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The welfare cost of vaccine misallocation, delays and nationalism

Abstract

I calibrate an eco-epidemiological age-structured SIR model of the B.1.1.7 covid variant on the eve of the vaccination campaign in France, under a stop-and-go lockdown policy. Three-quarters of the welfare benefit of the vaccine can be achieved with a speed of 100,000 full vaccination per day. A 1-week delay in the vaccination campaign raises the death toll by approximately 2,500, and it reduces wealth by 8 billion euros. Because of the large heterogeneity of the rates of hospitalization and mortality across age classes, it is critically important for the number of lives saved and for the economy to vaccinate older people first. Any departure from this policy has a welfare cost. Prioritizing the allocation of vaccines to the most vulnerable people save 70k seniors, but it also increases the death toll of younger people by 14k. Vaccine nationalism is modeled by assuming two identical Frances, one with a vaccine production capacity and the other without it. If the production country vaccinates its entire population before exporting to the other, the global death toll would be increased by 20%. I also measure the welfare impact of the strong French anti-vax movement, and of the prohibition of an immunity passport.

JEL Classification: N/A

Keywords: COVID, Pandemic, Vaccine, anti-vaxxer, covid immunity passport

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1 Introduction

At the end of 2020, two key events impacted the dynamics of the covid-19 pandemic in opposite directions. First, the B.1.1.7 ("British") variant emerged. It is more transmissible and more lethal than the original virus. The health measures implemented in France for example, that were strong enough to imply a R_0 smaller than 1 for the original virus, were insufficient to maintain the variant's R_0 below 1. In the anticipation of a vaccine, and without an effective test-trace-and-isolate strategy, or a cure to the covid-19, the French government implemented a stop-and-go policy to "flatten the curve", implying a terrible death toll among vulnerable people, and a sizable destruction of economic wealth in the medium term. But the good news at the end of 2020 was that several highly effective vaccines started their mass production and inoculation phases. These vaccines do not only erase the most severe consequences of the virus for the infected patients, in particular hospitalization and death. They also eliminate the risk of transmission of the virus from vaccinated but infected patients.

However, the production capacity for these vaccines is too small to allow most countries to win the race between mass vaccination and the dissemination of the new variant. This raises the critical question of the allocation of the flow of available vaccines over time. This issue is complex because of its ethical, health, social and economic implications. The WHO (2020a) has worked out a values framework based on 12 objectives and 6 principles (human wellbeing, equal respect, global equity, national equity, reciprocity, legitimacy). From this framework, WHO (2020b) "justifies an initial focus on direct reduction of morbidity and mortality and maintenance of most critical essential services, while considering reciprocity towards groups that have been placed at disproportionate risks to mitigate consequences of this pandemic (for example, front-line health workers)." Duch et al. (2020) surveyed 13 countries to measure the population's willingness to prioritize the supply of vaccines to different categories of citizens. In most countries, people favor giving priority to key workers and to those at high risk, but the public also favors giving priority to various categories of citizens such as poorer people.

In Table 1, I describe the most recent statistics on the infection-to-ICU and infection-to-fatality rates in France. The later (IFR) takes into account of a 64% increase in the mortality rate of the B.1.1.7 variant observed in the U.K. (Challen et al., 2021). According to Lapidus et al. (2020), the IFR increases exponentially with age, doubling every 5.2 years. This suggests that the vaccination strategy that maximizes the number of lives saved is to prioritize older people, together with people with co-morbidities. Most EU members are currently following a "stop-and-go" policy to "flatten the curve" of the ICU utilization. Because older people are also susceptible to need intensive care in case of infection, giving priority to older people is also useful for the economy, by relaxing the necessary lockdown.¹ In this paper, I measure the welfare benefit for France of this optimal vaccination campaign by combining its wealth and health impacts.

To perform this task, I improve the age-structured SIR model that I used in Gollier (2020c) to compare the welfare impacts of different age-sensitive lockdown policies. I removed from this model its PCR testing element, because no government has used the possibility of mass testing to unlock citizens with a negative test. I replaced this testing element by a vaccination module.

¹China is currently giving vaccination priority to the 18-60 category of ages. This may be due to the fact that China has a very low rate of prevalence of the virus. The economic effect of this priority rule is thus non-existent.

Age Class	Prob[ICU if infected]	Prob[deceased if infected]
0-18	0.01%	0.001%
19-64	0.48%	0.30%
65+	1.75%	7.79%

Table 1: Estimation of the infection-ICU and the infection-fatality rates by age class in France. Source: Saltje et al. (2020) for the ICU rate and Lapidus et al. (2021) for the IFR. This IFR is multiplied by 1.64, given the observation by Challen et al. (2021) of the 64% increased lethality of the variant.

The pandemic has both health and wealth impacts. As is usual in health and environmental economics, I use a Value of Statistical Life (VSL) to value lives saved in the welfare function.² To perform the welfare evaluation of various health policies, I use the official VSL of 3 million euros prevailing in France (Quinet, 2013). I show that the marginal welfare benefit of the vaccine is quickly decreasing with the speed of the vaccination. Compared to the no-vaccine solution, three-quarters of the welfare cost of the pandemic in 2021 would be eliminated in France with the current speed of 100k vaccinations per day. And postponing the vaccination campaign in France by one week would kill 2,500 additional people along the pandemic, and it would reduce wealth by 8 billion euros. This result could be useful for example when performing the benefit-risk evaluation of the (4 days) suspension of the vaccination campaign when some safety concerns emerged for the AstraZeneca vaccine in mid-March.

Suppose now that, for whatever reason, France does not prioritize the supply of vaccines to its most vulnerable citizens. A possible reason is the existence in France of a strong anti-vax movement. In Section 7, I measure the welfare impact of the presence of 30% anti-vaxxers. In my model, their presence does not affect the intensity of the lockdown, so that it does not worsened the economic crisis. But it increases the death toll by 60k, most of them anti-vaxxers. They also exercise a negative externality on senior pro-vaxxers, 5k of them will die due to additional senior infections during the first three months of the campaign, before their immunization.

Vaccine nationalism is another source of misallocation of the vaccine. In late March, countries like the U.S., the U.K. and Israel have been able to vaccinate a majority of their population, whereas the most vulnerable people in other countries remain exposed to the virus. According to Mullard (2020) given information available at the end of 2020, the U.S. has reserved more than 1.2 billion doses, and Canada has delivery contracts covering more than 9 doses per persons. Hafner et al. (2020) estimate the economic cost of the predicted disruptions in pandemic-sensitive sectors generated by this nationalism. In this paper, I analyze a thought experiment of vaccine nationalism by assuming a world composed of two identical Frances, one with a vaccine production capacity and the other without it. I compare the first-best allocation where vulnerable people of both countries are vaccinated first, to the nationalistic allocation in which the producing country keeps the production for itself until the completion of its vaccination campaign. I show that such an extreme form of

²For more information, see for example Drèze (1962), Schelling (1968), Jones-Lee (1974), Shepard and Zeckhauser (1984), Murphy and Topel (2006), Viscusi (2009), and US-EPA (2010).

vaccine nationalism raises the aggregate death toll by 20%. I also show that the producing country gains so much from banning vaccine exports that any sizable international vaccination cooperation, such as the COVAX project supervised by WHO, looks like a definitive illusion, in spite of its public support (Clarke et al., 2021).

A few papers have examined age-structured SIR models. Most of them examine strategies of mass confinement and/or testing, but none of them have considered a severely constrained vaccination campaign. Acemoglu, Chernozhukov, Werning and Whinston (2020), Favero, Ichino and Rustichini (2020), Fischer (2020) and Wilder et al. (2020) all support a strong sheltering of the vulnerable persons. All these models share the same fundamental structure of the age-structured SIR framework that I use in this paper. Contrary to Gollier (2020b), I suppose here that all parameters of the pandemic are known with certainty.

2 The age-structured SVIR model

The SIR model was introduced by Kermack and McKendrick (1927). As of today, this model remains the backbone of epidemiological literature. It has long been extended to allow for differences across groups. These extensions are referred to as "multi-group", and when focusing on age, "age-structured" or "age-stratified". In the spirit of Acemoglu et al. (2020), Favero et al. (2020) and Gollier (2020c), I examine such an extension of a discrete-time version of the SIR model, by adding an economic module and by allowing for a vaccination stage. The whole population, whose size is normalized to unity, is partitioned in 3 age classes $j \in \{y, m, o\} = \{0-18, 19-64, 65+\}$. The share of class j in the whole population is denoted N_j . Each person is either Susceptible, Vaccinated, Infected, Recovered or Death, i.e., the health status of a person belongs to $\{S, V, I, R, D\}$. This implies that $S_{j,t} + V_{j,t} + I_{j,t} + R_{j,t} + D_{j,t} = N_j$ at all dates $t \geq 0$, where $I_{j,t}$ for example measures the number of infected persons in class j at date t . The number of infected persons at date t is denoted $I_t = \sum_j I_{j,t}$, with a symmetric notation for S_t, V_t, R_t and D_t . I consider a daily frequency.

The flow chart of the SVIR model is described in Figure 1. Day 0 corresponds to the date at which the vaccination campaign begins, with exogenous initial conditions $(S_0, V_0, I_0, R_0, D_0)$. From day 0 on, a flow $\{x_t\}$ of daily vaccinations can be performed.³ This daily vaccination capacity must be allocated to the different age classes according to a specific allocation strategy. Let $s_t = \{s_{yt}, s_{mt}, s_{ot}\}$ represent this dynamic allocation, with $\sum_j s_{jt} = x_t$ for all t . The total number of people in age class j who have been vaccinated prior to or on day t is

$$v_{jt} = \sum_{\tau=0}^t s_{j\tau}. \quad (1)$$

The cumulative number of vaccinated people in the population on day t is $v_t = v_{yt} + v_{mt} + v_{st}$.

Newly vaccinated people are transferred into the V pool. Because antigens take time to be produced, people in that pool remain susceptible. A fraction μ of the V pool is transferred into the R pool every day, i.e. they become immunized. Thus, the mean transit time in the V pool is $1/\mu$ days. I assume that vaccination is 100% efficient after the V -transition, and that infected people who recovered from the virus are permanently immunized. They are

³For simplicity, I assume that only one dose per person is sufficient to be vaccinated. Because all vaccines currently distributed in France require two doses, the speed of vaccination in my model should be estimated by dividing by 2 the daily number of doses inoculated.

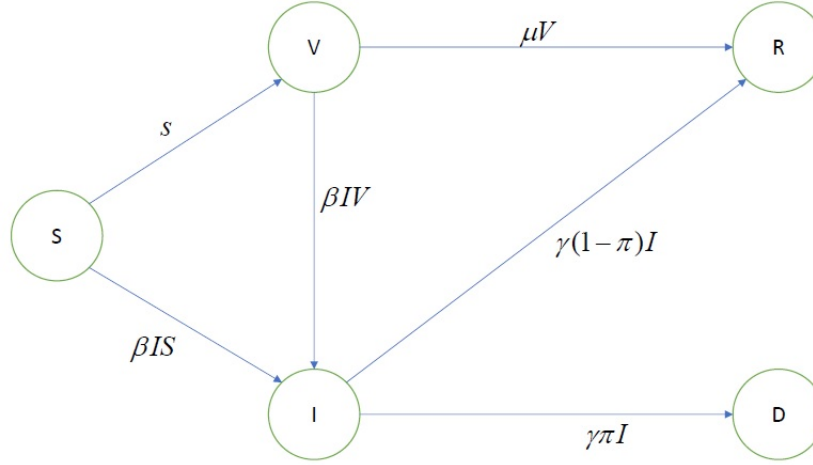


Figure 1: Flow chart of the SVIR model

also all detected as such at no cost. Thus, the R status can be attained either through a successful vaccination or from recovering from the disease.

People with the S status and the V status face the same risk to become infected. They can be infected by meeting an infected person. Following the key assumption of all SIR models, this number of new infections is assumed to be proportional to the product of the densities of infected and susceptible persons in the population, weighted by the intensity of their social interaction. Under the SIR framework, and with no further justification, this is quantified as follows:

$$I_{i,t+1} - I_{i,t} = \left(\sum_{j=1}^J \beta_{ijt} I_{j,t} \right) (S_{i,t} + V_{i,t}) - \gamma_i I_{i,t}. \quad (2)$$

I will soon describe how β_{ijt} , which measures the intensity of the risk of contagion of a susceptible person in class i by an infected person in class j at date t , is related to the social interactions between these two groups and by the confinement policy. Once infected, a person in age class i quits this health state at rate γ_i , as described by the last term in equation (2). The net outflow of susceptible persons between days t and $t + 1$ combines people who are infected and people who get vaccinated:

$$S_{i,t+1} - S_{i,t} = - \left(\sum_{j=1}^J \beta_{ijt} I_{j,t} \right) S_{i,t} - s_{it}. \quad (3)$$

Similarly, the net outflow from the V pool is given by the following equation:

$$V_{i,t+1} - V_{i,t} = s_{it} - \left(\sum_{j=1}^J \beta_{ijt} I_{j,t} \right) V_{i,t} - \mu V_{i,t}. \quad (4)$$

There are two exit doors to the infection status, as one can either recover from the virus or die:

$$R_{i,t+1} - R_{i,t} = (1 - \pi_i)\gamma_i I_{i,t} + \mu V_{i,t} \quad (5)$$

$$D_{i,t+1} - D_{i,t} = \pi_i \gamma_i I_{i,t}. \quad (6)$$

The mortality rate among the infected persons of class i at date t is denoted π_i . In this paper, I compare health policies that all share the same property of never overwhelming hospitals. This allows me to assume that the mortality rate is constant along the pandemic cycle. Equations (2), (3), (4), (5) and (6) fully describe the age-structured SVIR model examined in this paper. The dynamics of the pandemic depends in particular upon the β coefficients, which are sensitive to the intensity of the social interaction within and across different age groups. They also depend upon the policy of social distancing. Symptomatic infected people are quarantined, whereas the remainder of the population – which includes the asymptomatic infected people – faces some restrictions in terms of social distancing. I assume that a fraction κ of infected people is asymptomatic and cannot be identified during their contagion period.

The policy of social distancing on day t is described by vector $\{b_{jt}\}$ where $b_{jt} \in [0, 1]$ is the intensity of the lockdown imposed to age class j . Symptomatic infected people have a low contagion index β_q because they are quarantined. Asymptomatic infected people cannot be detected and are just partially confined. They have a contagion index $\underline{\beta}b_{jt} + \bar{\beta}(1 - b_{jt})$. Thus, infected people in age class j have a mean contagion of $\beta_q(1 - \kappa) + (\underline{\beta}b_{jt} + \bar{\beta}(1 - b_{jt}))\kappa$. Susceptible people in age class i are confined in intensity b_{it} . Given the frequency α_{ij} of interactions between age-classes i and j , the rate of transmission of the virus between infected people of age class j and susceptible people of age class i is given by:

$$\beta_{ijt} = \alpha_{ij} \left(\beta_q(1 - \kappa) + (\underline{\beta}b_{jt} + \bar{\beta}(1 - b_{jt}))\kappa \right) (1 - b_{it}) \quad (7)$$

An important feature of equation (7) is that the intensity of the contagion between age classes i and j is a quadratic form of the confinement intensities b_i and b_j . In the case of a uniform confinement rule, the intensity of contagion is quadratic in the intensity b of confinement. This is due to the fact that the lockdown reduces the interaction from both sides, infected and susceptible.

How can we compare different policies in relation to their welfare impacts? Two dimensions should be taken into account. First, life is valuable, so death has a welfare cost. Let me associate a cost ℓ_j to the death of a person in age class j .⁴ The pandemic has also an economic cost associated to the deaths, quarantines, confinements and vaccination during the pandemic. I assume that quarantined people are unable to work. A fraction ξ_j of confined people in class j can telework. The value loss of a person in class j who cannot work is denoted w_j . For workers, w_m can be interpreted as their labor income. For young people,

⁴Some recovered people suffer from long-lived side effects after their infection. Because this phenomenon remains difficult to measure in frequency, intensity and duration, I have not included this adverse effect of the pandemic in my welfare analysis. Other missing welfare effects of the pandemic include the psychological cost of the measures of social distancing, or the increasing risk of new variants when the rate of prevalence increases.

w_y includes the lost human capital due to the reduced quality of their education during lockdown. For the retired people, it's the value of their contributions to the common good. We must also take account of the economic cost of mass vaccination. In total, assuming a unit cost of vaccination equaling p , the economic loss of the pandemic in class j is measured as follow:

$$W_j = pv_{jT} + w_j \sum_{t=0}^T \left((1 - \xi_j)b_{jt}(S_{j,t} + \kappa I_{j,t} + (1 - \omega)R_{j,t}) + (1 - \kappa)I_{j,t} + D_{j,t} \right), \quad (8)$$

where T is the time horizon of the social planner. I assume that a proportion ω of people with the R status receives an "immunity passport" which allows them to be relieved from the lockdown constraints. Finally, the total loss is thus equal to

$$L = \sum_{j=1}^J \left(\ell_j D_{j,T} + W_j \right). \quad (9)$$

A key dimension of the health policy during a pandemic is the risk of overwhelming the health care system facing limited capacities in health workers, beds, ICUs or respirators. I summarize this capacity problem by a capacity limit on covid ICUs in hospitals. The social distancing policy $\{b_t\}$ is aimed at making sure that the national ICU capacity \overline{ICU} is never overwhelmed. I assume that at the end of the infection period, a fraction h_i of infected people needs an ICU.

$$newICU_{i,t} = h_i \gamma_i I_{i,t},$$

where h_i is the fraction of infected people in class i developing an acute version of the virus and requiring intensive care. Because the mean duration in intensive care is T_{ICU} , the total number of people of age class i in intensive care on day t is given by

$$ICU_{i,t} = \sum_{\tau=1}^{T_{ICU}} newICU_{i,t-\tau}.$$

I constrain health policies to make sure that the ICU capacity is never overwhelmed: $\sum_j ICU_{j,t} \leq \overline{ICU}$. Finally, I assume that the virus can be obliterated by an aggressive testing-and-tracing strategy if the global infection rate in the whole population goes below some threshold I_{min} .

In this paper, I measure the impact of the vaccination strategy on social welfare under the standard uniform "stop-and-go" lockdown policies that have been implemented in Europe after the first wave of the pandemic. These policies have the advantage of preserving some ICUs, but they ignore the fact that the short term economic advantage of the weak lockdown could be dominated by the medium term cost of the much longer duration of the lockdown, waiting for herd immunity or a mass vaccination campaign. They also ignore the benefits of sheltering more intensely the most vulnerable fraction of the population (Gollier, 2020c). So, I assume $b_{jt} = b_t$. The limited social acceptability of these measures justifies the more realistic approach considered in this paper. The stop-and-go policy is characterized by three possible intensities of confinement, $b^l < b^m < b^h$, and three ICU thresholds: $0 \leq r_l < r_m < r_h \leq \overline{ICU}$. I assume that the medium intensity b^m of lockdown is implemented on day 0. This intensity is maintained as long as ICU_t remains in between r_l and r_h . If ICU_t goes below r_l , the intensity is reduced to b^l , and remains at that level as long as ICU_t is below r_m . If ICU_t goes

above r_h , the lockdown intensity is increased to b^h , and remains at that level as long as ICU_t is above r_m . Finally, we must recognize that the usefulness of the lockdown is reduced when the proportion of vaccinated people increases. I therefore assume that the effective lockdown intensity is linearly decreasing with the fraction of vaccinated people: $b_t = b^i(1 - v_t)$.

Because older people faces a much larger risk of needing intensive care and of mortality in case of infection, the efficient vaccination strategy is to allocate the vaccine in priority to this age class.⁵ The benchmark calibration of the model is based on the assumption that the vaccination campaign allocates the vaccine according to this first-best rule. I then examine the welfare cost of alternative allocation strategies.

3 Calibration of the SVIR model

I calibrate the model on French data. I normalize the French population of $n = 67$ million people to unity. The size of the population in the different age classes is $N = (0.227, 0.568, 0.205)$. At date $t = 0$, I assume that 1% of the population is infected, uniformly across the 3 age classes. At that time, there is a number $R_{.,0} = (0.24, 0.17, 0.12) \cdot N$ of recovered people in the population.⁶ I also assume that 1% of the population is in the I status at that date. All others are in the S pool on day 0.⁷

I calibrate the virulence of the B.1.1.7 variant as follows. According to Volz et al. (2020), it is 40% to 70% more transmissible than the original virus. I therefore increase the $(\beta, \bar{\beta})$ by 50% compared to my original calibration in Gollier (2020c). It yields $\underline{\beta} = 0.15$ and $\bar{\beta} = 0.9$, whereas I continue to assume that quarantined (symptomatic) individuals do not transmit the virus. According to Challen et al. (2021), the B.1.1.7 variant is also 64% more lethal than the original virus. Thus, I multiplied by a factor 1.64 the historical infection-fatalities ratio estimated for France by Lapidus et al. (2021). This yields a infection-fatality ratio π equaling 7.79% and 0.3% for respectively the 65+ and the 19-64. Compared to the calibration for the original virus, these are very bad news.

The daily outflow rate $\gamma_i = \gamma = 1/18$ from the infection pool is assumed to be the same across age classes. This corresponds to the observation that infected people remain sick for 2 or 3 weeks on average. The daily outflow rate $\mu = 1/20$ from the recently vaccinated V pool to immunity R pool corresponds to a mean time of 20 days to develop antigens. The rate of asymptomatic cases is particularly difficult to calibrate. The Center for Evidence-Based Medicine has estimated this rate somewhere between 5% and 80%.⁸ He, Lau, Wu et al. (2020) found a 95% confidence interval of [25%, 69%] for the proportion of asymptomatic cases. The US Center for Disease Control and Prevention (CDC) has edicted 5 scenarios of the pandemic with two plausible levels of the rate of asymptomatic, 0.2 and 0.5, with a

⁵More generally, the vaccine should be allocated on the basis of a vulnerability index that would include the existence of co-morbidities. This is how the categorization of the population should be interpreted in this model. This research suffers from the lack of information about the number of people with relevant co-morbidities, their social interaction and their labour participation. In this paper, I also ignore the critical importance of vaccinating people serving vulnerable people in hospitals and nursing homes.

⁶In its report of March 11, 2021, the Conseil Scientifique chaired by J.-F. Delfraissy stated that 17% of the French population tested positive to the SARS-CoV-2 antigen in early 2021, with twice as much immunized people among younger people than among people aged 50 or more.

⁷This also means that the death toll is reset to 0 on day 0.

⁸<https://www.cebm.net/covid-19/covid-19-what-proportion-are-asymptomatic/>

central assumption at 0.35.⁹ I assumed a $\kappa = 35\%$ rate of asymptomatic people. The social contact matrix across age classes has been estimated in France by Béraud, Kazmerczak, Beutels, Levy-Bruhl, Lenne, Mielcarek et al. (2015). Social interactions go down with age, within and across age classes. I approximate their results by the following contact matrix:

$$\alpha_{..} = \begin{pmatrix} 2 & 0.5 & 0.25 \\ 0.5 & 1 & 0.25 \\ 0.25 & 0.25 & 0.5 \end{pmatrix} \quad (10)$$

The social distancing policy is characterized by the lockdown intensities $b^l = 0$, $b^m = 40\%$ and $b^h = 80\%$, and by the ICU thresholds (r_l, r_m, r_h) of respectively 30%, 60% and 90% of the ICU capacity \overline{ICU} . The minimum rate of infection below which the virus can be obliterated in the population is assumed to be $I_{min} = 30,000/n$.

Wealth losses are measured in fractions of annual GDP (around 2,400 billion euros). I assume that a full lockdown would reduce the flow of wealth production by $\xi = 50\%$, coming from a mixture of people who cannot telework and of the inefficient nature of teleworking technologies compared to work in presence. This is in line with the estimation of a 8.3% of GDP loss in France in 2020, assuming a 20% average intensity of lockdown during that year.¹⁰ I assume an economic loss of a full confinement by a middle-aged person equaling $1/N_m$. This means that a 100% confinement of the middle-aged people without any telework capability during one year would generate a 100% GDP loss. In this calibration, telework halves that loss. I also assume that confining a young or a senior person yields no economic loss. This is in line with the worrying fact that GDP does not take account of most contributions of these two age classes to the wealth of the nation.

In the benchmark calibration of the model, I prohibit immunity passports, so that $\omega = 0$. Recovered and vaccinated people are assumed to be confined with the same intensity as susceptible people.

What is the cost of the vaccination campaign? The purchasing prices of the vaccines have mostly remained secret as I write this paper. The Belgian health authorities told the media that the EU purchased the AstraZeneca vaccine at a unit price of 2.15 euros.¹¹ Pharmacists are allowed to inoculate the vaccine in France since mid-March 2021. They are paid 10 euros per inoculation. Because two doses are necessary, I estimate the total cost of the vaccination to around 30 euros per person. This implies a total cost around 2 billion euros, or approximately $p = 0.1\%$ of annual GDP.

In France in 2021, we have 6733 beds in ICU. The probability of requiring an ICU bed in case of infection has been estimated by Saltje et al. (2020). It equals 0.01%, 0.48% and 1.75% for the 3 age classes.¹² It remains to calibrate the value of lives. I discuss this critical issue in Gollier (2020a), remarking in particular that the absence of any democratic debate on this issue over the last five decades during which Western governments used a "value of statistical life" for policy evaluation is problematic. In this paper, I value a life lost at 100

⁹<https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html>

¹⁰<https://www.insee.fr/fr/statistiques/5018361>

¹¹Hafner et al. (2020) claim that the United States deal for the Pfizer/BioNTech agreement was set at the much larger price of 19.50 USD per dose.

¹²The ICU probability is smaller than the mortality rate for the seniors, probably because many of them die in nursing home without benefiting from an intensive care unit.

	Value	Description
γ	1/18	Daily recovery rate
μ	1/20	Daily immunization rate among newly vaccinated
β_q	0	Daily contagion rate of quarantined persons
β	0.15	Daily contagion rate of confined persons
$\overline{\beta}$	0.9	Daily contagion rate of working persons
κ	35	Proportion of asymptomatic positives (in %)
ω	0	Proportion of immunized people with an immunity passport
ξ	0.5	Proportion of telework
I_{min}	30000	Extinction threshold of the pandemic
\overline{ICU}	6733	ICU capacity
(b^l, b^m, b^h)	(0,40,80)	Intensities of lockdown (in%)
$(r_l, r_m, r_h)/\overline{ICU}$	(30,60,90)	Policy limits in ICU capacity (in%)
N	(22.7, 56.8, 20.5)	Age-distribution of population (in %)
π	(0.002, 0.30, 7.79)	Infection-fatality proportion (in %)
h	(0.01, 0.48, 1.75)	Prob. of ICU if infected (in %)
R_0/N	(24,17,12)	Fraction of initially immunized people (in %)
α_1	(2, 0.5, 0.25)	Intensity of transmission from young
α_2	(0.5, 1, 0.25)	Intensity of transmission from adult
α_3	(0.25, 0.25, 0.5)	Intensity of transmission from senior
T_{ICU}	15	Days in ICU
w	(0, 176, 0)	Economic loss of confinement (in % of GDP/cap)
ℓ	(100,100,100)	Value of life lost (in years of GDP/cap)
p	0.1	Cost of vaccine for the entire population (in % of GDP)

Table 2: Benchmark calibration of the SVIR model.

annual GDP/cap, independent of age. This is aligned with the official VSL of 3 million euros in France (Quinet, 2013).

This benchmark calibration is summarized in Table 2. In my reference scenario, I will assume that France is able to maintain its current speed of vaccination at 200k doses per day (see Figure 2), i.e. 100k full vaccinations per day. This is compatible with a start of the vaccination campaign in late January 2021. In reality, the French campaign started earlier, but at a much lower speed.

4 Welfare impacts of the vaccination campaign

In this section, I examine the dynamics of the pandemic as a function of the speed of the vaccination campaign. In Figure 3, I describe this dynamics when a constant flow of 100k vaccinations per day is performed. This corresponds to the objective of vaccination of France for the spring of 2021. The two graphs on the left describe the health policy, in terms of the intensity of lockdown (top) and of vaccination (bottom). The seniors not yet naturally immunized are fully vaccinated within the first 110 days of the campaign. It takes 200 more days to vaccinate the middle-aged people that have not yet been infected at that time. The

vaccination campaign is finished before the end of the year. A mild gradually decreasing lockdown is imposed for 260 days, with a short period of strong lockdown after the first two months of the campaign to limit the exponential growth of ICU utilization that occurs at that time. This shows that the speed of vaccination is too slow to compensate for the large transmission rate of the new variant. When reversing to the milder intensity of lockdown, a new wave of the virus hits the country, but it concerns only the younger generations with a low rate of hospitalization. This implies that this second wave does not require imposing a new intense lockdown, in spite of the fact that the number of daily new cases is larger than during the first wave. Herd immunity is attained within 300 days from the vaccination campaign and from the fraction of the population that recovered from the infection.

Table 3 describes the welfare costs of the pandemic from day 0 of the vaccination campaign. For this speed of 0.1×10^6 vaccinations per day, one should expect 92k lives lost. The vaccination of the seniors is not fast enough to save 50k of them from the deadly new variant. The purely economic GDP loss in 2021 is estimated around 14%, coming mostly from the extended duration of the lockdown. The cost of the vaccination campaign counts for 0.07% of annual GDP. Finally, valuing lives at 100 years of annual GDP/cap raises the welfare cost of the pandemic from day 0 to 28% of annual GDP.

It is a useful theoretical exercise to compare this outcome to what would have happened in the absence of a vaccine. Under this scenario described in the first line of Table 3, the stop-and-go policy is a dead-end, with no other outcome than herd immunity in the long run. A long succession of ups and downs in the lockdown policy will be necessary to preserve hospital, and herd immunity would be attained only after 3 years, with a cumulative economic loss of 35% of annual GDP. Under these catastrophic circumstances, the new variant would kill 470k people, 85% of them being older than 65 years. This dismal outcome reminds us how bad was the news of the emergence of this B.1.1.7 variant on the eve of 2021 in France. The good news is that the 100k/day vaccination campaign reduces the number of deaths among seniors by 87% and among adults by 42%. The economic loss of the pandemic is reduced from 35% to 14% of annual GDP. The welfare loss is reduced by a factor 4 when aggregating economic and human costs of the pandemic.

vaccine speed $10^6/\text{day}$	lives lost			loss	
	19-64	65+	total	wealth %GDP	total %GDP
0.00	72705	396464	469351	34.71	104.80
0.05	55387	78780	134337	18.45	38.50
0.10	41641	50026	91817	13.82	27.53
0.15	32857	41609	74605	11.13	22.26
0.20	26159	37166	63450	9.31	18.78
0.25	22642	32883	55638	8.04	16.34
0.50	16245	29151	45470	5.06	11.84

Table 3: Impacts of the pandemic as a function of the speed of the vaccination campaign, starting from day-0 of the campaign.

A key insight from Table 3 is the steeply decreasing nature of the marginal benefit of

accelerating the vaccination campaign. If going from 0 to 100k vaccinations per day reduces the welfare cost of the pandemic by 73%, going from a speed of 100k/day to 200k/day reduces it by only 30%. Three-quarters of the total cost of the pandemic since day 0 can be eliminated with the benchmark 100k speed. The dynamics of the pandemic under 200k vaccinations per day is described in Figure 4. The increased speed of vaccination is again primarily beneficial to the seniors in their race between vaccination and infection. But it also allows for a reduction of the intensity and of the duration of the lockdown, which is beneficial to the economy.

In Figure 5, I represent the welfare benefit of the vaccination campaign as a function of its speed. This welfare benefit is measured in euros per capita rather than by the reduction in total loss expressed in a fraction of annual GDP. For a speed of 100k/day, it equals $(0.1048 - 0.2753)$ multiplied by 2400×10^9 and divided by 67×10^6 . It equals 27,679 euros per capita. For a unit cost of vaccination at 30 euros, this vaccination campaign has a social return of approximately 100,000%.

The decreasing marginal benefit of the speed of vaccination should not hide the fact that countries implementing a faster vaccination campaign will vastly outperform the others both in terms of lives saved and economic performances.

It is useful to measure the welfare cost of forcing immunized people to face the same restrictions as the remainder of the population in spite of the absence of any health and economic benefit of this egalitarian rule. The refusal of the immunity passport is based on an egalitarian principle that is symmetric to the prohibition of requiring a more intense lockdown for more vulnerable people. These prohibitions are not compatible with the minimization of the number of lives lost, or of the economic loss. Offering an immunity passport to immunized people, i.e. replacing $\omega = 0$ in the calibration by $\omega = 1$, reduces the economic cost of the pandemic from 14% to 9.5% in the benchmark case with 100k vaccinations per day.

In this paper, I combine a vaccination campaign with a stop-and-go policy of lockdown and social distancing. I follow this approach because most western governments currently consider that there is no socially acceptable alternative. But one may question whether this stop-and-go policy is optimal. In this section, I have shown that it is a viable policy in the context of the development of a massive vaccination campaign, which provides a medium term exit to the pandemic. It is legitimate to ask whether a "no-covid" policy would generate a better outcome. To answer this question, let me re-calibrate the same model with $b^l = b^m = b^h = 0.8$, i.e., with the imposition of a 80% lockdown until the rate of prevalence I_{min} is attained to eradicate the virus with a test-trace-and-isolate procedure. Under this no-covid policy, the rate of prevalence I_{min} is attained after 78 days to eradicate the virus. The economic loss is limited to 8% of annual GDP, and fatalities are limited to 13,351. At a speed of vaccination of 100k per day, the vaccination campaign is almost irrelevant for this eradication strategy (although the herd immunity that the vaccination campaign creates is key for the stability of the no-covid outcome). Notice that this result favorable to the no-covid policy heavily relies on the possibility to implement an efficient test-trace-and-isolate strategy at the end of the lockdown, and on the necessity to coordinate such a policy at the EU level. It also raises the question of the social acceptability of a strong lockdown in the spring of 2021.

5 The welfare cost of delaying the start of the campaign

A simple way to measure the urgency of the vaccine is obtained from performing the thought experiment of a one-week translation of the vaccination campaign. This experiment is related to the suspension by France and Germany (together with other EU members on a different time frame) of the AstraZeneca vaccine from the afternoon of Monday March 15 to the morning of Friday March 19. This interruption in the distribution of that vaccine (which represented half of the daily doses distributed in France in mid-March) was related to a suspicion of a lethal side effect after a number of people developed blood clots and thrombosis soon after receiving a dose.

Technically, as of 16 March 2021, around 20 million people in the UK and the EU had received the vaccine, and the European Medicines Agency (EMA) had reviewed 25 cases of blood clots in this cohort, 9 of which resulted in death. A causal link with the vaccine is not proven. Overall the number of thromboembolic events reported after vaccination was lower than that expected in the general population.¹³

It is useful to compare this potential adverse effect of the vaccine with the additional lives lost and economic cost associated to delaying the campaign by one week. As shown in Table 4 and in Figure 6, this delay to launch the campaign increases the death toll by 2,481 and it reduces GDP by 0.34%, or more than 8 billion euros. These estimations suggest that France suffered heavily from the half-week suspension of the AstraZeneca vaccination campaign, without any identified benefit. Moreover, the suspension reduced the public confidence in the vaccination.¹⁴

delay	lives lost			loss	
	19-64	65+	total	wealth	total
0 day	41641	50026	91817	13.82	27.53
7 days	41980	52168	94298	14.16	28.23

Table 4: Impacts of delaying the vaccination campaign by one week.

6 The welfare cost of randomizing the allocation of the vaccine

In this section, I compare the outcome of the health policy when vaccines are prioritized on the basis of vulnerability (proxied in this model by age), to the outcome when no such priority is implemented. More precisely, I assume here that vaccines are randomly distributed until the whole population get inoculated. This is related to various tendencies to allocate the vaccine to specific groups of people on the basis of other principles than vulnerability. WHO (2020b) justified many of these alternatives principles to allocate priority to the vaccine,

¹³<https://www.ema.europa.eu/en/news/covid-19-vaccine-astrazeneca-benefits-still-outweigh-risks-despite-possible-link-rare-blood-clots>

¹⁴If the suspension occurs during the campaign rather than at its start, the number of lives lost is smaller because the most vulnerable are already immunized. For example, if the 1-week suspension takes place after 60 days, the death toll is increased by 1862 compared to the benchmark. The economic loss remains unchanged at 0.34%.

such as a compensation for front-line essential workers (health workers, teachers,...). Other allocation procedures are also discussed, such as the creation of a free market for the vaccine, or prioritizing the poor. Public decision-makers are indeed right to integrate other morale principles of justice when allocating the scarce vaccine supply. In this section, I inform them about the utility cost of integrating these other dimensions into their decisions, in the extreme case of an allocation procedure orthogonal to vulnerability.

It is noteworthy that my model cannot take account of the observed heterogeneity in the intensity of social interactions within a specific age-class. Specific individuals and professions have more potential than others to transmit the virus to vulnerable people. The best examples are health workers in nursing homes. There is a clear efficiency rationale for offering a high priority to these individuals.

I describe in Figure 7 the dynamics of the pandemic under a random distribution of the vaccine with 100k vaccination per day. Obviously, the randomization improves the welfare of those who were not prioritized in the benchmark, i.e., the two younger classes. They are much less infected, and their mortality rate drops. The opposite outcome prevails for the seniors. Globally, the second wave imposes less stress to ICUs, but a high ICU utilization prevails longer at the end of the pandemic. Because the randomized vaccination procedure reduces the circulation of the virus, the virus can be erased earlier. This reduces the economic loss by 1% of annual GDP, as shown in Table 5. But the global death toll is increased by 56k, with 70k more fatalities among the seniors, whereas 14k middle-aged lives will be saved.

allocation procedure	lives lost			loss	
	19-64	65+	total	wealth	total
first-best	41641	50026	91817	13.82	27.53
random	27277	120463	147807	12.83	34.89

Table 5: Impacts of fully randomizing the allocation of the vaccine.

7 The externalities generated by the anti-vaxxers

The presence of anti-vaxxers provides another illustration of the welfare cost of an inefficient allocation of the vaccines. France is the western country with the larger share of anti-vaxxers.¹⁵ Suppose that 30% of the French population, uniform across age classes, are going to prefer not to be inoculated. What are the consequences of these individual choices on social welfare? In Figure 8, I depicted the dynamics of the pandemic in that context. Table 6 summarize my findings. This phenomenon has several implications. First, many more senior anti-vaxxers will die. But because the virus will circulate more intensely in the senior age class, more senior vaccinated people who are not yet immunized (they have the V status) will also die. Remember that senior people interact much more within their own age class than with other classes, so that the presence of senior anti-vaxxers is a very bad news for other senior people. This illustrates the negative externality that the anti-vaxxers exercise

¹⁵In a February 2021 survey conducted by Imperial College London, among 15 surveyed countries, France had the highest proportion of respondents who stated that they would not take any covid-19 vaccine (44%).

on pro-vaxxers. How can we measure this effect? If everyone would be inoculated, we should expect 35k deaths among the senior pro-vaxxers. In reality, with 30% anti-vaxxers in the population, I predict that 40k senior vaxxers will die. Thus, the negative externality of the anti-vaxxers on senior pro-vaxxers is estimated around 5k additional deaths among this pro-vaxxer population.

	lives lost			loss	
	19-64	65+	total	wealth	total
Without anti-vax global	41641	50026	91817	13.82	27.53
With 30% anti-vax global	41080	114333	155548	13.73	36.91
vaxxers	24442	40160	64691		
anti-vaxxers	16638	74173	90857		

Table 6: Impacts of 30% anti-vaxxers.

A second effect comes from the fact that younger people will be inoculated earlier than in the benchmark scenario. The virus will circulate less in these age classes as soon as they start their vaccination period. Globally, the ICU capacity is more stressed because of the misallocation of the vaccine during that second wave, with many senior people needing intensive care. But the net effect of the presence of anti-vaxxers on middle-aged pro-vaxxers is positive. Indeed, without the anti-vax movement, one should expect 29k lives lost among middle-aged pro-vax at the end of the pandemic. Thanks to the anti-vaxxers, this death toll is limited to 24k for this category of people, a reduction by 5k deaths. This is a positive externality from the anti-vax movement. At the aggregate level across age classes, 419 more pro-vaxxers will die due to the presence of the anti-vaxxers. It is noteworthy that I assume that all people that are vaccinated and that are not infected before producing antigens become fully immunized. This assumption is based on currently available scientific information about the efficacy of the 3 vaccines used in France.¹⁶ In an initial version of this paper, I assumed an efficacy rate of 95%, which implied a much larger global negative externality from anti-vaxxers.

On their side, the anti-vaxxers benefit from the herd immunity built by the vaccination effort of the pro-vaxxers. At the aggregate level, if nobody would get the vaccine, one should expect that 141k anti-vaxxers will die. But the presence of the pro-vaxxers in the population will reduce the death toll faced by the anti-vaxxers to 91k, a 35% reduction. This is the positive externality exercised by pro-vaxxers on anti-vaxxers.

Finally, the global effect of a 30% strong anti-vax movement would increase the death toll by 64k, a 69% increase compared to the benchmark without the movement and an efficient vaccination campaign of 100k vaccinations per day. The presence of anti-vaxxer has a small positive effect on the economy by reducing the duration of the lockdown.

¹⁶See for example the report dated 11 March 2021 by the French "Conseil Scientifique" for the pandemic.

8 The welfare cost of vaccine nationalism

Vaccine nationalism is another good example of misallocation of a vaccine, because vulnerable people in importing countries will be vaccinated (if they survive) potentially long after people with much lower risk in vaccine-rich countries. To explore this effect, let me examine the following thought experiment. Suppose that the world is made up of two identical Frances as described in this paper, except that one France, named the producer, controls the unique production site of the vaccine whereas the other must import the vaccine for its vaccination campaign. Finally, suppose that the production site has a production capacity of 200k vaccines per day. I compare two solutions. In the first-best solution under the veil of ignorance, the two countries equally share the resource by vaccinating 100k people each every day. Figure 3 describes the dynamics of the pandemic in the two countries in that context. Suppose alternatively that the producing country is able to secure priority in the allocation of the vaccine so that its whole population must be vaccinated before allowing exportation. For the producing country, the dynamics of the virus is described in Figure 4.

In the nationalistic scenario, the importing country must wait 211 days before starting its vaccination campaign. In that country, this long delay has dramatic consequences in terms of lives lost that is only partially compensated by the more intense and longer lockdown, as described in Figure 9. I summarized the impacts of the different international allocations of the vaccine in Table 7. The importing country must maintain some form of social distancing rules for almost one year, whereas the producing country can fully exit the pandemic within 6 months. This implies that the economic damage in that country is more than twice its equivalent in the producing country. And the death toll at the end of the pandemic is more than 150% larger in the importing country. Given the large discrepancy between the intensities of the health and economic crises incurred by the producing and importing countries, it is illusory to expect any politically acceptable cooperation to allocate the vaccine capacity efficiently at the international level, in spite of the efforts of the World Health Organization (COVAX).

scenario	lives lost			loss	
	19-64	65+	total	wealth	total
First-best					
Mean	41641	50026	91817	13.82	27.53
Nationalistic					
Mean	32560	78708	111398	14.42	31.04
Producer	26159	37166	63450	9.31	18.78
Importer	38969	120250	159347	19.53	43.31

Table 7: Impacts of vaccine nationalism.

Because of the vastly inefficient allocation of the vaccine in this nationalistic scenario, the worldwide death toll is 20% larger than under the first best allocation, yielding 39k additional deaths globally. Because the wealth creation technology used in this model is linear, the average economic loss of the pandemic is increased only marginally, from 13.82% of world annual GDP to 14.42%. Global welfare is reduced by approximately 13%.

9 Conclusion

Because the degree of vulnerability to the B.1.1.7 variant is highly sensitive to individual characteristics such as the age of the infected person, and because the covid vaccines are a scarce resource in 2021, it is critically important to allocate them wisely. If the objective is to minimize the welfare loss, the optimal solution is to give vaccination priority to the most vulnerable people. I first show that, under this optimal rule, the marginal benefit of the vaccine quickly decreases with the cumulated number of vaccinated people in the population. The key issue is to vaccinate the most vulnerable people quickly, so that the pressure on ICUs and hospitals can be relaxed, together with the intensity of the lockdown. For France, the planned speed of vaccination is not sufficient to compensate for the emergence of the highly transmissible variant, so that the intensity of the lockdown must be temporarily increased to "flatten the curve". The race undertaken by our vaccination campaign against the variant cannot be won in the short term given its high virulence and the lack of vaccination capacity. However, the current vaccination capacity at 100k vaccinations per day, if maintained permanently at that level, would reduce the welfare cost of the pandemic by 74%. Doubling the vaccination capacity would only reduce the welfare cost by an additional 8% (to 82% of the initial cost). This result should not hide the dismal death toll of the pandemic.

The objective of this paper was to estimate the welfare cost of the misallocation of the vaccine, with a special focus on the consequences of the vaccine nationalism that is currently raging in the western world. By vaccinating low-risk people in vaccine-rich countries before high-risk people in vaccine-poor countries, we worsen the global welfare consequences of the pandemic. There is no doubt that the vaccine-rich countries will greatly benefit from hoarding their vaccine. But under the veil of ignorance, this allocation is undesirable. In a simple two-country model, I show that the extreme form of vaccine nationalism in which vaccine-rich countries fully prioritize their own population before exporting their vaccine, the global death toll could be increased by 20%.

The allocation of the vaccines entails a large range of societal issues. Counting the number of additional fatalities and the additional GDP loss of the different possible allocations provides only a partial view of the deeper societal questions that emerge in this context. For example, some workers have faithfully accepted to expose themselves to the virus to save other lives, or to exercise essential activities for the economy. Decision-makers may consider a reciprocity or recognition measure that could take the form of giving them priority for the vaccine. My ambition in this paper is limited to the measure of the measurable costs of such a decision, in terms of expected lives lost and economic loss. Finally, my estimations should be taken with caution, given the many uncertainties surrounding many parameters of the standard SIR model calibrated on the new variant.

Bibliography

Acemoglu, D., V. Chernozhukov, Ivan Werning and Michael Whinston, (2020), A multi-risk SIR model with optimally targeted lockdown, NBER WP 27102.

Béraud G, S. Kazmerczak, P. Beutels, D. Levy-Bruhl, X. Lenne, N. Mielcarek et al., (2015), The French connection: The first large population-based contact survey in France relevant for the spread of infectious diseases, *PLoS ONE* 10,

Challen, R., E. Brooks-Pollock, J.M. Read, L. Dyson L, K. Tsaneva-Atanasova, L. Danon, (2021), Risk of mortality in patients infected with SARS-CoV-2 variant of concern 202012/1: matched cohort study, *The British Medical Journal* 372. BMJ 2021;372:n579

Clarke, P.M., L.S.J. Roope, P. Loewen, J.-F. Bonnefon, A. Melegaro, J. Friedman, M. Violato, A. Barnett, and R. Duch, (2021), Public opinion on global rollout of COVID-19 vaccines, mimeo, Toulouse School of Economics.

Drèze, J., (1962), L'utilité sociale d'une vie humaine, *Revue Française de Recherche Opérationnelle*, 23, 93-118.

Favero, C., A. Ichino and A. Rustichini, (2020), Restarting the economy while saving lives under covid-19, WP Bocconi University.

Duch, R., L.S.J. Roope, M. Violato, M.F. Becerra, T. Robinson, J.-F. Bonnefon, J. Friedman, P. Loewen, P. Mamidi, A. Melegaro, M. Blanco, J. Vargas, J. Seither, P. Candio, A.G. Cruz, X. Hua, A. Barnett, P.M. Clarke, (2021), Who should be first in line for the COVID-19 vaccine? Surveys in 13 countries of public's preferences for prioritisation, medRxiv 2021.01.31.21250866

Fischer, C., (2020), External costs and benefits of policies to address COVID-19, mimeo.

Gollier, C., (2020a), If herd immunity is the objective, on whom should it be built?, *Environmental and Resource Economics* 76, 671-683. Prepublished in *Covid Economics* 16, 98-114.

Gollier, C., (2020b), Pandemic economics: Optimal dynamic confinement under uncertainty and learning, *Geneva Risk and Insurance Review* 45, 80-93. Prepublished in *Covid Economics* 34, 1-14.

Gollier, C., (2020c), Cost-benefit analysis of age-specific deconfinement strategies, *Journal of Public Economic Theory* 22, 1746-1771. Prepublished in *Covid Economics* 24, 1-31.

Hafner, M., E. Yerushalmi, C. Fays, E. Dufresne, and C. Van Stolk, (2020), COVID-19 and the cost of vaccine nationalism, Santa Monica, CA: RAND Corporation.

- He, X., E.H.Y. Lau, P. Wu et al., (2020), Temporal dynamics in viral shedding and transmissibility of COVID-19, *Nature Medicine* 26, 672-675. <https://doi.org/10.1038/s41591-020-0869-5>.
- Jones-Lee M. (1974) The value of changes in the probability of death and injury, *Journal of Political Economy* 82, 835-849.
- Kermack, W.O., and A.G. McKendrick, (1927), A contribution to the mathematical theory of epidemics, *Proceedings of the Royal Society* 115, 700-721.
- Lapidus, N., J. Paireau, D. Levy-Bruhl, X. de Lamballerie, G. Severi, M. Touvier, M. Zins, S. Cauchemez, F. Carrat, (2021), Do not neglect SARS-CoV-2 hospitalization and fatality risks in the middle-aged adult population, *Infect Dis Now*.
- Mullard, A., (2020), How COVID vaccines are being divvied up around the world, *Nature* (30 Nov 2020).
- Murphy, K. M. and R. H. Topel, (2006), The value of health and longevity, *Journal of Political Economy* 114, 871-904.
- Quinet, E., (2013), L'évaluation socioéconomique des investissements publics, *Commissariat Général à la Stratégie et à la Prospective*, Paris.
- Salje, H., C. Tran Kiem, N. Lefrancq, N. Courtejoie, P. Bosetti, et al., (2020), Estimating the burden of SARS-CoV-2 in France. [.pasteur-02548181](https://doi.org/10.1101/2020.12.30.20249034)
- Schelling, T., (1968), The life you save may be your own, in "Problems in public expenditure analysis" (Chase, S.B., ed.), Washington, D.C., The Brookings Institution, 127-162.
- Shepard, D.S., and R.J. Zeckhauser, (1984), Survival versus Consumption, *Management Science* 30, 423-39.
- US-EPA, (2010), Valuing mortality risk reductions for environmental policy: A white paper, SAB-EEAC Review Report.
- Viscusi, W.K., (2009), The devaluation of life, *Regulation & Governance* 3, 103-127.
- Volz, E. et al. (2020), Transmission of SARS-CoV-2 lineage B.1.1.7 in England: Insights from linking epidemiological and genetic data, [medRxiv 2020.12.30.20249034](https://doi.org/10.1101/2020.12.30.20249034).
- Wilder, B., M. Charpignon, J. Killian, O. Han-Ching, A. Mate, S. Jabbari, A. Perrault, A. Desai, M. Tambe and M. Majumder, (2020), The role of age distribution and family structure on COVID-19 dynamics: A preliminary modeling assessment for Hubei and Lombardy, mimeo.

WHO, (2020a), WHO SAGE values framework for the allocation and prioritization of COVID-19, World Health Organization, Geneva.

WHO, (2020b), WHO SAGE roadmap for prioritizing uses of covid-19 vaccines in the context of limited supply, World Health Organization, Geneva.

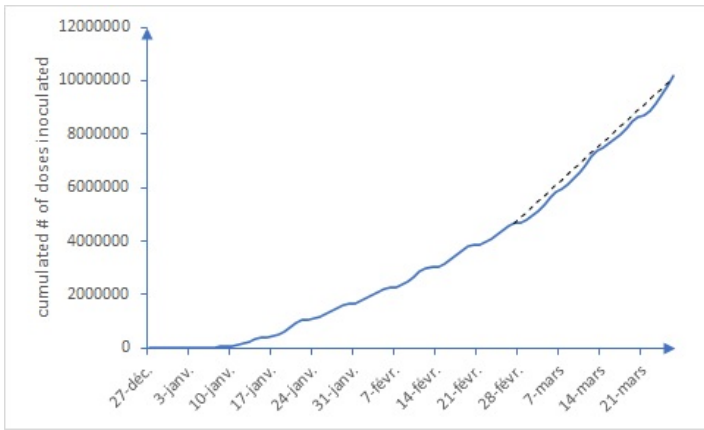


Figure 2: Cumulated number of doses inoculated in France during the first three months of 2021. The dashed curve corresponds to a speed of vaccination of 200k doses per day.

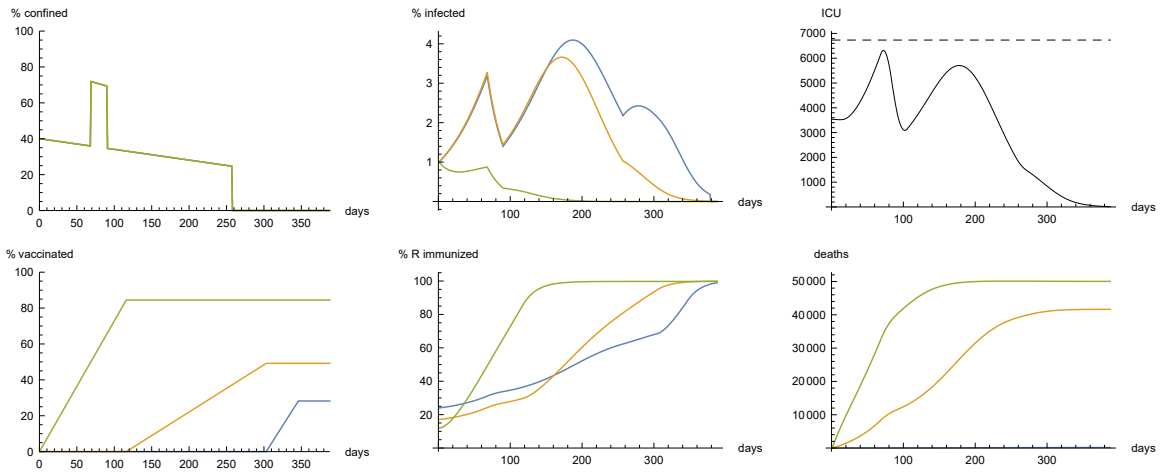


Figure 3: Dynamics of the pandemic under 100k vaccinations per day. The blue, orange and green curves correspond respectively to the young, middle and old age classes.

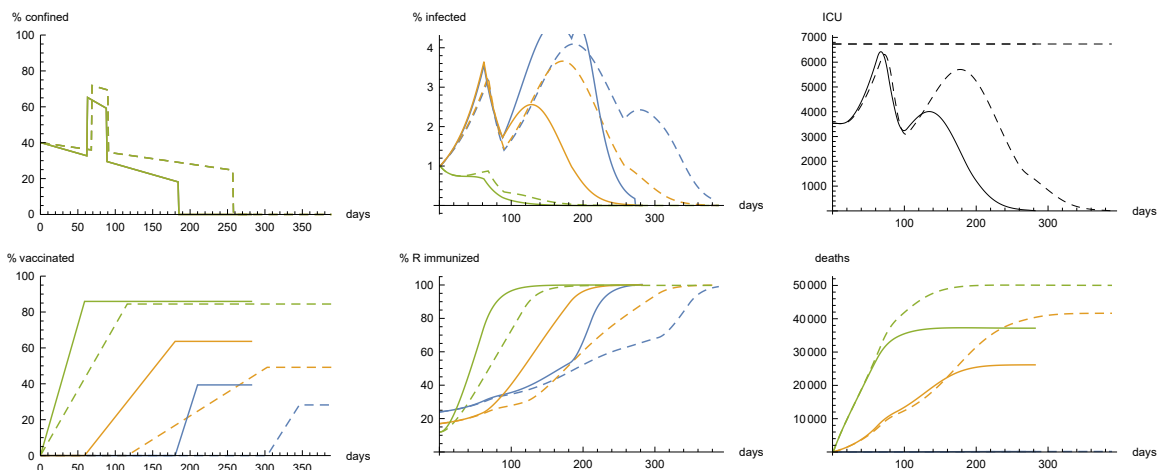


Figure 4: Dynamics of the pandemic under 200k vaccinations per day. Dashed curves correspond to the dynamics under the benchmark vaccination speed of 100k vaccinations per day.

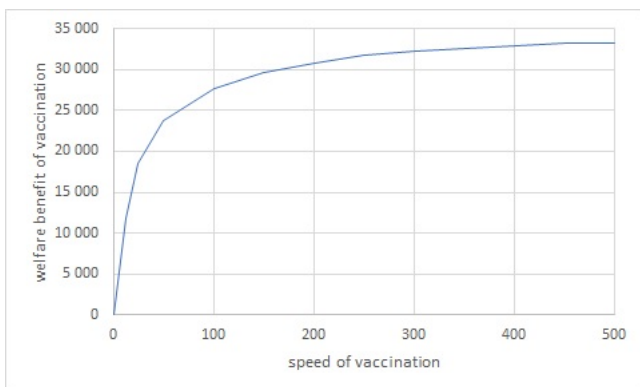


Figure 5: Welfare benefit (in euros per capita) of the vaccination campaign as a function of the speed of vaccination (in thousands of vaccinations per day).

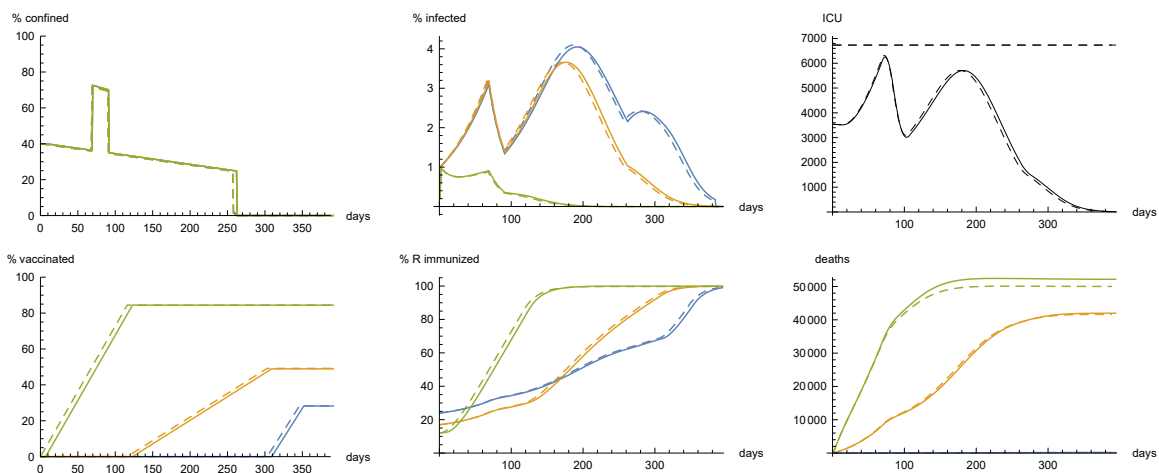


Figure 6: Dynamics of the pandemic under 100k vaccinations per day delayed to start on day 7. Dashed curves correspond to the dynamics under the benchmark vaccination speed of 100k vaccinations per day started on day 0.

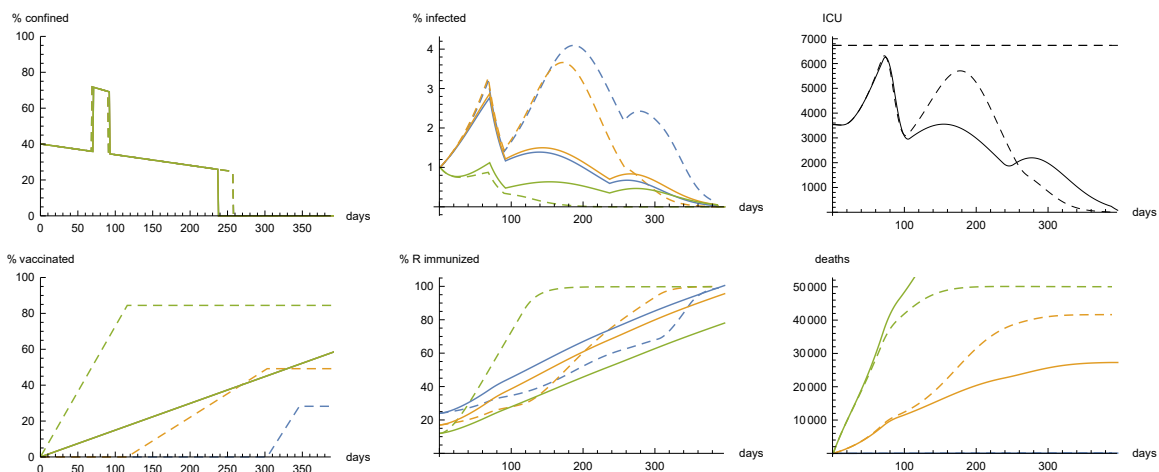


Figure 7: Dynamics of the pandemic under the 100k vaccinations per day when the vaccine is randomly distributed.

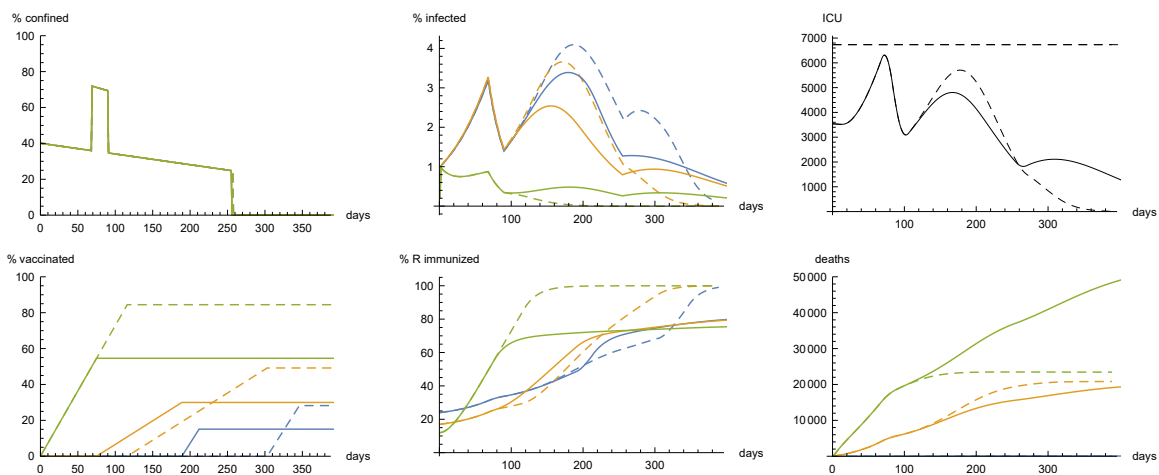


Figure 8: Dynamics of the pandemic under the 100k vaccinations per day with 30% anti-vaxxers in the population.

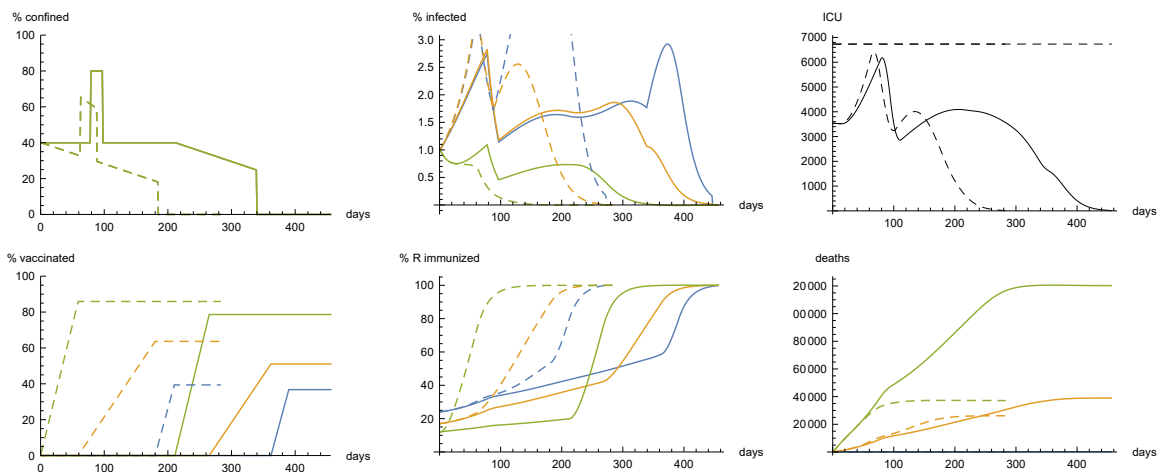


Figure 9: Dynamics of the pandemic in the thought experiment of vaccine nationalism. The importing country (plain curves) starts its vaccination campaign on day 211 after the producing country (dashed curve) has fully vaccinated its population.