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ABSTRACT

The irreversibility of dying coupled with gradual information acquisition over time on the likely arrival and eventual effectiveness of vaccines confers a real option value to lockdown strategies that delay the incidence of pandemics given a stochastic vaccine arrival/effectiveness process.

1. Introduction

Epidemiologists recommend lockdowns to dampen down waves of contamination, yet their imposition has remained hugely controversial. A growing body of research uses coupled epidemiology/economic models to explore a potential trade-off between economic costs and health benefits of different strategies (cf Kaplan et al., 2020) for a recent contribution and a literature review. In this note we provide a different angle: we look at a vaccine of uncertain arrival date and effectiveness as a binary option and a lockdown as a strategy that provides more people with access to that binary option.

Lockdowns delay and 'flatten' a pandemic's incidence, lower the risk of ICU overload and thereby save life years; also lockdowns may lead to lower overall mortality once herd immunity is reached because of a faster rampdown after reaching herd immunity (Moll, 2020). This note focuses on another advantage of lockdowns that has received less attention in the literature but that we show makes up a substantial component of the total value of Lockdown strategies. With any new pandemic, there is uncertainty about whether a vaccine will become available, if so when, and whether it will be effective if it comes. A vaccine of less than 100% effectiveness is like a binary option but dying before the vaccine becomes available clearly precludes access to that option. Lockdowns delay the disease's incidence and thereby make the option available to more people since less will have died by the time the vaccine becomes available.[2]

Kaplan et al. (2020) also discuss vaccines, but with known and certain arrival date and effectiveness. In Eichenbaum et al. (2020) and Garriga et al. (2020) vaccine arrival occurs with a fixed per period probability, so the probability that no vaccine arrives at all limits to zero with time, and once it arrives the vaccine is 100% effective, so uncertainty is more about when a vaccine arrives than whether it arrives or its effectiveness. Garriga et al. (2020) do not discuss lockdowns. Closer to our analysis is Collard et al. (2020), who setup an interactive game between susceptible and infected individuals and analyze optimal confinement policies. They show how individual behavior and optimal confinement policy change when the possibility of a future vaccine discovery is introduced. Finally Park (2016) employs a real option approach in determining optimal vaccine stockpiling with an application to the H1N1 Influenza epidemic outbreak in Korea but the vaccine arrival rate plays no role since a vaccine is already available and 100% effective. We highlight the analogy with binary options and

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[2] Whether Lockdowns bring with them economic costs is less clear: the direct effect of people getting sick or having to stay in restrictive quarantine conditions obviously reduces labor supply, but Goolsbee and Syverson (2021) indicate that the direct effects may well be inframarginal to voluntary stay-at-home behavior when contagion becomes increasingly more likely at points of contact. See also Lin and van Wijnbergen (2022).

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provide pricing formula's to quantify the option value component of vaccine valuation.

In the remainder we first sketch a highly stylized model designed to bring out the real options aspect of lockdowns, to the exclusion of all other mechanisms. Next we present a richer pandemic model with a stochastic process representing vaccine arrival rates and their potential effectiveness and we actually price the option value embedded in lockdowns. The final section concludes.

2. A skeleton model

To sharpen focus on the real options perspective we set up a simple model just focusing on population dynamics under a Laissez-Faire (LF) approach versus a LockDown (LD) strategy (the first stage of the binomial tree diagram in Fig. 1). The premise is that a lock down postpones incidence of the virus infections but that the pandemic will not die out before Herd Immunity levels of infection have been reached, unless a vaccine is developed earlier.

Time starts at $t = 1$, with population size normalized to Δ_1. At $t = 1$, either a Laissez Faire LF (no policy) or Lock Down (LD) strategy is chosen. Under LF a fraction ϕ_{LF} survives until $t = 2$, at which time a vaccine may or may not become available and if one arrives it may or may not be effective. The probability of an effective vaccine arriving at $t = 2$ is π. If the vaccine arrives and is effective ($v = 1$), population stabilizes. If no effective vaccine arrives ($v = 0$) a further fraction dies, We ignore any population overshooting. Under the lockdown strategy (LD) a smaller fraction dies before vaccine arrival ($phi_{LD} \gg \phi_{LF}$. But in the absence of an effective vaccine, the LD strategy also arrives at Δ_{HI} at t =3. The tree diagram 1 summarizes. In equations:

$$\begin{aligned} &\text{If} \quad v = 0: \quad \Delta_3^{LF} = \Delta_3^{LD} = \Delta_{HI} \\ &\text{If} \quad v = 1: \quad \Delta_3^{LF} = \Delta_1\phi_{LF} \\ &\qquad\qquad\qquad \Delta_3^{LD} = \Delta_1\phi_{LD} > \Delta_1\phi_{LF} \end{aligned} \tag{1}$$

Compare the two strategies, both with and without the vaccine effort succeeding, using the final number of survivors as welfare criterion: $W_i = \Delta_3^i$. *Ex post* we get:

$$\begin{aligned} &\text{v} = 0: W_{LD} - W_{LF} = \Delta_3^{LD} - \Delta_3^{LF} = 0 \\ &\text{v} = 1: W_{LD} - W_{LF} = \Delta_1 * (\phi_{LD} - \phi_{LF}) > 0 \end{aligned} \tag{2}$$

In *ex ante* terms we get:

$$E(W_{LD} - W_{LF}|t = 0) = \pi * \Delta_1 * (\phi_{LD} - \phi_{LF}) \tag{3}$$

From Eqs. (1) and (3) the option characteristic is clear: a fraction $(\phi_{LD} - \phi_{LF})$ of the original population Δ_1 receives a binary option on the vaccine being a success, a binary cash-or-nothing call (Hull, 2009). The lockdown strategy delays the pandemic's incidence; if there is no vaccine (the option is out-of-the-money), it makes no difference which strategy is chosen; but if the vaccine development strategy is successful, the option is in-the-money, the lockdown allows an additional fraction $(\phi_{LD} - \phi_{LF})$ of the original population to profit from the vaccine availability and survive, an option that is not available to them under the Laissez Faire strategy.

3. Moving beyond the skeleton model: the SIR model

We add a more realistic epidemiology model to quantify. We model vaccine discovery as a one-shot jump process with known arrival time if it does arrive.[3] Switching to continuous time introduces another extension: the HI threshold is the threshold

[3] Lin and van Wijnbergen (2022) for a more general stochastic vaccine arrival process.

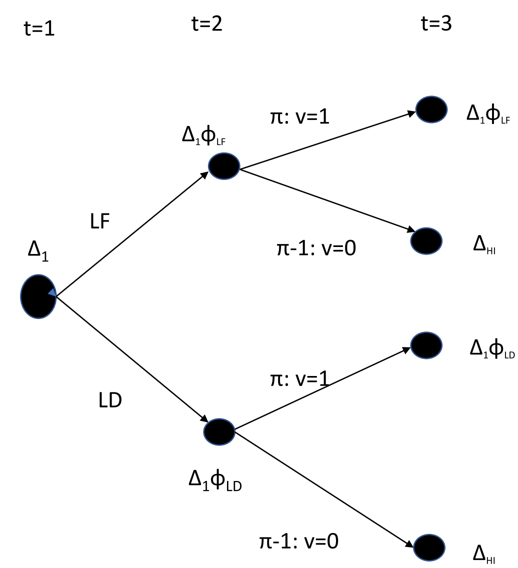


Fig. 1. Tree diagram population dynamics.
Note: The diagram traces the dynamics of population Δ_1 under different vaccine arrival/effectiveness scenario's.

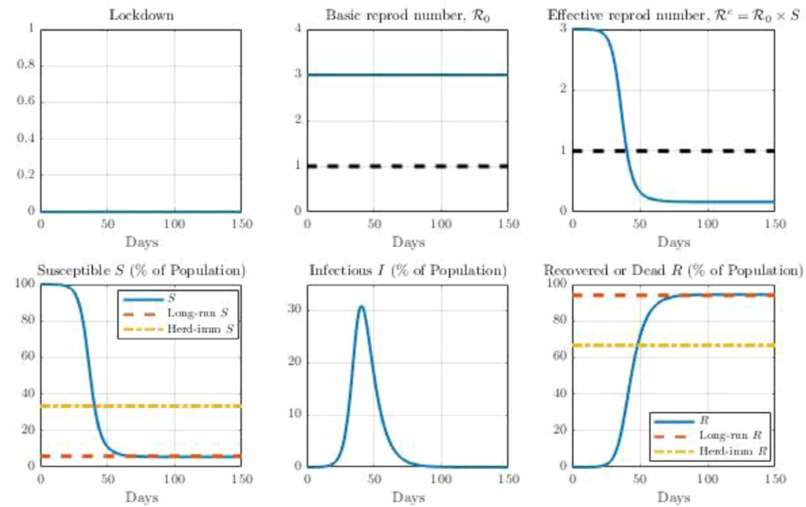
after which infections start to decline; the burden of the disease includes the "rampdown" phase after HI has been reached. We distinguish Susceptibles S_t, Infectious I_t and recovered or death R_t:

$$\begin{aligned} &\dot{S} = -\beta SI \\ &\dot{I} = \beta SI - \gamma I \\ &\dot{R} = \gamma I \\ &\dot{D} = \eta \dot{R} \\ &S_t + I_t + R_t = 1 \end{aligned} \tag{4}$$

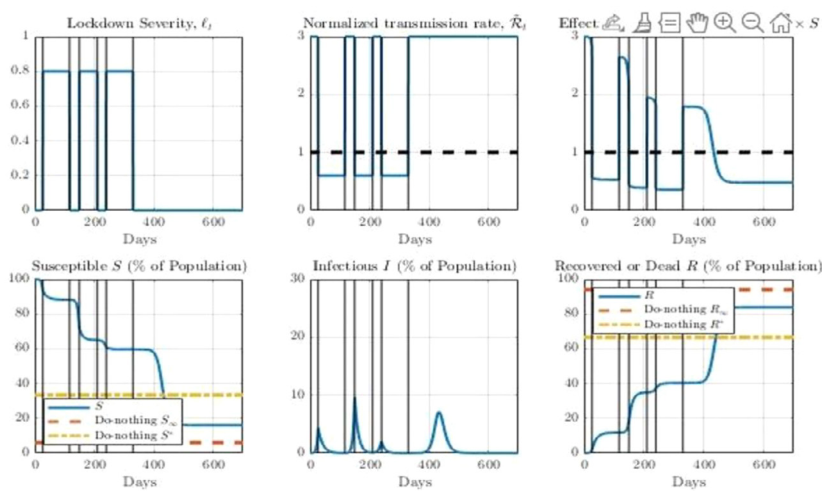
The rate of increase in infections depends on how many are already infected and can therefore spread the virus (S), and on how many are yet to be infected (I), and thus depends on SI. The number of infected increases in line with the number of newly infected βSI and declines with those who either die or survive ($\dot{R}$). The basic reproduction number is $R_0 = \beta/\gamma$ which implies a Herd Immunity threshold $S^* = 1/R_0$. This corresponds to a cumulative number of people infected $R^* = 1 - \beta/\gamma$. R^∞ is total incidence. A lockdown is simulated by assuming a β that pushes β_t/γ below one. We set $R_0 = 3$ following Atkeson (2021). The exit rate γ from the infectious state I to state R is based on the infectious period reported in Davies et al. (2020), $T_{inf} = 7$ which corresponds to $\gamma = 0.143$ since $\frac{1}{T_{inf}}$. The value of β then follows from $\beta = R_0\gamma$: $\beta = 0.43$.

The no-lockdown LF scenario (Panel A in Fig. 2), shows a sharp single peak of infections, a slow decline in S_t, with R rising until R^* is reached (yellow dotted lines), after which the decline in the infections starts and the eventual incidence level settles at $R^\infty > R^*$. With a repeated-roll-over lockdown strategy LD (panel B in Fig. 2) a wave pattern of infections emerges, and R_t switches between values above and below 1. The herd Immunity level is reached eventually, but later and since the decline at the last peak starts from a much lower level than in the no-lockdown case, the final total incidence is substantially lower because the rampdown starts at a lower level.

The vaccine is discovered 320 days after the start of the pandemic, the time between the first infections 19/11/2019 and the approval date of the Pfizer–Biontech, 11/12/2020. After 320 days under the LF scenario the final disease incidence level has



A: Laissez Faire scenario



B: Repeated Lockdown scenario

Fig. 2. Laissez-Faire versus Lockdown Scenario's.

already been reached, with 97% of the population infected and mortality at 2% (cf Table 1). But after 320 days, only 40% has been infected under the lockdown scenario. So an additional 53% of the population will receive the binary vaccine option because of the lockdown strategy. This corresponds to the expression $(\phi_{LD} - \phi_{LF})$ in 2.

These results show that lockdowns increase welfare in several ways: (A) even without vaccine discovery (the binary option ends up out-of-the-money), less people get sick and less people die. (B) even those who do get sick and eventually die, do so later than would have occurred under LF, which implies additional life years saved for given cumulative mortality. And (C) when the binary option ends up in-the-money, an additional 53% of the population receives the vaccine option under the lockdown strategy.

MacPherson et al. (2021) reports that the probability for a vaccine transitioning from the testing phase (Phase 1) to the next stage (Phase 2), based on a large number of vaccines developed for a variety of infection diseases, is 38.2%, while the probability of transitioning from Phase 2 to licensure is 10%. Combining these arrival probabilities with effectiveness of the discovered vaccines gives an estimate for the probability of the vaccine option ending up "in-the-money". We explore two effectiveness numbers: 70%, in between the minimum level of effectiveness required for approval (50%) and the maximum of 100%, and that maximum. This yields two values for the binary option ending up "in the money", 2.7% (0.38*0.10*0.7) and 3.8% (0.38*0.10*1.00).

Table 1 uses the model to calculate total infections and corresponding deaths both at the vaccine discovery date and once the final incidence level R^{**} has been reached, under both the lockdown and a Laissez Faire strategy.

Table 2 uses these numbers to construct option values based on the Value of a Statistical Life VSL and the related concept Value of a Statistical Life Year VLSY estimated in Kniesner et al. (2012): VSL = $ 7 million and VSLY = $ 0.3 million. These estimates of VSL and VSLY allow us to quantify the various effects of lockdowns (A), (B) and (C).

Table 2 shows that a higher effectiveness percentage (or higher arrival rate probability) will lead to a higher probability of the option ending up "in the money" and correspondingly to a higher

Table 1
Pandemic incidence of different policies (fraction of population).

	Lockdown	Laissez Faire
Total (cumulative) number of infections at Vaccine-discovery-date	0,40	0,97
Total death at Vaccine-discovery-date	0,008	0,019
Total (cumulative) nr of infections at Final-date	0,82	0,97
Total death at Final-date, no Vaccine discovered	0,016	0,019
Expected nr of days until R** reached	50	300

Table 2
Components of Lockdown strategy value (perc GDP).

Value of life years saved if Vaccine does NOT arrive/is ineffective (A)	0,078
Value of lives saved if V = 0, because of difference in F-mortality (B)	0,394
Value of Vaccine option (C)	0.040
Effectiveness/arrival probability	0.027–0.038
Total Value Lockdown Strategy	0,514–0.528

Table 3
Total value of the Lockdown strategy as a function of arrival/effectiveness probabilities (perc GDP).

Total value of Lockdown Strategy	0.514	0.528	0.621	0.770	0.920	1.07	1.219	1.97
Effectiveness/arrival probability	0.027	0.038	0.10	0.20	0.30	0.40	0.50	1.00

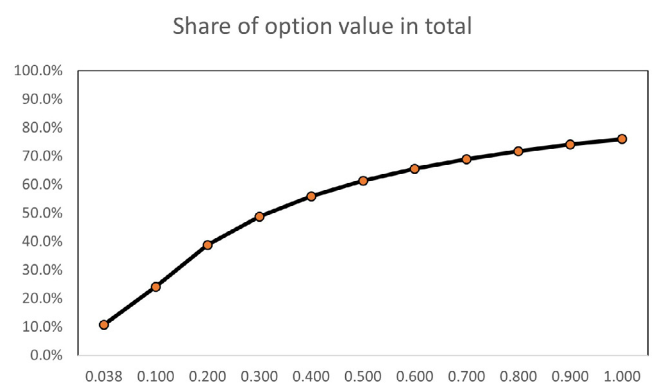


Fig. 3. Option Value as a share of total value Lockdown strategy.
Note: option value as share of total value lockdown strategy versus Combined arrival/effectiveness probability.

value of the Lockdown strategy. Table 3 shows the mapping from arrival/effectiveness probabilities to total LD strategy value:

Fig. 3 plots the option value component as a share of the total valuation of the lockdown strategy against the probability of the option ending in-the-money': at higher "in the money" probabilities the option element (C) contributes more to the total valuation of the Lockdown strategy, although increasingly less so. Calculating this graph and Table 3 all the way through to probability 1 (100%) is of interest: the higher range applies when we know the vaccine is highly effective but is not yet available because of production delays.

We can also use Table 3 to answer another question: early data indicate a decline in infection prevention because of vaccination of about one third (from 75% to 50% over approximately 6 months, cf CDC, 2022), which has led to booster vaccination after six months. Assuming approximate linearity this means that in the half year in between the first round of vaccinations and the boostershot, the option value declined from its initial value by 1.5% in the lower combined probability range and by about 0.45% in the higher probability range.[4]

4. Conclusions

Avoiding ICU overload by delaying and spreading out the pandemic's incidence is the argument most commonly used to defend a lockdown strategy over the Laissez Faire approach of just letting the pandemic escalate until herd immunity is reached. Moreover a lockdown will lead to lower cumulative mortality because herd immunity will be reached at lower rates of infection, which causes a shorter tapering-down time (Moll, 2020). We show that these arguments for lockdowns underestimate the value of a lockdown strategy for two reasons. First, even if the Lockdown strategy only delays the pandemic's incidence without affecting cumulative mortality, that still implies additional life years saved. Second, delaying the disease's incidence has the additional benefit of giving a larger segment of the population access to a vaccine if and when it is discovered and turns out to be effective. We interpret this as a larger segment of the population receiving a *binary option* on the vaccine, with the in-the-money state corresponding to the discovery of an effective vaccine, an option that they do not receive if they do not survive long enough, and less of them will survive long enough under Laissez Faire. In an economist's language: lockdowns have a real option value in addition to their traditionally recognized advantages in terms of avoiding ICU overloads and leading to less overall loss of life. We show that this option value component can range from about 10% to close to 80% of the overall value of the lockdown strategy depending on the specifics of the stochastic process driving Vaccine discovery. The option value emerges because of the stochastic nature of vaccine arrival and effectiveness combined with the unfortunate fact that death is irreversible. Dying prematurely blocks access to options that only become available after once's death. This leads to a second message: the case for a lockdown strategy strengthens the more likely a vaccine discovery is, the less uncertainty there is about its effectiveness and the closer we are to the day the vaccine will become available.

[4] Averaging the 20% and 30% values and the 90% and 60% values respectively.

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