines are minimum (scenario (a)), all the schemes allocate the minimum vaccines to each state (equal to the cost). However, as the number of total vaccines increases, different solutions are found by each allocation scheme. Figure 3 shows the allocations for scenario (b). Here, we observe that the social welfare scheme gives preference to state 1 and allocates the minimum to the other states. The social welfare II scheme provides a similar allocation, but it gives preference to the state 6. Note that almost the same amount of vaccines is allocated to states 1 and 6 by these different schemes. This illustrates how, despite having the same constraint for the availability of vaccines, multiple solutions can be obtained through the social welfare approach. On the other hand, the Nash and Rawlsian schemes give the same solution. These schemes allocate the minimum to each state (equal to the cost) and then, the remaining vaccines are allocated equally among all states.

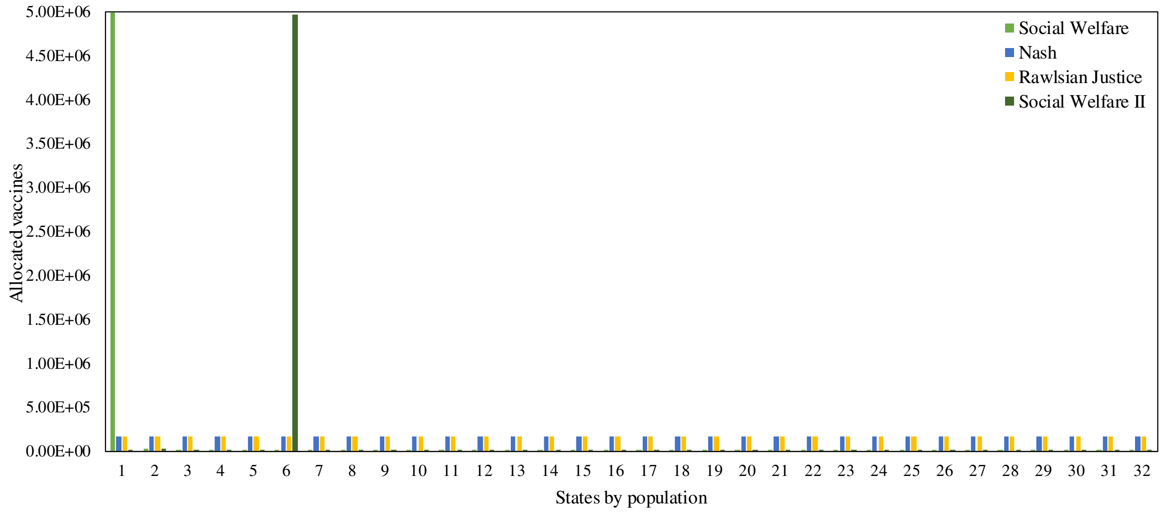

Figure 3. Allocated vaccines under different allocation schemes (scenario (b) of availability).

Then, for the scenario (c) of availability, the allocated vaccines to each state are presented in Figure 4. Again, the Nash and Rawlsian schemes allocate an equal number of vaccines for each state (higher than in scenario (b) due to the higher availability). Whereas the social welfare approach keeps giving preference to the state 1. Now, this scheme allocates a number of vaccines higher than half the population of this state. The social welfare II scheme gives preference to states 2 and 3. However, the main preference is for state 2 since the allocated vaccines are equal to its population. In scenario (d), where the availability of vaccines is increased to 12%, the trends of all schemes are similar (see Figure 5). The only variation for the Nash and Rawlsian approaches is that more vaccines are allocated to every state, but again, in an equitable amount. For the social welfare scheme, more vaccines are allocated to state 1. In the social welfare II scheme, the same vaccines to state 2 than in scenario (c) are allocated. Whereas the assigned vaccines to state 3 are increased to more than half the population of this state.

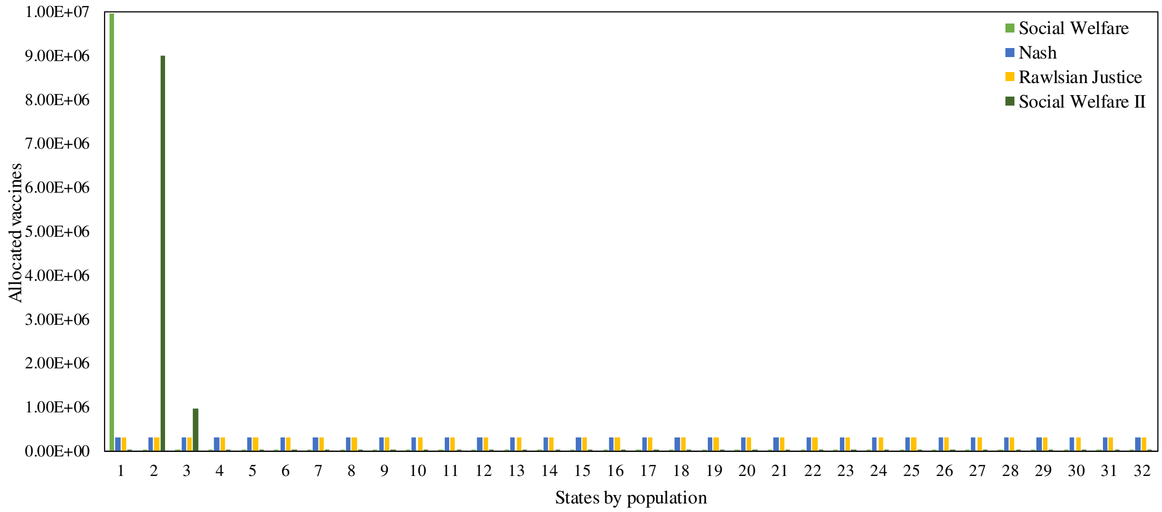

Figure 4. Allocated vaccines under different allocation schemes (scenario (c) of availability).

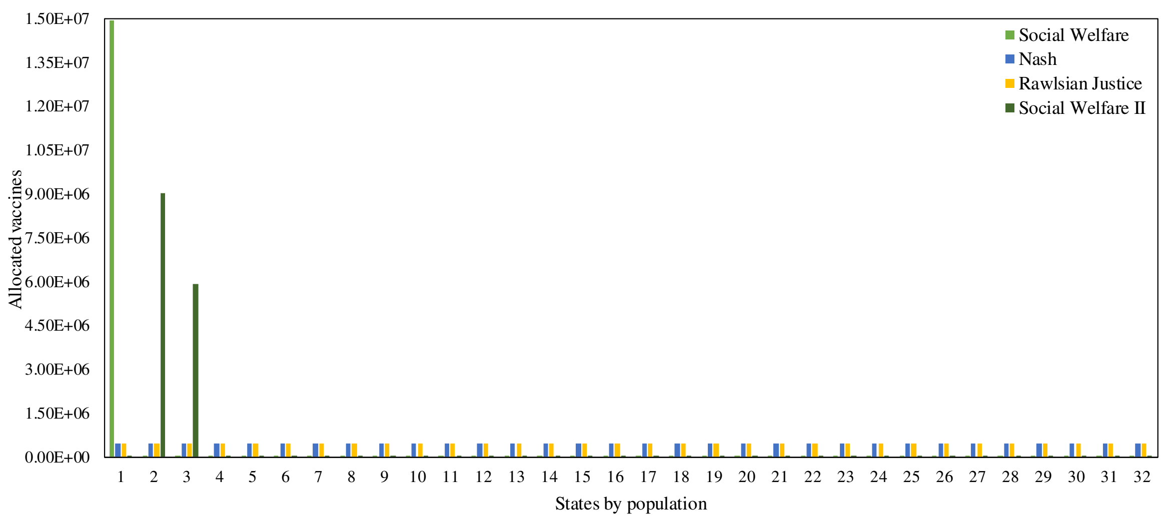

Figure 5. Allocated vaccines under different allocation schemes (scenario (d) of availability).

On the other hand, when the scenario (e) is considered (vaccines availability is 16% of the total population), the allocation varies for the social welfare schemes (see Figure 6). For the social welfare approach, we observe that it favors both states 1 and 2. Here, the maximum amount of vaccines for the state 1 is allocated (equal to its population) and the rest is allocated to state 2. The social welfare II scheme gives the most preference to states 3 and 4 (allocated vaccines are equal to its population), it also favors state 5 but with fewer vaccines. For the Nash and Rawlsian schemes, the allocation keeps giving preference to all states equally.

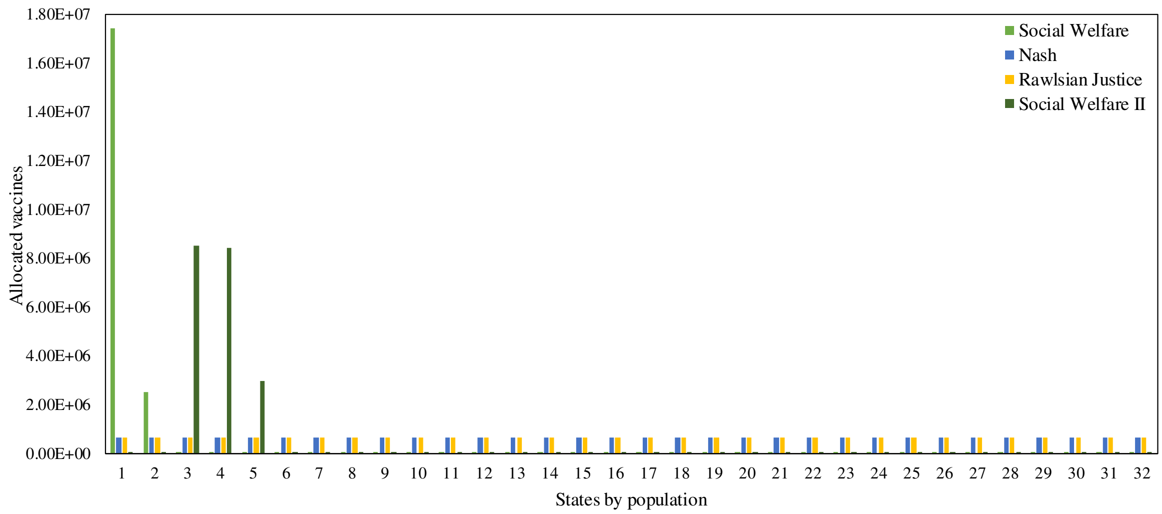

Figure 6. Allocated vaccines under different allocation schemes (scenario (e) of availability).

In Figure 7, the allocations for scenario (f) are presented. Here, the availability of vaccines is increased to 32%. Since the amount of available vaccines is twice greater than in scenario (e), the complexity of the allocation increases. Therefore, different allocations are found with each scheme. For the social welfare approach, the maximum vaccines for states 1, 2, and 3 are allocated (equal to its population). Whereas the rest is allocated to the state 4. The social welfare II scheme favors several states. It allocates the maximum vaccines to states 6, 7, 10, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, and 28. The remaining vaccines are allocated to the state 12. Contrary to the other scenarios, the Nash and Rawlsian schemes do not provide identical allocations. We can observe that the Nash scheme allocates the same amount of vaccines to almost all the states. However, fewer vaccines are allocated to some states (29-32). This occurs because the maximum vaccines for each of these states are assigned (equal to their population). The rest of the vaccines is allocated equally among the other states (1-28). On the other hand, the Rawlsian scheme favors the state 1 by allocating a number of vaccines close to its maximum. In this scheme, the remaining vaccines are assigned equally among the other states (2-32). This allocation corresponds to assigning the smallest state (32) its maximum.

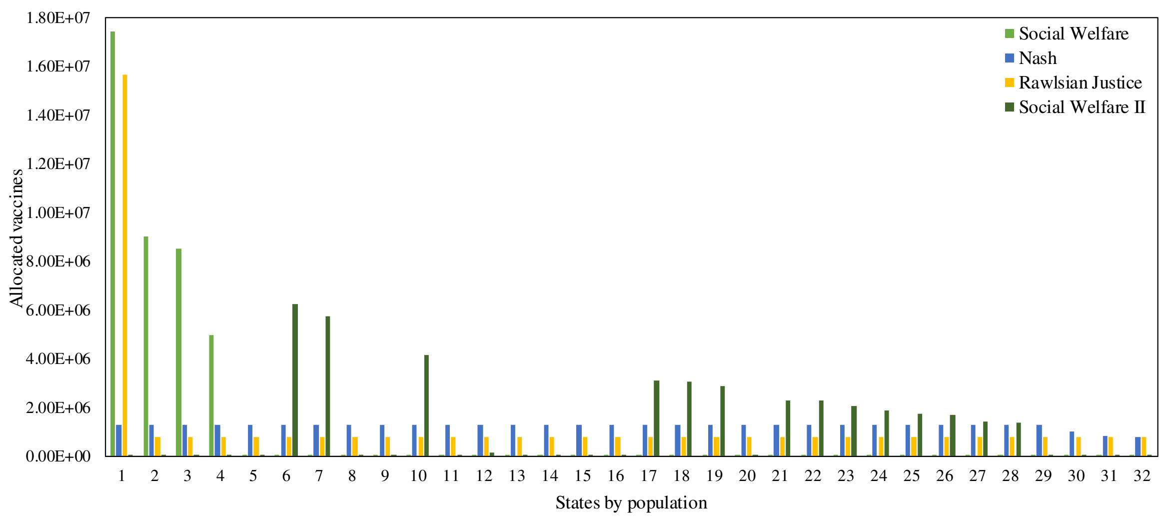

Figure 7. Allocated vaccines under different allocation schemes (scenario (f) of availability).

Conclusions

In this work, we presented an optimization formulation for the allocation of potential COVID-19 vaccines through fairness schemes. Distinct parameters to model the distribution of vaccines were considered. Specifically, the case study of Mexico was addressed. We analyzed the allocated vaccines to each state of Mexico given by the allocation schemes (social welfare, Nash, Rawlsian justice, and social welfare II scheme) under different availability scenarios. We observe that the allocation of resources is a complex problem that can result in unfair distributions if it is not addressed properly. Mainly when several stakeholders (32 states in our case study) are involved since the possible assignations are greater. We also observe that the inequalities become critical when the resources are scarce. Such as in scenario (b) where the social welfare approaches (standard and II) give preference only to one particular state by depriving the others. Specifically, the first solution obtained by the social welfare approach (standard) tends to favor large stakeholders (greater population) in all scenarios. On the other hand, when the available vaccines are greater, the complexity of the allocation increases since the possible solutions increase as well (such as in scenario (d)). Therefore, it is important to consider all the possible allocations that the fairness schemes provide to identify the most suitable solution.

Nomenclature

Parameters

b_s Demand for hospital beds for COVID-19 patients that cannot be satisfied

b_s^{ho} Available beds in each state s for all diseases

c_s "Cost" of each state s (refers to the minimum amount of population that should receive a vaccine)

d_s^p Discharged patients in each state s per year for all diseases

d^y Days in the year

f_s^{dm} Prevalence of diagnosed diabetes mellitus in adults in each state s

f_s^e Fraction of elderly population in each state s

f^h Fraction of COVID-19 patients that require hospitalization

f_s^{hy} Prevalence of hypertension in adults in each state s

f_s^{ob} Prevalence of obesity in adults in each state s

i^o Occupancy index

m_s COVID-19 mortality rate

m^{dm} Mortality of COVID-19 patients with diabetes mellitus

m^e Mortality of elderly patients with COVID-19

m^{hy} Mortality of COVID-19 patients with hypertension

m^{ob} Mortality of COVID-19 patients with obesity

p_s Population of each state s

r_s Rate of COVID-19 cases of each state s

s_s^a Average stay in days of patients in each state s for all diseases

v_s^{SW} Allocated vaccines to each state s by the social welfare scheme

VT Total available vaccines

Variables

v_s Allocated vaccines to each state s

σ^N Variable to denote the objective function in the Nash scheme

σ^R Variable to denote the objective function in the Rawlsian justice scheme

σ^{SW} Variable to denote the objective function in the social welfare scheme

σ^{SII} Variable to denote the objective function in the social welfare II scheme

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Notes

The authors declare no competing financial interest.

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Figures

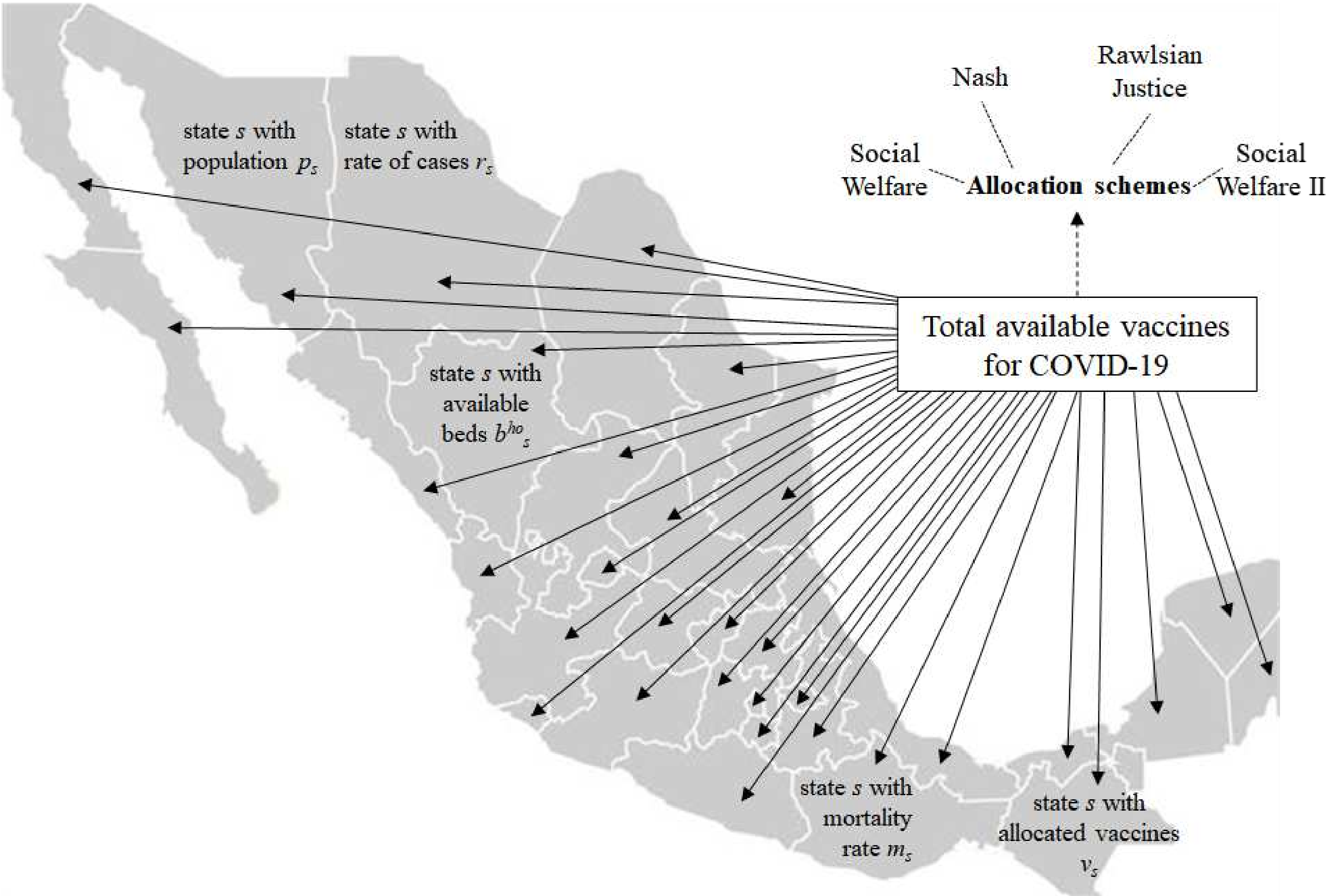

Figure 1

Superstructure proposed for the allocation of potential vaccines among the different states in Mexico.

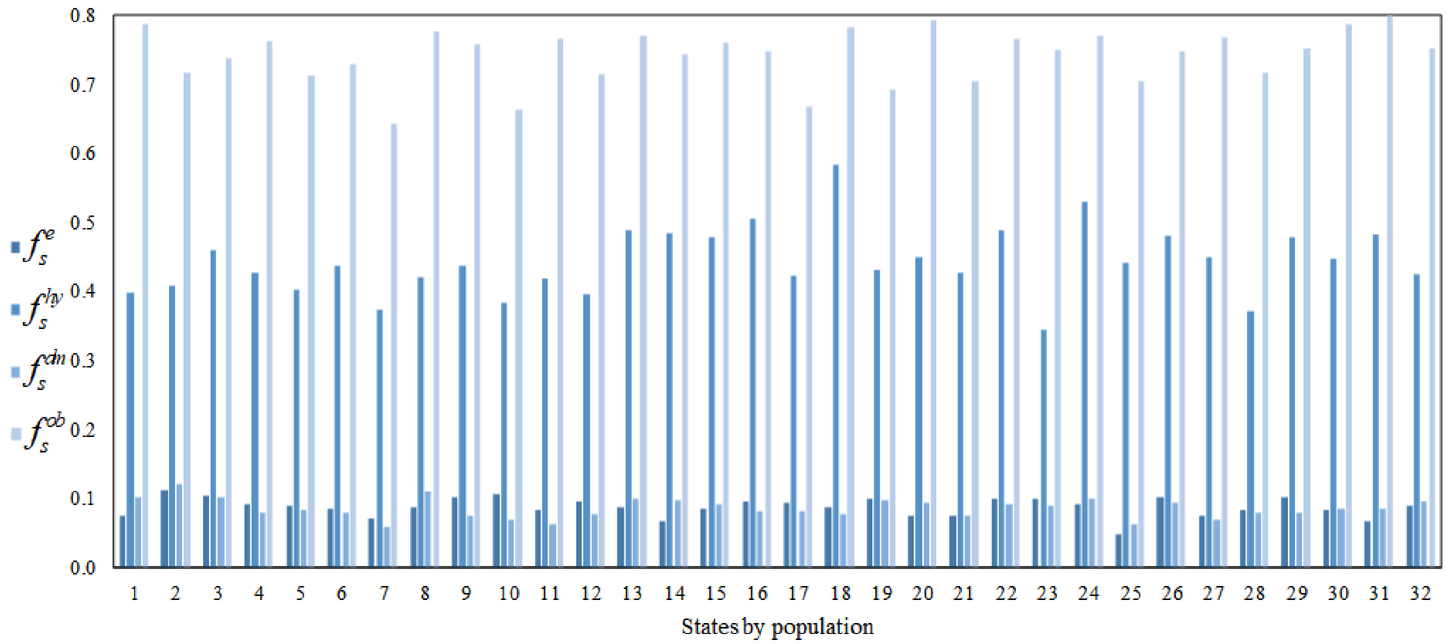

Figure 2

Parameters for each state include the fraction of the elderly population (f^e), the prevalence of hypertension in adults (f^hy), the prevalence of diagnosed diabetes mellitus in adults (f^dm), and the prevalence of obesity in adults (f^ob) (INEGI 2014; Barquera et al. 2010; Hernández-Ávila et al. 2013; Barquera et al. 2013).

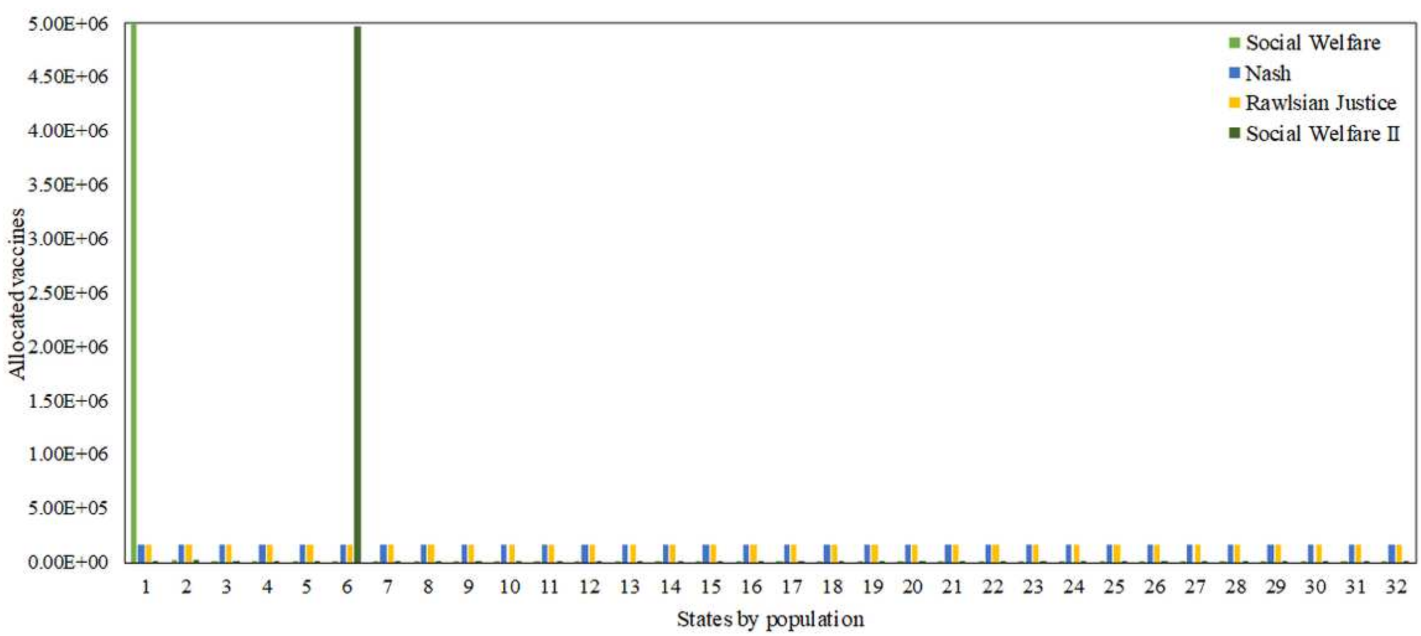

Figure 3

Allocated vaccines under different allocation schemes (scenario (b) of availability).

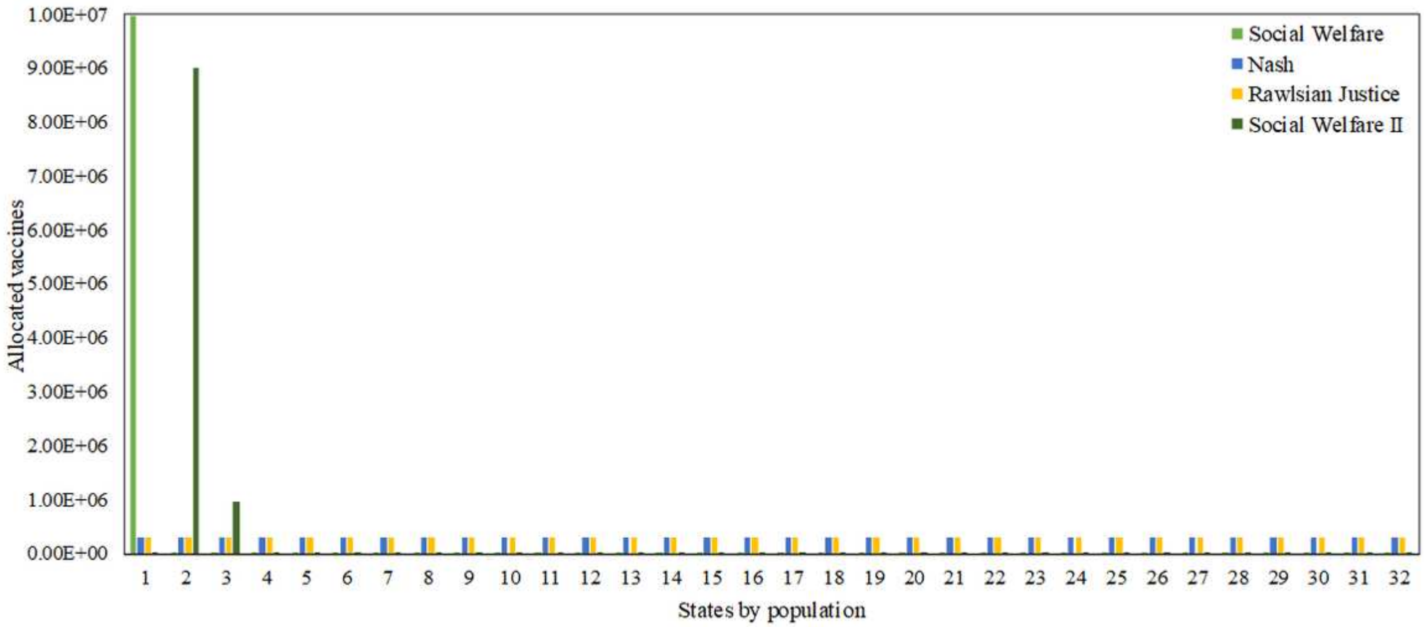

Figure 4

Allocated vaccines under different allocation schemes (scenario (c) of availability).

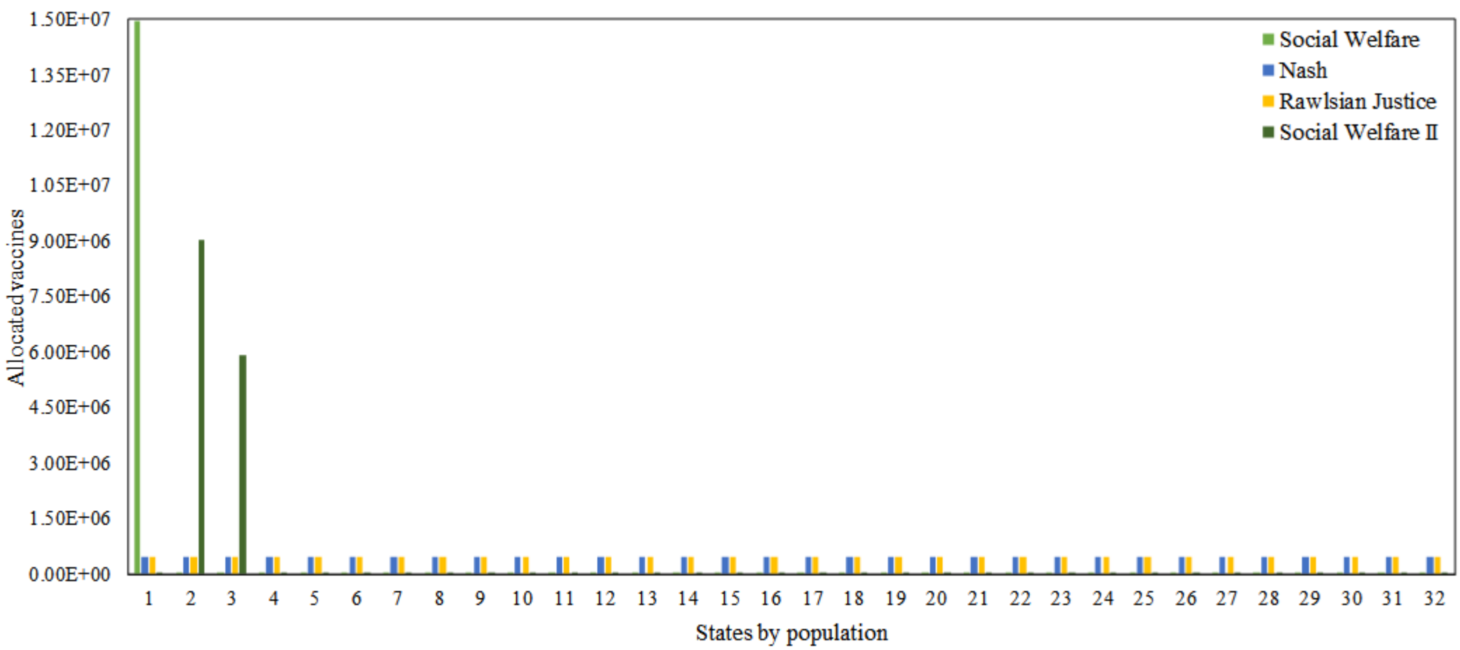

Figure 5

Allocated vaccines under different allocation schemes (scenario (d) of availability).

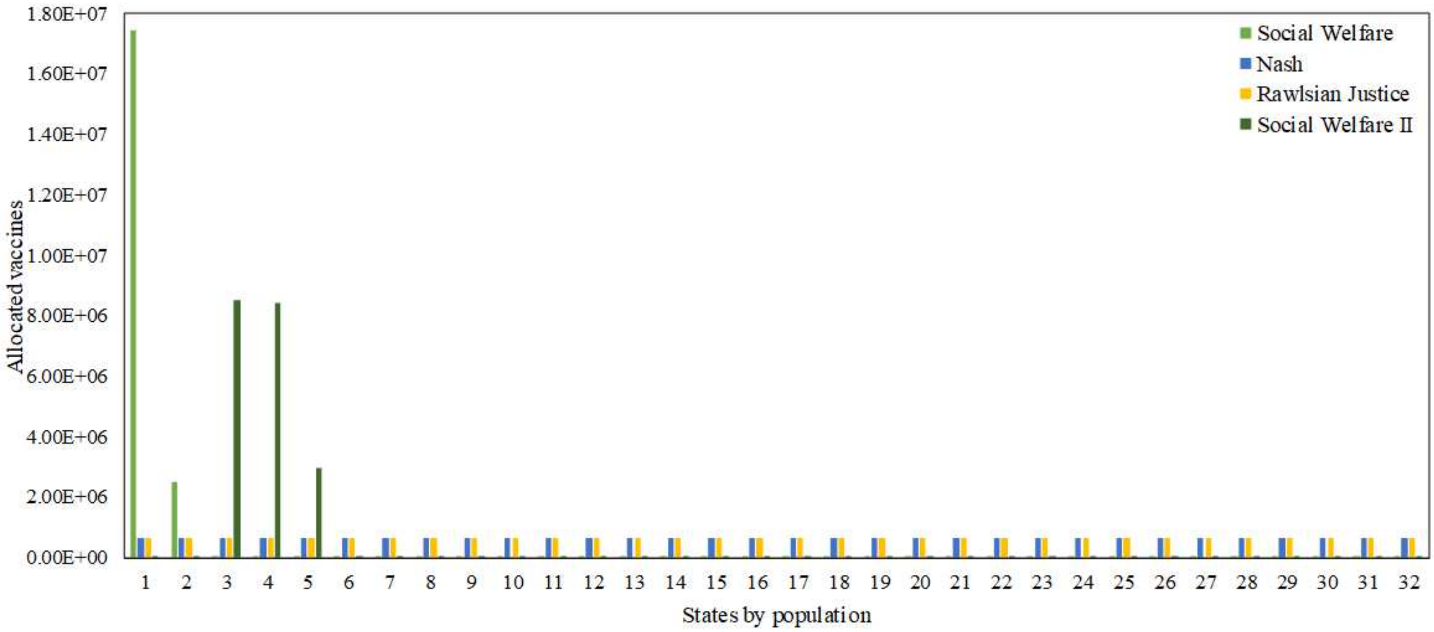

Figure 6

Allocated vaccines under different allocation schemes (scenario (e) of availability).

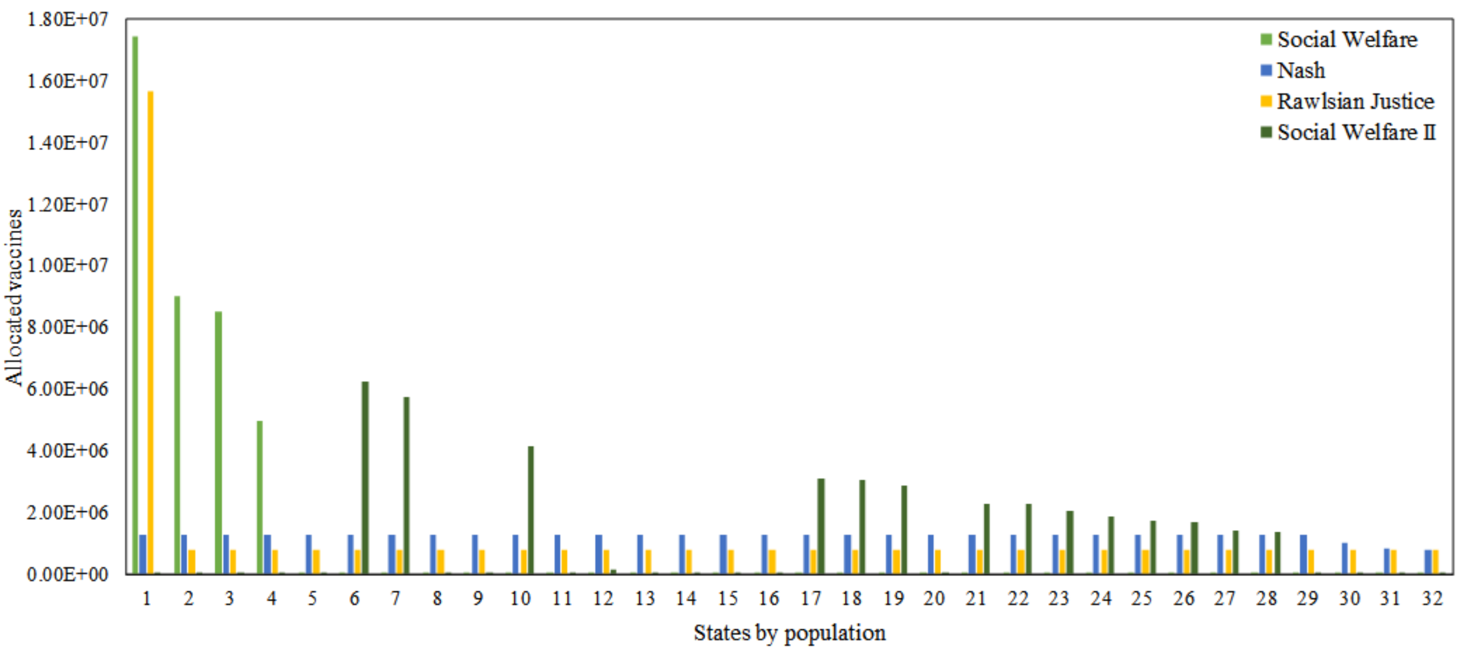

Figure 7

Allocated vaccines under different allocation schemes (scenario (f) of availability).