

HOW TO PLAN AN EFFICIENT VACCINATION DRIVE: THE VACCINOMY MODEL

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Abstract

The coronavirus pandemic has always emphasized on identifying quicker ways to produce and distribute vaccines across the globe. However, besides producing and procuring vaccines, they need to be executed efficiently so that a country can immunize its population against the contagious disease well within the target days. The process of strategizing an efficient vaccination drive requires authorities to take into consideration numerous variables, from virology to economics, making it a very ambiguous process. This ambiguity calls for a standard resilient model on “How vaccination drives should be strategized to achieve maximum economic efficiency”. Our paper presents one such model where we have planned vaccination drives to minimize import cost and maximize export surplus by identifying relevant variables.

Keywords: D-Days, Reproduction number, Degree Centrality, Virulent Mutation

Introduction

The ongoing pandemic has taken a toll on the national health systems of countries across the globe. As cases increased exponentially throughout the world, governments of various nations had to impose lockdowns but the introduction of vaccines proved to be a beam of comfort. However, almost all the vaccines manufactured till date require two doses of administration. The World Health Organization (W.H.O.) recommends a time lag of 1-3 months between the two doses and the countries are left with the discretion to choose the exact number of days, depending on their target number of days to complete the vaccination drives.

The model in this paper comments on the optimal duration of the vaccination drive (n), the time period (t) between two vaccine doses as well as the policies the government of a country can implement, such that imports are minimized and exports are maximized. This ‘Vaccinomy’ model can be applied to any novel communicable disease which governments might have to deal with in the future. Thus, the nature of this model is pragmatic and resilient.

Defining the Model

Before the subject country decides upon an optimum interval between two doses of vaccine, it is important to decide upon the number of days, which we call D-days, in which it wants to conduct the vaccination drive, including both the first dose and the second dose drive. This is because if the disease is spreading rapidly then the subject country needs to accelerate the vaccination drive. Otherwise, it can conduct the drive at a moderate rate. Thus, *D-days have an inverse relationship with the rate of spread of disease.*

The quantification of D-days has been divided into two parts:

- (i) Estimation of the rate of spread of the disease
- (ii) Calculation of D-days

(i) Estimation of the Rate of Spread of the Disease

In epidemiology, the rate of spread of a novel disease is quantified by the reproduction number of the disease or the R number of the disease. R number of a disease is the expected number of cases directly generated by one case in a population where all individuals are susceptible to infection. However, in reality, some part of the population is naturally immune to the infection. Thus, a basic reproduction number or R number will not be a good criterion for the model.

There exists another R number in epidemiology known as the effective reproduction number, denoted by R_t which takes this problem into account. R_t is the average number of new infections caused by a single infected individual at time t in the partially susceptible population. Thus, we will be using R_t to find out the rate at which disease will spread in the subject country if the vaccination drive does not happen. But R_t is calculated every week and this model requires a single solid rate of spread on which D-days will be based.

Thus, the following steps are used to solidify the R number:

Step 1. Find the mean value of R that can be anticipated to follow during the vaccination drive

Firstly, there is a need to identify time periods in the subject country, since the disease came into existence when the social conditions were similar to one expected to prevail during the vaccination drive. Then we need to find the mean value of R^t for the subject country for this time period. This R number can be an estimate of the rate of spread the country can anticipate. However, as infections are continuously mutating, there is a possibility that a new variant would emerge during the vaccination drive which might increase the rate of spread. To make D-days resilient to such a possibility, there is a need to find the probability of such a possibility and the projected R that can follow.

Step 2. Find the probability of the introduction of a virulent mutant in the subject country.

The probability of emergence of a new variant in the subject country depends on the probability of two independent events:

1. Probability of a virulent mutation- It is exogenous to this model and needs to be borrowed from the domain of virology.
2. Probability of introduction of the mutant in the subject country- This depends upon the degree to which the subject country is globally connected. The greater the connectivity, the greater are the chances that a virulent mutant can arrive from some other country.

To calculate this probability, we consider the notion of the “degree centrality” of a country.

$$\text{Degree Centrality} = \frac{\text{Number of links that the country has}^1}{\text{Total number of countries} - 1}$$

As these two events are independent, the resultant probability (P) is the multiplication of the aforesaid probabilities. Thus,

$$\begin{aligned} &P(\text{emergence of a new variant}) \\ &= P(\text{emergence of virulent mutation}) * P(\text{introduction of the mutant}) \\ &= P(\text{emergence of virulent mutation}) * \text{Degree Centrality} = P \end{aligned}$$

Step 3. Find a projected R that one can anticipate in case a new mutant emerges during the vaccination drive

We denote the new projected R by R', which is exogenous to this model and needs to be borrowed from the domain of epidemiology. The reproduction number will be just R' in the extreme case that a new variant will emerge. On the other hand, the reproduction number will be simply R in the extreme case that no such variant will emerge. Thus, to find the expected reproduction number prevalent in the country, we find the weighted average of R and R':

$$E(R) = P' * R + P * R'$$

where,

E(R) = Expected value of R in the vaccination period

P = Probability of emergence of new variant in the subject country

P' = Probability that no new variant emerges = 1-P

(ii) Calculation of D-Days

After calculating the expected reproductive number, we now calculate the number of days (N) it will take to spread the infection to M% of the population. Here, the aim of the authorities is to finish the vaccination drives (both first and second) before it infects M% of the population². To find this, let us assume that R=2 i.e. every infected person spreads the disease to 2 more persons. Thus, we can draw the following network:

1 For the data on a number of links, simply count the number of countries that are connected through a direct passenger flight or at most have one intermediate stop in between.

2 For COVID-19, M is generally around 70 to 80%. Thus, the government will try to conduct both vaccination drives before the infection spreads to 70-80% of the population.

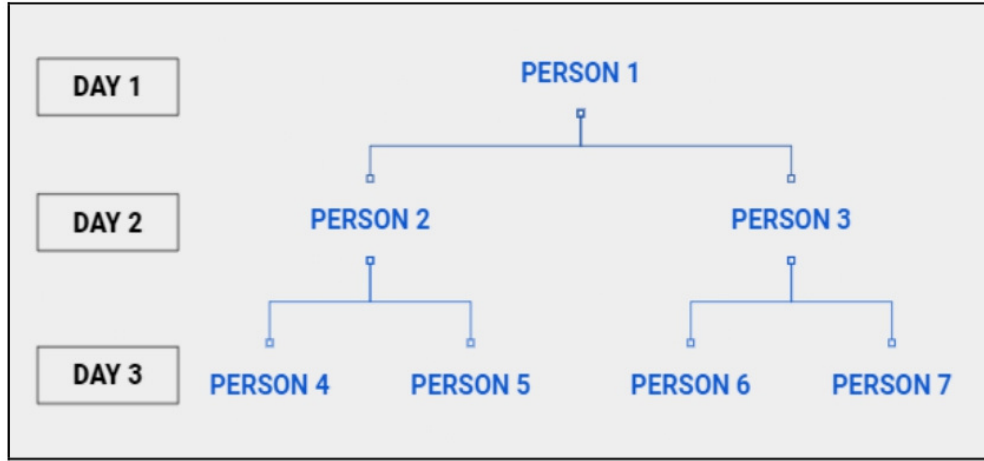


Fig 1. Network of spread of disease when R=2 and A=1

Assuming that there is a single case initially (A=1), there will be 3 cases at the end of day 1, 7 cases at the end of day 2 and so on. Thus, a more general form of the cumulative number of cases can be expressed below in the form of a geometric progression:

$$A * R^0 + A * R^1 + A * R^2 + \dots + A * R^N = \frac{M}{100} * p \quad (\text{Assuming } R > 1^3)$$

where,

A = Initial cases in the country when disease was first introduced

R = Reproduction number (assuming R is the number of distinct people the person transmits the disease to)

p = Total population of the country

The above calculation gives N, which is the approximate number of days it will take for M% of the population to get infected by the disease. Then, we multiply N by 'h' assuming it roughly takes h⁴ days for a person to become positive after coming in contact with an infected person. This gives an approximation of D-Days, in which it wants to conduct the vaccination drive, including both the first dose and the second dose drive.

Note: A country examines changes in the reproductive number (R) during the vaccination period and revises the D days accordingly. Therefore, the policy can be switched as per the circumstances.

The Vaccinomy Model

The above calculation has given a rough estimate of when the government should target to finish its vaccination drive against the novel disease. We can now move forward with the mechanism to describe how the authorities can decide the interval t between the first dose of vaccine and the second dose of vaccine such that:

3. If R is less than 1, it would mean that one infected person will not transfer the disease to one more person. Thus, the disease will die out and there would be no situation of a pandemic.

4. For COVID-19, h is generally 4-5 days.

- (i) Vaccination drives finish within the target D-days,
- (ii) Surplus/Exports of vaccines get maximized,
- (iii) Import of vaccines get minimized
- (iv) Cost of the imported vaccines gets minimized

Before moving forward, we define some constants and assert the assumptions used in the model. Usually, whenever a new vaccine gets launched, the vaccine producers recommend a range for the interval of days 't' that needs to be kept before someone gets the second dose of the vaccine. Let us assume that this range is $c1 < t < c2$, where $c1$ and $c2$ are the minimum and the maximum number of days recommended. Throughout the model, this condition must be satisfied in order to consider implementing a policy.

Further, we assume that the subject country is endowed with the production capacity to manufacture vaccines domestically. However, the principle of microeconomics suggests that the production capacity cannot be increased in the short run. Thus, the maximum rate at which the vaccines are manufactured domestically can be assumed to be r vaccines/day.

In order to achieve herd immunity, epidemiologists usually suggest that 70% of the population should be vaccinated. But the model assumes that the subject country is aiming to vaccinate at least M proportion of the population till or before D-days. So, M is constant in our model and is at the discretion of the policymakers.

In addition, the model assumes that the subject country has an efficient supply chain so that the supply of vaccines is equal to the demand of the vaccines. Thus, the rate at which vaccine doses are produced is equal to the rate at which the vaccine doses are executed i.e. *the rate of vaccine execution* = r .

Let us suppose the number of days it will take to conduct the first dose drive is 'n'. Thus,

$$n = \frac{M * Total Population}{r} = \frac{Mp}{r}$$

Similarly, the number of days it will take to conduct the second dose drive will also be n .

Let us imagine that a person is getting his first dose on the last day of the first drive and he is supposed to get the second dose t days later which in turn will be the last day of the second dose drive. Thus, the maximum number of days it will take to conduct both the drives will be $n+t$ days. The authorities are supposed to finish the drive in D-days. So, ideally $n+t$ should be less than or equal to D-days. If that is not the case, what can the authorities do? We consider various cases to accommodate all possibilities.

Case 1. $n+t > D$

Here, the time it will take to finish both the drives is greater than the target number of days. So, the authorities must follow a policy such that $(n+t)$ decreases to the point where it becomes equal to or less than D . They can do so by either following a strategy to decrease n or following a strategy to decrease t .

Note: We consider only the strategies that try to equalize $n+t$ to D . The strategies that try to achieve $n+t$ less than D are only accentuated versions of the following.

Strategy 1. Decreasing the number of days 'n'

Here, we will assume that the authorities cannot make any changes to t due to the constraint $c1 < t < c2$.

The number of days to conduct any drive, n , can be decreased by increasing the rate of vaccine execution. However, the rate of vaccine execution is maximum through domestically produced vaccines. Thus, the authorities would be required to import vaccine doses to increase the rate of vaccine execution beyond r .

Let us assume the authorities import x vaccines per day to decrease n sufficiently such that $n+t = D$. Thus, the new rate of vaccine execution will be $r+x$ per day and the new number of days to conduct any drive is n' . So, we have

$$n' = \frac{Mp}{r+x}$$

Now consider if the first dose drive and the second dose drive are conducted successively then the number of days to finish both the drives will be $2n'$. But if $2n' > D$, then the authorities will be required to start the second dose drive before it finishes the first dose drive by $(n'-t)$ days.

Thus, the import function in this case will constitute of two parts:

(i) As the number of imported vaccines per day is x , the total number of vaccines imported due to an increase in r during the first dose drive = $x \cdot n' = I_1(\text{say})$

(ii) Similarly, total number of vaccines to be imported due to an increase in r during the first dose drive = $x \cdot n' = I_2(\text{say})$

(iii) During the period $(n'-t)$ days when both drives will be happening simultaneously, the country would require $2(r+x)(n'-t)$ vaccines per day. But the maximum vaccine doses the country can produce domestically is r . Also, we have already computed the number of vaccines imported due to increase in r . Thus, the total number of vaccines imported due to simultaneously conducting drives is $2 \cdot (r+x) \cdot (n'-t) - (n'-t) \cdot r - 2(n'-t) \cdot x = r \cdot (n'-t) = I_3(\text{say})$

Finally,

$$\text{Import Function} = I_1 + I_2 + I_3 = n'x + n'x + (n'-t)r = (2x+r)n' - tr$$

Differentiating this with respect to n' gives $(2x+r)$ which is greater than zero implying that the import function is an increasing function. As n' decreases, the import function decreases. *This indicates that the authorities have done the right thing by choosing to decrease n .* Here the export surplus will be zero because the vaccination drive is ending in exactly D days.

Now, consider $2n' < D$ i.e. the number of days to conduct both the drives is less than D-days so the country has the discretion to conduct both the drives successively.

Also, since $D = n' + t$, this means $2n' < n' + t$ or simply, $n' < t$. i.e. the number of days it takes to conduct any drive is less than the interval between the two doses. Therefore we get,

$$\text{Import Function} = 2n'x$$

$$\text{Export Function} = (t - n')r$$

Differentiating the export function with respect to n' gives $-2r < 0$, implying that it is a decreasing function in n' . So as n' decreases, exports increase which is a good enough indication that the *subject country has done the right thing by decreasing n'* .

Differentiating the import function with respect to n' gives $2x > 0$, implying that it is an increasing function in n' . So as n' decreases, imports decrease which again is an indication that *the subject country has done the right thing by decreasing n'* .

Policy Recommendation: The orders for importing vaccines must be placed months before it is required as imported vaccines are needed from the very first day of the vaccination drive.

Thus, this strategy should be followed only when the subject country has enough time to do the bilateral deals in advance with the vaccine manufacturers.

Strategy 2. Decreasing the time interval ' t '

Here, we are assuming that the government cannot change n due to some underlying reason. Thus, t is decreased by $D - (n + t)$. So we define $t' = D - n$, where t' is the revised time interval between two doses.

Now, we have $D = n + t'$

Again, we subject this strategy to the cases when $2n > D$ and when $2n < D$.

If $2n > D$, then the subject country needs to start the second drive $(n - t')$ days before it finishes the first drive. So,

$$\text{Import Function} = (n - t')r$$

Differentiating it with respect to t' gives $-r < 0$ implying that the import function is a decreasing function in t' . So as t decreases, imports increase, which is the opposite of what we want. *Thus, this is a mild indication that the government might not have done the right thing by decreasing t* .

In this case, clearly, there will be no export surplus.

If $2n < D$ i.e. the number of days to conduct both the drives is less than D-days, then the country

can conduct both the drives successively. Also, $2n < n+t'$ or $n < t'$ i.e. the number of days it takes to conduct any drive is less than the interval between the two doses.

Clearly, the import function will be zero and exports will be:

$$\text{Export Function} = (n - t')r$$

Differentiating it with respect to t' gives $-r < 0$ implying that the export function is a decreasing function in t' . So as t decreases, exports increase, which is what we want. *Thus, this is an indication that the government has done the right thing by decreasing t .*

Thus, in this case, the government will be able to eliminate imports while at the same time produce export surplus.

Policy Recommendation: This strategy can be used if the authorities want to buy some time to do bilateral deals with the producers as the imported vaccines will be needed only t days later.

Note: These are two extreme cases when the authorities can change only one variable. In real life, the authorities can change both n and t in such a way that $n+t=D$ in order to satisfy their needs. Comparing the two strategies, Strategy 2 will be better than Strategy 1 as it requires fewer vaccines to be imported and thus, lesser cost.

Case 2. $n+t = D$

This is a special case wherein there is no need to change either t or n to achieve the condition we needed to, in the previous case.

Again, consider a situation in which the cumulative time period to conduct both the drives successively exceeds D -Days i.e. $2n > D$. Then, the authorities will be required to start the second dose drive before it finishes the first dose drive $(n-t)$ days before.

Thus the import function will be:

$$\text{Import Function} = (n - t)r$$

Moreover, exports will be zero in this case as there is no surplus left.⁵

Note: When $n=t$, $D=2n$. This is defined as the equilibrium condition wherein there are zero imports and zero exports.

Now, consider a case when $2n < D$.

Then, clearly, there will be no imports and the export function will be:

$$\text{Export Function} = (D - 2n)r = (t - n)r$$

⁵ The country can try to create Exports by reducing t further if the condition allows but the Imports will be generally greater than exports. Thus, the trade balance is likely to be negative.

Policy Recommendation: It is a highly unlikely but an ideal situation for the subject country. When $2n > D$, the subject country will have enough time to do bilateral deals with producers to get the imported vaccines for $(n-t)$ period. While if $2n < D$, there is no need to import any vaccines.

Case 3. $n+t < D$

In this case, the time it will take to finish both the drives is less than the target number of days. Again, authorities need not alter either n or t to achieve their targets.

If $2n > D$, then similar to previous cases, we have:

$$\text{Import Function} = (n - t)r$$

$$\text{Export Function} = (D - n - t)r$$

$$\text{Trade Balance} = \text{Exports} - \text{Imports} = (2n - D)r > 0$$

On the other hand, if $2n < D$, then, clearly, imports will be zero and

$$\text{Export Function} = (D - 2n)r$$

$$\text{Trade Balance} = \text{Exports Function} = (D - 2n)r > 0$$

Policy Recommendation: This is a plausible scenario. The subject country will be able to attain positive and equal trade balance (in absolute terms) in both the situations but will not have to incur any cost in the latter case when $2n < D$.

Finding the Import Portfolio

To calculate the optimal number of vaccines of each type that should be imported per day, we set up a cost minimization problem.

We define the total cost function (C) in the following two parts:

(i) The Variable Cost (VC) - Assuming that there are K types of different vaccines available to the subject country to import, the variable cost function will be the summation of the product of the number of vaccines and its corresponding price. Therefore,

$$VC = P_A * A + P_B * B + \dots + P_K * K = \sum_{i=A}^K (P_i * i)$$

Where,

P_i = Price of type i vaccine

A = number of type A vaccines

B = number of type B vaccines

K = number of type K vaccines

(ii) The Fixed Cost (FC) - This is the fixed cost incurred to import vaccines in a country, irrespective of the number of vaccines imported. In the short run, this cost cannot be changed. Hence,

$$FC = F \text{ (say)}$$

So, the total cost function is:

$$C = VC + FC = P_A * A + P_B * B + \dots + P_K * K + F = \sum_{i=A}^K (P_i * i) + F$$

To find the optimal import portfolio, we set up a minimization problem subject to the constraint that the total number of imported vaccines must be equal to x (as defined above in the model).

So we have the following problem:

$$\begin{aligned} &\text{Minimize } C = P^A * A + P^B * B + \dots + P^K * K + F \\ &\text{Subject to } A + B + \dots + K = x \end{aligned}$$

The corresponding Lagrange function will be defined as:

$$\mathcal{L} = [P_A * A + P_B * B + \dots + P_K * K + F] + \lambda (x - A - B - \dots - K)$$

Where, λ is the Lagrange multiplier.

Differentiating $\mathcal{L}$ partially with respect to the number of vaccines of different types as well as λ , and setting it equal to 0 gives us the following equations:

$$\frac{\delta \mathcal{L}}{\delta A} = 0 \dots \dots \text{(equation 1)}$$

$$\frac{\delta \mathcal{L}}{\delta B} = 0 \dots \dots \text{(equation 2)}$$

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$$\frac{\delta \mathcal{L}}{\delta K} = 0 \dots \dots \text{(equation K)}$$

$$\frac{\delta \mathcal{L}}{\delta \lambda} = 0 \dots \dots \text{(equation K+1)}$$

Solving this system of k+1 equations with k+1 variables, we will obtain the optimal number of vaccines of each type (A,B,....,K) that must be imported in order to minimize the cost incurred. Thus, we get the required import portfolio.

Note: While choosing the import portfolio, countries also consider other factors such as efficiency, number of doses etc. of a vaccine, apart from its price.

Conclusion

In conclusion, the policy that a country chooses depends upon various factors like the duration of the vaccination drive (n), the population of the country (p), the rate of domestic production (r), the rate of spread of the disease (R), the target days (D) and the number of t days it sets, while making sure that t lies between the recommended range of c_1 and c_2 . Depending on the objective the subject country wants to achieve, the government can choose which out of the above cases to go for. However, it is to be noted that this model is rigid in nature as it considers extreme scenarios and includes some underlying assumptions. Moreover, it is only valid for countries that are capable of domestic production of vaccines. In reality the subject country needs to analyze various variables in order to choose which policy action to take. The above cases can be manipulated in a way which suits the situation prevailing in the country during the disease outbreak and help in strategizing the vaccination drives efficiently.

Policy Revision

In the above described model, we took the proportion of population (M), rate of producing vaccines domestically (r) and D -days as constant. It is highly suggestive that the authorities keep an eye on these constants and revise the policy implemented in case these factors fluctuate. Alternatively, the government can also try to implement policies that control these fluctuations without tampering with the vaccination drive.

Moreover, the subject country must monitor the R number closely during the vaccination period and check whether it lies near the estimated value of R by this model. If that is not the case, a policy revision is highly recommended. This paper leaves scope for future research papers to design a method to revise D -days by keeping an eye on R number during the vaccination period.

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