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Analyze the Optimal International Allocation of Vaccine to Maximize Benefit in Terms of Minimizing the Risk of Infection

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Abstract: The COVID-19 pandemic brought the problem of disparities in vaccine production and distribution among nations into sharp focus, as this problem may leave people in low-income countries more vulnerable to the virus. Based on this background, this paper introduces a model that helps donors determine their vaccine donation strategy, aiming to maximize donor benefit by minimizing the risk of infection for their domestic people. Meanwhile, by receiving donated vaccines, the lower-income countries would also benefit, leading to a win-win situation. This model is based on a simplified condition where there are only two countries, and each vaccine is used by domestic people or donated to the other country. By analyzing the effects of the risk of disease, the relative importance of vaccines, and the level of contact between countries, this essay provides an equation that enables the calculation of the optimal number of vaccines that should be consumed by domestic people given the values of parameters. It analyzes the relationship between each parameter and the optimal number. This simple model can be employed to inspire the allocation of resources for other infectious diseases or similar situations.

Keywords: resource allocation, vaccine distribution, benefit-maximizing model.

1. Introduction

During Covid-19, the production of vaccination is dominated by several countries. For instance, up to March 03, 2021, 413 million doses of vaccines had been produced [1]. Among these, 34.3% were contributed by China, and 24.9% were from the United States. In contrast, South Africa accounted for only 0.039 % of those vaccines. The difference in the ability to develop and produce vaccines may inevitably lead to the unequal distribution of vaccines globally, with people from low-income countries being more susceptible. To promote the equitable accessibility of vaccines and other healthcare resources, a scheme called COVAX was launched that provided equal access to vaccines for all participating countries [2]. In the meantime, some countries donated vaccines to be distributed through COVAX, mainly for low and middle-income countries. For example, until August 2021, the United States had endowed 110 million doses of vaccines, mostly through COVAX [3]. The recipients of donations would benefit from reducing the risk of infection. At the same time, it is also beneficial for the donors as by giving people worldwide access to vaccines, the resurgence of the

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pandemic would be restrained, and the crisis would be more likely to end. This paper suggests a way for donors to decide the number of vaccines to donate to optimize the benefits they acquire. A benefit-maximizing model is created based on a simplified scenario involving only two countries where each vaccine is consumed by domestic people or donated. Eventually, this essay provides an equation that can be used to calculate the optimal number of vaccines consumed by domestic people given the parameters determined by the risk of disease, the relative importance of vaccines, and the level of contact between countries, and it analyzes the correlation between these parameters and the optimal allocation. This model can be employed in allocating vaccines and healthcare resources for infectious diseases, and it can inspire similar resource allocation. Moreover, by making the wealthier countries aware of the potential benefits of donation, the distribution of merit goods may become more equitable.

2. Literature Review

This literature review provides four dissections of the topic discussed. Previously, using budget-balanced resource-sharing mechanisms to create cooperation between countries and numerous policies for the pandemic showed that the optimal allocation of vaccines is a huge challenge [4]. One study indicated that vaccine hoarding and vaccine nationalism by rich nations can lead low- and middle-income countries to struggle to get enough doses to protect themselves. Thus, the inequitable distribution of vaccines puts the world on the brink of "catastrophic moral failure" [5]. To help find the solution, this paper proposes a benefit-maximizing model to help balance the distribution of vaccines based on maximizing the benefit for the donor country. Some research has proposed that global health challenges need help from international cooperation, particularly developed-developing country partnerships that can generate effective solutions for the problem [6]. A study shows that international institutions provide financial help in developing assistance for health. Still, the allocation decisions have had some shortcomings, both from a political and ethical aspect. The recipient country, in fact, has low efficiency in the allocation process itself [7]. From this aspect, our model finds the optimal option for the donors, making them willing to donate, and the recipient countries would also receive benefits. In conclusion, all the studies in this literature review reveal that they could not yet effectively explain the optimal way for the donors to determine the number of vaccine doses they should donate; this is the gap where our research lies.

3. Model

To interpret the benefit-maximizing model stated, this paper assumes that there is a scenario where Country A is capable of developing and producing vaccines. At the same time, Country B lacks the ability to make vaccines. For each dose of vaccine produced, Country A can either give it to domestic people or donate it to Country B. To determine how to allocate the limited vaccines, a model is created that can help Country A analyze the optimal choice to maximize the benefit, mainly in terms of minimizing the risk of infection for its domestic people.

To begin with, this paper suggests a preliminary function (1). In this function, x is the number of vaccines consumed in Country A, t is the total number of vaccines produced by Country A, so $(t-x)$ denotes the number of vaccines donated to Country B. $h(x)$ is the total benefits Country A can obtain from the finite vaccines it produces, and it is composed of $f(x)$ which is the benefit generated from vaccines provided to domestic people and $\lambda \times g(t-x)$ which is the benefit gained from donating some vaccines to Country B. Specifically, $g\ (t-x)$ illustrates the benefits acquired by Country B from receiving $(t-x)$ vaccines, and λ is an index ranging from 0-1 that indicates the level of contact between two countries. If Country A and B are in close contact, the risk that a person from Country B brings disease to Country A and infects local people will increase. As a result, by

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donating vaccines to Country B, the risk of infection for people in both countries would decrease. Therefore, the more closely the two countries contact, the greater the benefit Country A can obtain from donating vaccines to Country B, so λ should be higher.

$$h(x) = f(x) + \lambda \times g\,(t - x) \tag{1}$$

The marginal benefit gained from each additional dose of vaccine tends to decrease as the total number of doses increases because as the number of people immune to the contagious disease increases, there would be fewer potential carriers of the pathogen, reducing the probability of infection for the remaining population without immunity. As a result, it can be concluded that $f(x)$ is an increasing function at a decreasing rate, which can be expressed as shown in (1.2). In this function, α indicates the level of risk of the disease. If the disease is more infectious or fatal, the α would be higher, meaning the benefit of getting vaccinated is more significant.

$$f(x) = x^{\alpha}\ (0 < \alpha < 1) \tag{2}$$

As the risk of the disease can be considered uniform in each country, $g\,(x)$ can be formulated as displayed in (1.3). β represents the relative importance of the vaccine ($\beta > 0$). For example, if people in Country B have poor accessibility and affordability to good healthcare, infected people may not be treated effectively on time, so the country would be more dependent on curbing the spread of disease instead of curing the disease. This means that the vaccine is valued in Country B, which is reflected by the higher β.

$$g(x) = \beta \times f(x) \tag{3}$$

Substituting (2) and (3) into (1), a function (4) can be obtained.

$$h(x) = f(x) + \lambda \times \beta \times f(t - x) \tag{4}$$

In order to optimize Country A's benefit, $h(x)$ needs to be maximized. This can be done by taking the first-order condition of $h(x)$ which is when $h'(x)$ equals zero (5). After solving (5), function (6) is derived ,which can be used to calculate the benefit-maximizing quantity for x. Therefore, if all the parameters are given and x obeys function (6), the country can reach the optimal allocation by giving x vaccines to domestic people and donating $t - x$ vaccines.

$$\alpha \times x^{\alpha-1} - \lambda \times \beta \times \alpha \times (t - x)^{\alpha-1} = 0 \tag{5}$$

$$x = \frac{t \times \sqrt[\alpha-1]{\beta \times \lambda}}{1 + \sqrt[\alpha-1]{\beta \times \lambda}} \tag{6}$$

To verify that the number calculated from (1.6) will maximize $h(x)$, the second-order condition for $h(x)$ is introduced (7). According to the range for each variable (0<α<1, 0<λ<1, β>0, x>0, t>0), $(\alpha - 1)$ is negative while all other terms are positive, so overall, $h''(x)$ is negative, justifying that at the x value calculated from (1.6), $h(x)$ is at its maximum point.

$$h''^{(x)} = \alpha \times (\alpha - 1) \times x^{\alpha-2} + \lambda \times \beta \times \alpha \times (\alpha - 1) \times (t - x)^{\alpha-2} \tag{7}$$

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4. Result

4.1. Proposition 1

x is a fixed proportion of t. Since all the parameters are fixed for specific countries and diseases, $\frac{\sqrt[\alpha-1]{\beta\times\lambda}}{1+\sqrt[\alpha-1]{\beta\times\lambda}}$ can be considered as a constant. Therefore, x would always be a fixed proportion of t, while the proportion can be calculated by $\frac{\sqrt[\alpha-1]{\beta\times\lambda}}{1+\sqrt[\alpha-1]{\beta\times\lambda}}$.

4.2. Proposition 2

x is inversely proportional to β and λ. To analyze the correlation between x and the parameters β and λ, the equation (1.6) can be differentiated to find the derivative of x with respect to each parameter. The results for $\frac{dx}{d\lambda}$ and $\frac{dx}{d\beta}$ are similar as shown in equations (1.8) and (1.9). Given the range for all parameters, it can be deduced that for both derivatives, $\frac{1}{\alpha-1}$ is negative and all other terms are positive, so $\frac{dx}{d\lambda}$ and $\frac{dx}{d\beta}$ are both negative. This implies that the x is inversely proportional to both β and λ. As β and λ increase, the x would decrease, meaning fewer vaccines should be given to domestic people and more should be donated.

$$\frac{dx}{d\lambda}=\frac{\sqrt[\alpha-1]{\beta}\times\frac{1}{\alpha-1}\times\lambda^{\frac{\alpha-2}{\alpha-1}}\times t}{\left(1+\sqrt[\alpha-1]{\beta\times\lambda}\right)^2} \tag{8}$$

$$\frac{dx}{d\beta}=\frac{\sqrt[\alpha-1]{\lambda}\times\frac{1}{\alpha-1}\times\beta^{\frac{\alpha-2}{\alpha-1}}\times t}{\left(1+\sqrt[\alpha-1]{\beta\times\lambda}\right)^2} \tag{9}$$

4.3. Theorem 3

when $\beta\times\lambda$ is smaller than one, x is directly proportional to α; when $\beta\times\lambda$ is higher than one, x is inversely proportional to α. To prove theorem 3, $\sqrt[\alpha-1]{\beta\times\lambda}$ can be made equal to c, so (6) can be written as $x=\frac{t\times c}{1+c}$. Then by taking the derivative of x in respect to c, the equation of $\frac{dx}{dc}=\frac{1}{(1+c)^2}$ can be derived, which is always positive, illustrating that x increases when c increases, and vice versa. After that $\sqrt[\alpha-1]{\lambda\times\beta}$ can be substituted by $(\lambda\times\beta)^y$, where $y=\frac{1}{\alpha-1}$. As α is between 0 and 1, an increase in α would lower the value of y. Given that $0<\lambda<1$, when β is greater than zero but smaller than one, $\lambda\times\beta$ is smaller than one, so the value of $(\lambda\times\beta)^y$ increases when the value of α increases which lowers y. As a result, x is directly proportional to the value of α. When the value of β is greater than one, but the value of $(\lambda\times\beta)$ remains smaller than one, the value of $(\lambda\times\beta)^y$ will also increase when the value of α increases, so x is directly proportional to the value of α. However, when the value of β is great enough to offset the effect from λ and causes $\lambda\times\beta$ to be greater than one, the value of $(\lambda\times\beta)^y$ would be higher if y is higher, so it is in inverse proportion to the value of α. Therefore, in this case, x would be inversely proportional to α, meaning that if the risk of disease is higher, fewer vaccines should be consumed in the domestic country and more should be endowed.

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5. Conclusion

In this paper, a benefit-maximizing model is proposed that can help a country determine the optimal allocation of limited doses of vaccines between giving to domestic people and donating to another country. This paper states the relationship between the total number of vaccines produced and the number of vaccines that should be provided to domestic people, and it analyzes the effects of the risk of disease (α), the level of contact between two countries (λ), and the relative importance of the vaccine (β) on the optimal number of vaccines that should be given to domestic people. This model can be applied to similar situations, such as the allocation of other medical resources and international donation of other goods. However, as the scenario on which the model is based involves only two countries and each vaccine is only consumed by domestic people or donated, the model is very simplified, and the benefit of vaccines considered by this model mainly focuses on the decrease in the number of people infected. For future research, to make the model more realistic, more impacts such as political reputation can be considered, a multi-country scenario can be analyzed, and the situation where vaccines can be sold to another country can be included.

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