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Vaccination Problem: Matching Theory Approach in Vaccination against Coronavirus

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Abstract: In this article, we examine an allocation issue faced by European Health Union (EHU). Given this situation, we introduce the issue of vaccine selection. The model proposed in this paper helps to implement vaccination optimally using matching theory. By adopting the mechanism presented in this article, this is done more easily and more quickly, so that mortality in society is lower and public satisfaction is increased. This is similar to the issues analyzed in the literature on the design mechanism of non-perishable goods.

Keywords: matching theory; allocation; COVID-19; vaccine; vaccination

JEL Classification: C78, D61

1. Introduction

The 2019 Coronavirus (SARS-CoV-2) outbreak, which causes the atomic pneumonia syndrome of COVID-19, spread from mid-December 2019 in Wuhan, China, and spread rapidly around the world. The virus was detected on December 29, 2019 in the wholesale seafood market of Huan, Wuhan City, Hubei Province, China. COVID-19 spreads rapidly with human-to-human transmission over an average incubation period of 3 days (range 0 to 24) and the onset of symptoms to pneumonia is 4 days (range 2 to 7). Respiratory droplets and direct contact are common transport routes for COVID-19. It is a new viral disease, several commercial vaccines have been made available so far [1].

By January 2021, all 30 EU/EEA countries had started COVID-19 vaccination campaigns [2] and different COVID-19 vaccine products have been gradually introduced as they became available through the EU Coronavirus Vaccines Strategy.

Currently, four COVID-19 vaccines have received conditional marketing authorisation in the EU [3], following evaluation by EMA, and are part of the EU Coronavirus Vaccines Strategy Portfolio: Comirnaty (BNT162b2) developed by BioNTech/Pfizer, COVID-19 Vaccine Moderna (mRNA-1273), Vaxzevria (AZD1222) previously COVID-19 Vaccine AstraZeneca, and COVID-19 Vaccine Janssen (Ad26.COV 2.5). Rolling reviews for additional COVID-19 vaccines are ongoing: NVX-CoV2373 by Novavax (started 03 February 2021), CVnCoV by Curevac (started 12 February 2021), and Sputnik V (Gam-COVID-Vac) by Gamaleya (started 4 March 2021)[4–6].

All EU/EEA countries have received and are using Comirnaty, COVID-19 Vaccine Moderna and Vaxzevria, except for Liechtenstein, where only the first two products are being used. By week 17, 2021 (2 May 2021), supplies of COVID-19 Vaccine Janssen have also been distributed to 24 EU/EEA countries. In addition, Hungary has received supplies of Sputnik V by Gamaleya and Inactivated Beijing CNBG by Sinopharm through bilateral negotiations with the manufacturers.

People welcome some vaccines for reasons such as safety, efficacy, and side effects and the removal of some restrictions (removal of travel bans), and if negative information about some vaccines is published, the public acceptance of those vaccines will decrease.

Vaccination means that there are different types of vaccines that are effective against a disease and the target population for injecting these vaccines. The goal is that vaccination of the target population is necessary to control the disease, and the target population prefers to inject the vaccine rather than not.

Our question is which vaccine to inject into which individual in the community to gain public satisfaction. Vaccine injection priorities for vaccination centers should first be identified in a research program, then this prioritization should be communicated to the community as needed, after which a preference profile should be received from each individual for vaccine injections. Now we have a vaccination issue. It may seem simple to inject vaccines into every individual in the community, but due to limited vaccine production and the large population of the target community and the lack of sufficient time for vaccination, it must be planned quickly to reduce mortality.

The issue of vaccination is one of the most important issues in the Ministry of Health. This means giving people the opportunity to choose their own vaccine. Because there was only one vaccine available for a disease in the past, people chose the vaccine regardless of its effectiveness. Wealthy people, on the other hand, now have the right to choose a vaccine because they can get vaccinated for themselves and their families by traveling to a well-vaccinated area. Other people in the community have no choice but to get the vaccine, regardless of the quality of the vaccine. As a result of these concerns, the issue of vaccination may become popular for social welfare.

Since it is not possible to inject the vaccine that everyone wants, the main issue in vaccination is the design of a vaccine allocation mechanism. While the Ministry of Health does not provide a specific mechanism, many vaccination programs have protocols and guidelines for assigning vaccines to individuals without explicit procedures. In fact, you should have a set of procedures that comply with the rules. In this paper, we propose a vaccine allocation mechanism that may be useful in addressing important vaccination issues.

A starting point is to study how to solve similar allocation problems in real life as well as in mechanism design articles. A closely related problem is the allocation of university dormitory rooms to students [7] or the following mechanism, known as the *random serial dictatorship*, applies almost in real life [8,9]: Classify people by lottery and select the first person. The next person is his best choice among the remaining slots and so on. This mechanism is not only *Pareto efficient*, but also *strategiy-proof* (i.e., it cannot be manipulated by misrepresenting preferences) and can accommodate any hierarchy of seniority. So why not use the same mechanism to give vaccines to people? The main point of this approach is as follows: According to the rules of the Ministry of Health, a person's preference for different vaccines is different. for example:

- People who work in the vicinity of Corona's patients have priority over those who do not work in the hospital for the vaccine.
- People with underlying disease should be given priority, and
- Older people are given priority over younger people.

Therefore a single lottery cannot be used to give vaccines to individuals. Vaccine priority feature complicates the vaccine allocation process. The mechanism of vaccine allocation should be sufficiently flexible. This point draws our attention to another related problem, the *college admissions problem* [10].

The main concept in the college admissions literature is *stability*: there should be no unmatched individual-vaccine (a, v) so that person a prefers vaccine v to assignment vaccine and vaccine v prefers person a to none. This means that vaccines do not have preferences but instead have a preemptive right: there should be no unmatched individual-vaccine (a, v) so that person a prefers vaccine v to the specific vaccine and he or she has a higher priority than other The type of vaccine is assigned to them.

Thus, consistent adaptation eliminates *justified envy* in the matter of vaccination. In addition, the existence of a stable matching that is preferred to any stable matching is well known in college admissions [10]. Since only the welfare of individuals is important in the vaccination problem, this matching Pareto dominates any other matching that eliminates justified envy. We refer to this mechanism as the optimal stable vaccination mechanism.

The optimal stable vaccination mechanism has a very attractive feature: it is *strategy-proof*. That is, honest preferences are a dominant strategy for individuals. In particular, people do not have to worry

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about losing their priorities after reporting their preferences correctly. This mechanism (the optimal stable vaccination mechanism) relieves people from devising complex allocation strategies.

However, the optimal stable vaccination mechanism is not without problems in the field of vaccination.

2. Vaccination Problem

In a *vaccination problem*, there are a number of people in the community, each of whom is assigned a type of vaccine. Each vaccine has a number of doses, but there is no shortage of vaccines overall. Everyone has strict preferences for all vaccines, and each vaccine from the EHU is a priority ordering for everyone. Here, priorities do not reflect vaccine preferences but are enforced by the EHU. For example, veterans or a specific illness are given priority for that vaccine according to the rules of the National Corona Headquarters, for each vaccine given priority between two people in each aspect. The corresponding ones are the same, usually determined by lot.

The vaccination problem is closely related to the well-known college admissions problem introduced by Gale and Shapley [10]. The college admissions problem has been widely studied (see Roth and Sotomayor [11] for a survey) and has worked successfully in the American and British markets (see Roth [12,13]). The main difference between the two problem is that in the vaccination problem, vaccines are things that should be "consumed" by agents, while in college admissions, vaccines themselves are agents who have preferences over people in the community.

The outcome of a vaccination problem is an assignment that the vaccine is given to individuals so that each person is given one vaccine and no vaccine is given in more than one dose. We refer to each such outcome as a *matching*. If there is no other matching to give each person a weakly better vaccine and a strictly better vaccine to at least one person, matching is Pareto efficient. A *vaccine assignment mechanism* is a systematic method that selects a matching for each vaccination problem. The vaccine assignment mechanism is a *direct mechanism* if individuals are asked to indicate their preferences for vaccines and to selectively matching to these preferences and preferences of individuals. A vaccine assignment mechanism is Pareto efficient if it always selects a Pareto efficient matching. A direct mechanism is *strategy-proof* if no one can take advantage of it by misrepresenting their preferences.

3. Model

We now introduce our formal model. A set of applicants must choose between m vaccines, where the number of doses of each vaccine is q_i. Each applicant ranks the vaccines as they see fit and only removes vaccines that they do not accept under any circumstances. If the applicant is indifferent between two or more vaccines, he/she is nevertheless asked to list them in order. The EHU similarly prioritizes applicants. First, it eliminates those applicants who do not want the q_i vaccine under any circumstances, even if it means completing their quota. From this data, which includes vaccine doses and two ranking sets, we want to vaccinate individuals according to the agreed fairness standard.

Stable Allocation and Vaccination Problem: It is very simple to extend the deferred admission algorithm to the vaccination problem. For convenience, we assume that if the EHU is not willing to inject a vaccine into a person under any circumstances, as described above, that person will not even be allowed to apply for that vaccine. With this description, the following method is used: First, all people apply for the vaccine of their first choice. According to the number of doses of a vaccine (the number of q_i doses), the EHU puts the number of q_i of priority people on the vaccination list. Places all applicants less than q_i on the vaccination list and rejects the rest. The rejected applicants then apply for the next vaccine of their choice, and again the EHU selects the top q_i from the new applicants and those on the vaccine vaccination list, places them on the new vaccination list, and rejects the rest. This process ends when each applicant is either on the vaccination list or has been rejected by the EHU for vaccination with each vaccine. At this stage, the EHU announces all the people who are on the vaccination list and the vaccination is stable.

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Theorem 1. *Every applicant is at least as well off under the assignment given by the deferred acceptance procedure as he would be under any other stable assignment.*

Proof. See proof of theorem 2 in [10]. □

In parentheses we may notice that we do not have the symmetrical side of the vaccination problem. We can reverse our approach to the task of making "optimal vaccination" unique. The reverse method starts with the proposal of the EHU to the applicants who it deems most desirable, up to the quota, and then the applicants reject all the offers except the most attractive ones and continue.

Example 1. *There are three agents α, β, γ and three vaccines A, B, C, each of which has only one dose. V_0 is an empty vaccine (here V_0 means not vaccinated). We assume that everyone prefers vaccination to empty vaccine. The priorities of EHU and the preferences of agents are as follows:*

$$\begin{array}{ll} P_A : \beta \succ \alpha \succ \gamma & P_\alpha : B \succ A \succ C \succ V_0 \\ P_B : \beta \succ \alpha \succ \gamma & P_\beta : A \succ B \succ C \succ V_0 \\ P_C : \beta \succ \alpha \succ \gamma & P_\gamma : A \succ B \succ C \succ V_0 \end{array}$$

Let us interpret the EHU priorities as EHU prferences and consider the vaccination problem. In this case there is only one stable matching:

$$\begin{pmatrix} \alpha & \beta & \gamma \\ A & B & C \end{pmatrix}$$

But this matching is Pareto dominated by:

$$\begin{pmatrix} \alpha & \beta & \gamma \\ B & A & C \end{pmatrix}.$$

Here agents α and β have the highest priorities for vaccines A and B respectively. Therefore, there is no way to inject a vaccine into α that is worse than A, so he or she must inject B or A. Similarly, there is no way for β to inject a vaccine worse than the B vaccine, so he/she should inject A or B. Therefore, agents α and β should share vaccines A and B among themselves. Stability forces them to share these vaccines in an Pareto inefficient way: If vaccines B and A are given to agents α and β respectively, there is a situation where agent γ prefers vaccine A to their own vaccine and prioritizes It has more for vaccine B than agent β.

As Example 1 shows, complete elimination of justified envy may conflict with Pareto efficiency. If policy-makers rank complete elimination of justified envy above Pareto efficiency, then optimal stable vaccination mechanism is a very well-behaved mechanism.

4. Results

As of 10 Feb 2022, a total of 1,078,662,350 vaccine doses have been distributed by manufacturers to EU/EEA countries, including 12,474,880 in the last week (29 countries reporting; data for Malta not reported to TESSy). Comirnaty (BNT162b2) developed by BioNTech/Pfizer represents 62.9% of all doses distributed to EU/EEA countries via the European Commission's Vaccine Strategy, followed by Vaxzevria (AZD1222) previously COVID-19 Vaccine AstraZeneca (13.8%), COVID-19 Vaccine Spikevax has the same formulation as the EUA Moderna COVID-19 Vaccine (17.2%) and COVID-19 Vaccine Janssen (5.5%). In addition, Hungary and Slovakia have received supplies of Sputnik V by Gamaleya and Inactivated Beijing CNBG by Sinopharm through bilateral negotiations with the manufacturers. Table 1 shows the proportion of vaccine doses distributed by manufacturers to each EU/EEA country by vaccine product as of 10 Feb 2022.

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Table 1. Proportions of COVID-19 vaccine doses by product (%), distributed by the manufacturers to EU/EEA countries[1]

CountryProduct	**Comirnaty**	**Janssen**	**Spikevax**	**Vaxzevria**	**Beijing CNBG**	**Sputnik V**
Austria	64.2	4.6	12.9	18.3	0.0	0.0
Belgium	65.8	2.6	19.9	11.7	0.0	0.0
Bulgaria	53.1	21.3	11.3	14.3	0.0	0.0
Croatia	67.3	4.1	11.5	17.1	0.0	0.0
Cyprus	68.9	5.9	6.6	18.6	0.0	0.0
Czechia	74.0	5.9	11.9	8.2	0.0	0.0
Denmark	82.7	0.5	14.7	2.2	0.0	0.0
Estonia	71.2	4.8	10.0	14.0	0.0	0.0
Finland	76.4	0.6	17.6	5.4	0.0	0.0
France	65.7	2.3	25.7	6.3	0.0	0.0
Germany	65.7	2.6	16.4	15.3	0.0	0.0
Greece	66.6	9.8	7.2	16.4	0.0	0.0
Hungary	36.7	12.9	5.6	21.3	17.0	6.5
Iceland	67.8	6.3	14.9	11.0	0.0	0.0
Ireland	69.0	2.3	17.0	11.7	0.0	0.0
Italy	65.5	1.7	18.8	14.1	0.0	0.0
Latvia	46.3	16.5	21.4	15.9	0.0	0.0
Liechtenstein	33.4	1.0	65.6	0.0	0.0	0.0
Lithuania	72.5	7.1	8.0	12.3	0.0	0.0
Luxembourg	63.9	5.2	18.7	12.2	0.0	0.0
Netherlands	64.9	6.1	19.6	9.4	0.0	0.0
Norway	69.0	3.1	23.4	4.4	0.0	0.0
Poland	56.8	14.7	8.9	19.6	0.0	0.0
Portugal	60.7	5.7	15.8	17.9	0.0	0.0
Romania	68.1	10.9	9.4	11.6	0.0	0.0
Slovakia	66.0	5.1	9.4	17.4	0.0	2.2
Slovenia	60.2	4.7	12.4	22.8	0.0	0.0
Spain	53.1	8.6	20.4	18.0	0.0	0.0
Sweden	71.7	0.0	21.5	6.8	0.0	0.0

[1] *Source: TESSy; data reported by 29 countries as of 10 Feb 2022*

5. Conclusions

Countries have primarily prioritised elderly people (with various lower age cut-offs across countries), residents and personnel of long-term care facilities, healthcare workers, social care personnel, and people with certain comorbidities. Countries are currently continuing vaccination of these groups and progressing to vaccination of younger age groups and essential workers critical to societal infrastructure.

The National Corona Headquarters in Iran emphasizes the following characteristics that should be used to assign vaccines to individuals:

1. People who work in the vicinity of Corona's patients have priority over those who do not work in the hospital for the vaccine.
2. People with underlying disease should be given priority, and
3. Older people are given priority over younger people.

The mechanism we propose respects each of these factors.
Adopting the optimal stable vaccination mechanism may provide a practical solution to some important vaccination issues, this is done more easily and more quickly, so that mortality in society is lower and public satisfaction is increased. The model proposed in this paper helps to implement vaccination optimally using matching theory.

Depending on a country's condition, including epidemiology and vaccine availability, countries recommend COVID-19 specific vaccine products to different target groups/age groups, and changes in individual preferences may occur based on vaccine information such as safety, efficacy, or side effects. Come on. Maintaining an effective communication strategy is essential, especially with a focus on safety and risk/benefit messaging for target groups and the general public, and ensuring high vaccine uptake.

Countries will continue to adapt vaccination policies and strategies as the epidemiological situation evolves, with increases of vaccine availability and as continuous updates on vaccine safety and real-world evidence on vaccine effectiveness becomes available.

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Abbreviations

The following abbreviations are used in this manuscript:

EHU	European Health Union
COVID-19	Coronavirus disease 2019
EEA	European Economic Area
EU	European Union
EMA	European Medicines Agency
CNBG	China National Biotec Group
TESSy	The European Surveillance System

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