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Abstract

In this paper, we investigate how the presence of the COVID-19 pandemic—the increase in the probability of death, following Blanchard and Fischer (1989)—may affect growth and welfare in a scale-invariant R&D-based Schumpeterian model. Without money, the increase in the probability of death has no effect on long-run growth and a negative effect on welfare. By contrast, when money is introduced via the cash-in-advance constraint on consumption, the increase in the probability of death decreases long-run growth and welfare under elastic labor supply. Calibration shows that the quantitative effect of an increase in the probability of death on welfare is much larger compared to that on growth.

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Keywords: the COVID-19 pandemic; cash-in-advance constraint on consumption; Schumpeterian model

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1 Introduction

Due to the COVID-19 pandemic, scholars began to study the long-term consequences of pandemics (e.g., Barro et al., 2020; Jordà et al., 2020). For instance, Barro et al. (2020) find that the "Spanish Flu" caused a 6% and 8% decrease in GDP and consumption, respectively, but the long-run growth rate is not affected. The existence of level but not growth effects is expected because the pandemic eventually disappeared. However, it is intriguing to study the case in which the pandemic would not disappear. In this paper we give it a simple try. Following Blanchard and Fischer (1989), we model the presence of the COVID-19 pandemic as the increase in the fixed probability of death. We use a scale-invariant R&D-based Schumpeterian growth model based on Chu and Cozzi (2014).

Our finding is as follows. Without money, an increase in the probability of death has no effect on long-run growth and a negative effect on welfare. When money is introduced via the CIA (cash-in-advance) constraint on consumption, an increase in the probability of death reduces long-run growth and welfare. The reason is due to the lack of insurance market for real balance.

Calibration shows that the effect of an increase in the probability of death on welfare is larger compared to that on growth. As the probability of death increases from 0.0128 to 0.0136, 0.0208 and 0.0338 (corresponding to an increase in mortality of 0.08%, 0.8%, and 2.1%; 2.1% is the worse-case scenario of the Spanish flu in Barro et al., 2020), the annual growth decreases from 1.80% to 1.80%, 1.79% and 1.77%, respectively. The welfare is not directly comparable. Under the same change in scenarios, the decrease in initial consumption is 0.05%, 0.34%, and 1.37%, respectively, and the life expectancy decreases from 78 years to 73.5, 48 and 29.6 years, respectively. Therefore, the welfare losses are substantial if the pandemic does not disappear. For a given probability of death, there are significant growth and welfare gains from monetary contraction, and the gains from monetary contraction remain similar for the probability of death of very different magnitudes.

Our study relates to the literature on health, human capital, fertility and mortality in growth models (see, Chu, Cozzi and Liao, 2013; Prettner, 2013, 2014; He, 2018a,b,c), and that on inflation and growth (e.g., Dotsey and Sarte, 2000; He and Zou, 2016; Chu et al., 2019). Related to our study, scholars have studied the effects of longevity on long-run growth in R&D-based growth models (e.g., Prettner and Trimborn, 2012; Prettner, 2013, 2014). Prettner and Trimborn (2012), Prettner (2013), and Prettner (2014) all model longevity as the decrease in mortality (i.e., a decrease in the probability of death). These studies all find that a decrease in the probability of death promotes long-run growth in per capita output in endogenous growth models or semi-endogenous growth models where the size of population matters for growth. By contrast, we use the Schumpeterian model with no scale effects (see e.g., Segerstrom, 1998, for discussions of scale-effects), where the share of population allocated between R&D and manufacturing, rather than total population, matters for long-run growth. Additionally, we study the role of monetary policy.

Our study also relates to the most recent studies on the COVID-19 pandemic (e.g., Manski and Molinari, 2020; Atkeson, 2020; Acemoglu et al., 2020, and references therein). For instance, Manski and Molinari (2020) analyze data from Illinois, New York, and Italy, over the period March 16 to April 24, 2020 and find that the infection rate might be substantially higher than reported, but the infection fatality rates are substantially lower than reported:

> We find that the cumulative infection rates as of April 24, 2020, for Illinois, New York, and Italy are, respectively, bounded in the intervals [0.004, 0.525], [0.017, 0.618], and [0.006, 0.471]. Further analyzing the infection-fatality ratio, we find that as of April 24 it can be bounded, for Illinois, New York, and Italy, respectively, in the intervals [0, 0.033], [0.001, 0.049], and [0.001, 0.077]. The upper bounds are substantially lower than the death rates among confirmed infected individuals, which were, respectively, 0.045, 0.059, and 0.134 on April 24.

Acemoglu et al. (2020) focus on the effects of testing policy on voluntary social distancing and the spread of an infection. Testing enables the isolation of infected individuals, but greater testing also reduces voluntary social distancing, thereby yielding a non-monotone effect of testing on infections. Our study takes the infection rate and the infection-fatality ratio as given and focuses on the growth and welfare effects. Our study can be improved by endogenizing the probability of death with testing and voluntary social distancing.

The paper proceeds as follows. Section 2 presents the Schumpeterian model without money. Section 3 presents the monetary Schumpeterian model and calibrates the model to show the quantitative effects. Section 4 concludes.

2 Schumpeterian Model with the COVID-19 Pandemic

Following Blanchard and Fischer (1989), we model the COVID-19 pandemic as the increase in the probability of death. The Schumpeterian model follows Chu and Cozzi (2014).

2.1 Households

Each individual faces a constant probability of death per unit of time throughout life. The probability of dying is independent of age.

There is a unit continuum of identical households, which have a lifetime utility function

$$U = \int_0^{\infty} e^{-(\rho+p)t} \left[\ln(c_t) + \theta \ln(1 - l_t)\right] dt, \tag{1}$$

where c_t is per capita real consumption of final goods and l_t is per capita labor supply at time t. ρ is the rate of time preference; $p > 0$ captures the constant but increased probability of death due to the COVID-19 pandemic; $\theta \geqslant 0$ is the taste for leisure (note that it is not the elasticity of labor supply).

The population size is fixed at L. This is achieved by assuming that the size of new cohort is Lp, which means the fertility rate equals the death rate. Each household maximizes its lifetime utility given in equation (1) subject to the asset-accumulation equation given by

$$\dot{a}_t = (r_t + p)\, a_t + w_t l_t - c_t, \tag{2}$$

where a_t is the real value of equity shares in monopolistic intermediate-goods firms owned by each member of the household; r_t and w_t are the rate of real interest and the wage, respectively; p is the insurance premium. The insurance premium is equal to the death of probability, which is ensured by free entry and zero profit in the insurance industry (see Yaari, 1965; Blanchard and Fischer, 1989). Although the shock of death hits each individual/household randomly, there is no aggregate uncertainty. Therefore, there is scope for insurance as highlighted in Blanchard and Fischer (1989, p. 116): "He would be better off if he could sell the claim on his wealth in the event he dies, in exchange for command over resources while he is alive". With free entry and zero profit in the insurance industry, the insurance company pays a fixed premium in the amount of p (the probability of death) per unit of time to each person alive.

Using Hamiltonian, we can derive the optimality condition for consumption

$$\frac{1}{c_t} = \mu_t, \tag{3}$$

where μ_t is the Hamiltonian co-state variable on (2). Using (3), we rewrite the optimal condition for labor supply as

$$l_t = 1 - \frac{\theta c_t}{w_t}. \tag{4}$$

The Euler equation is

$$-\frac{\dot{\mu}_t}{\mu_t} = r_t - \rho. \tag{5}$$

Labor is either used in producing intermediate goods (manufacturing) or R&D. The labor market clearing condition is $L_{x,t} + L_{r,t} = l_t L_t$, where $L_{x,t}$ and $L_{r,t}$ are the total employment in manufacturing and R&D, respectively.

2.2 Production and Innovation

The production function of final-goods firms is

$$y_t = \exp\left(\int_0^1 \ln x_t\,(j)\, dj\right), \tag{6}$$

where $x_t\,(j)$ denotes intermediate goods $j \in [0, 1]$. The perfectly competitive final goods firms maximize their profit, taking the price of each intermediate good j, denoted $p_t(j)$, as given, which yields the demand function for $x_t(j)$:

$$x_t(j) = y_t / p_t(j). \tag{7}$$

There is a unit continuum of industries producing differentiated intermediate goods. Each industry is temporarily dominated by an industry leader until the arrival of the next innovation, and the owner of the new innovation becomes the next industry leader. The leader in industry j has the following production function:

$$x_t(j) = \gamma^{q_t(j)} L_{x,t}(j), \tag{8}$$

where $L_{x,t}(j)$ is the production labor in industry j; $\gamma > 1$ is the step size of innovation; $q_t(j)$ is the number of productivity improvements that have occurred in industry j as of time t. Standard Bertrand price competition leads to a profit-maximizing price $p_t(j)$ determined by a markup γ over the marginal cost $mc_t(j) = w_t/\gamma^{q_t(j)}$. The amount of monopolistic profit is

$$\Pi_t(j) = \left(\frac{\gamma - 1}{\gamma}\right) p_t(j)\, x_t(j) = \left(\frac{\gamma - 1}{\gamma}\right) y_t. \tag{9}$$

The labor income from production is

$$w_t L_{x,t}(j) = \left(\frac{1}{\gamma}\right) p_t(j)\, x_t(j) = \left(\frac{1}{\gamma}\right) y_t. \tag{10}$$

We denote by $v_t(j)$ the value of the monopolistic firm in industry j. In a symmetric equilibrium, $v_t(j) = v_t$. The no-arbitrage condition for v_t is

$$r_t v_t = \Pi_t + \dot{v}_t - \lambda_t v_t, \tag{11}$$

where λ_t is the arrival rate of the next innovation.

The zero-expected-profit condition of R&D firm $k \in [0, 1]$ in each industry is

$$\lambda_t(k)\, v_t = w_t L_{r,t}(k), \tag{12}$$

where $L_{r,t}(k)$ is the amount of labor hired by R&D firm k, and $\lambda_t(k)$ (the firm-level innovation rate per unit time) is $\lambda_t(k) = \frac{\varphi}{L} L_{r,t}(k)$, where φ is a constant. This assumption eliminates the scale effects (see discussions of scale effects in Laincz and Peretto, 2006; Segerstrom, 1998). The aggregate arrival rate of innovation is

$$\lambda_t = \int_0^1 \lambda_t(k)\, dk = \frac{\varphi}{L} L_{r,t} = \varphi l_{r,t}, \tag{13}$$

where $l_{r,t}$ is the share of labor employed in the R&D sector. Similarly, the share of labor in production is $l_{x,t} = L_{x,t}/L$.

2.3 Balanced Growth Path

The dynamics of the model remains similar to that in Chu and Cozzi (2014): the economy immediately jumps to a unique and saddle-point stable balanced growth path on which each variable grows at a constant rate. Plugging equation (8) into (6), we have

$$y_t = \exp\left(\int_0^1 q_t(j)\, dj \ln \gamma\right) L_x = \exp\left(\int_0^t \lambda_v dv \ln \gamma\right) L_x = Z_t L_x, \tag{14}$$

where $Z_t \equiv \exp\left(\int_0^t \lambda_v dv \ln \gamma\right)$ is the level of aggregate technology. The growth rate of Z_t is

$$g_z = \lambda_t \ln \gamma = \varphi l_{r,t} \ln \gamma. \tag{15}$$

On the balanced growth path, (14) yields $g_y = g_z$. The output market clearing condition implies that c_t and y_t must grow at the same rate: $g_c = g_y$. Therefore, the balanced growth rate g_t (the growth rate of per capita consumption or output) is the one given in (15).

Using $\dot{v}_t/v_t = g_t$, we rewrite equation (11) as $\lambda\Pi_t = (\rho + \lambda)\, w_t L_{r,t}$, where we have used (12). Further using equations (9), (10), and (13), we have

$$(\gamma - 1)\, l_{x,t} = l_{r,t} + \rho/\varphi. \tag{16}$$

Combining $c_t = y_t/L$ and (10), we have $c_t = \gamma w_t l_{x,t}$. Now the labor market clearing condition becomes

$$l_{r,t} + l_{x,t} = l_t = 1 - \theta\gamma l_{x,t}. \tag{17}$$

Equations (16)–(17) solve for $\{l_{r,t}, l_{x,t}\}$ as

$$l_x = \frac{1 + \rho/\varphi}{\gamma(1+\theta)}, \tag{18}$$

$$l_r = \frac{(\gamma - 1)(1 + \rho/\varphi)}{\gamma(1+\theta)} - \frac{\rho}{\varphi}. \tag{19}$$

Proposition 1 *The probability of death has no effect on long-run growth. By contrast, an increase in the time discount factor ρ decreases long-run growth. Moreover, an increase in the probability of death decreases welfare.*

Proof. Equations (18) and (19) show that both R&D labor and manufacturing labor are not functions of the probability of death. Therefore, long-run growth does not depend on the probability of death. Moreover, using (19), we have $\partial l_r/\partial\rho < 0$, therefore, R&D labor and thereby long-run growth would decrease in the time discount factor ρ.

We have $c_0 = Z_0 l_{x,0}$, where Z_0 is the aggregate technology at time 0. Imposing balanced growth on (1) yields

$$U = \frac{1}{\rho + p}\left[\ln\left(l_{x,0}\right) + \frac{g}{\rho + p} + \theta \ln(1 - l)\right], \tag{20}$$

where we normalize Z_0 to 1. Both R&D labor and manufacturing labor (and thereby total labor supply l) are not functions of the probability of death. Therefore, (19) shows that welfare is decreasing in p. Q.E.D.

Although Blanchard and Fischer (1989, p. 117) state: "The effect of the exponential probability of the death assumption is simply to increase the individual's rate of time preference", the effect of an increase in the probability of death on long-run growth differs from that of an increase in the time discount factor. The intuition is as follows.

In our Schumpeterian model, two conditions pin down the equilibrium: the labor market clearing condition (17) and the free labor mobility condition (16). An increase in the time discount factor has no effect on labor supply, as seen in (17). An increase in the time discount factor means consumers become less patient, which pushes consumers to substitute saving with current consumption, shifting labor away from R&D to manufacturing, as seen in (16). As a result, long-run growth decreases. By contrast, the increase in the probability of death does not affect the two conditions, ending up having no effect on long-run growth. This result holds because we use the scale-invariant R&D growth model. In semi-endogenous growth models where the size of population matters for growth, Prettner and Trimborn (2012) show that the probability of death (longevity) affects growth.

Concerning welfare, although the initial consumption and its growth rate are independent of the probability of death, the effective discount factor becomes $(\rho + p)$. Therefore, welfare decreases as p increases. This is understandable because the life expectancy is $\frac{1}{p}$. An increase in p reduces life expectancy, decreasing expected discounted utility (i.e., welfare).

Nevertheless, the prediction that the probability of death has no effect on long-run growth does not hold up in a monetary economy, as shown in Section 3.

3 A Monetary Economy

We introduce money via the CIA on consumption, following Clower (1967) and Lucas (1980).

3.1 Consumers

Each household maximizes its lifetime utility given in (1) subject to

$$\dot{a}_t + \dot{m}_t = \left(r_t + p\right) a_t + w_t l_t - c_t - \pi_t m_t + \tau_t, \tag{21}$$

where m_t is the real money balance held by each person, and π_t (the inflation rate) is the cost of holding money. Each individual receives a lump-sum transfer of seigniorage revenue τ_t. The CIA constraint is given by $c_t \leq m_t$.

Using Hamiltonian (see Appendix I for derivation), we can derive the optimality condition for consumption

$$\frac{1}{c_t} = \mu_t \left(1 + i_t + p\right), \tag{22}$$

where μ_t is the Hamiltonian co-state variable on (2), and $i_t = \pi_t + r_t$ (the Fisher equation) is the nominal interest rate. The appearance of the probability of death in (22) causes the difference in predictions. We will explain the intuition later on. The optimal condition for labor supply becomes

$$l_t = 1 - \frac{\theta c_t \left(1 + i_t + p\right)}{w_t}. \tag{23}$$

The Euler equation is still (5).

3.2 Monetary Authority

The monetary authority controls the nominal money supply, denoted M_t, which is equivalent to the case in which the nominal interest rate is chosen as the policy instrument. In equilibrium, the binding CIA constraint delivers $\dot{m}_t/m_t = \dot{c}_t/c_t$. Combining (22) and (5) yields $\dot{c}_t/c_t = r_t - \rho$. We have defined $i_t = \pi_t + r_t$. Therefore, $\dot{M}_t/M_t = i_t - \rho$. The monetary authority rebates the seigniorage revenue back to households. The per capita seigniorage revenue is $\tau_t = \dot{M}_t/\left(P_t L\right)$. The per capita real money balance is $m_t = M_t/\left(P_t L\right)$, where P_t is the price level of the final goods and $\dot{P}_t/P_t = \pi_t$. Therefore, $\dot{m}_t/m_t = \dot{M}_t/M_t - \pi_t$. Therefore, we have $\tau_t = \dot{m}_t + \pi_t m_t$.

3.3 The Effects of the COVID-19 Pandemic

Now the labor market clearing condition becomes

$$l_{r,t} + l_{x,t} = l_t = 1 - \theta\gamma\left(1 + i + p\right) l_{x,t}. \tag{24}$$

Given a fixed nominal interest rate, equations (16) and (24) solve for the unique and stationary pair $\{l_r, l_x\}$ as

$$l_x = \frac{1 + \rho/\varphi}{\gamma\left[1 + \theta\left(1 + i + p\right)\right]}, \tag{25}$$

$$l_r = \frac{\left(\gamma - 1\right)\left(1 + \rho/\varphi\right)}{\gamma\left[1 + \theta\left(1 + i + p\right)\right]} - \frac{\rho}{\varphi}. \tag{26}$$

Proposition 2 *In this monetary economy with a fixed nominal interest rate i, an increase in the probability death reduces long-run growth and welfare under elastic labor supply. By contrast, it has no effect on long-run growth and a negative effect on welfare under inelastic labor supply.*

Proof. Equations (25) and (26) show that both R&D labor and manufacturing labor are decreasing functions of the probability of death p. Therefore, long-run growth decreases in the probability of death p. Using Proposition 1, now the increase in p has an additional negative effect on welfare through decreasing the initial consumption and the balanced growth rate. Therefore, welfare is still decreasing in p. Under inelastic labor supply (i.e., $\theta = 0$), it is obvious that both R&D labor and manufacturing labor are not functions of the probability of death p, neither is the balanced growth rate. However, an increase in the probability of death p still raises the effective discount factor to $(\rho + p)$, decreasing welfare. Q.E.D.

The results in Proposition 2 are in contrast to those in the same model without money. For intuition, we still resort to the two above-mentioned conditions. The increase in the probability of death still does not change the arbitrage between consumption and saving and that between working in R&D and working in manufacturing (i.e., the labor reallocation effect is still absent). Nevertheless, in the monetary economy, it does affect the consumption-leisure choices that affects labor supply, as seen in (24). And it reduces labor supply through the consumption-leisure choice, thereby decreasing both R&D labor and manufacturing labor. This in turn decreases long-run growth and welfare. However, the consumption-leisure choice effect is absent under inelastic labor supply.

3.4 Further Discussions on the Mechanism

There are two crucial reasons for the different predictions in Propositions 1 and 2. The first is the individual uncertainty of death. If there exists a representative household with a fixed size L, then household members can pool together the risk from death. Because there is no aggregate uncertainty, the household simply transfers the wealth (equity plus money) of those who died to the new cohort. However, there is an infinite amount of identical households. The inter-generational transfer within households is impossible because the shock of death hits each individual/household randomly. Therefore, there has to be a market solution or scope for insurance as highlighted in Blanchard and Fischer (1989, p. 116): "He would be better off if he could sell the claim on his wealth in the event he dies, in exchange for command over resources while he is alive". The insurance company pays a fixed premium in the amount of p (the probability of death) per unit of time to each person alive.

The second reason is that there is no such market solution/insurance for real balance. Suppose there exists an insurance company for real balance as well, which is equivalent to the case in which the insurance contract is written on total wealth $(a_t + m_t)$ in stead of on real assets a_t: the asset-accumulation equation becomes

$$\dot{a}_t + \dot{m}_t = r_t a_t + w_t l_t - c_t - \pi_t m_t + p\left(a_t + m_t\right) + \tau_t. \tag{27}$$

In this case, the per capita lump-sum transfer of the seigniorage revenue would become $\tau_t = \dot{m}_t + \pi_t m_t - p m_t$. As discussed, due to the random shock to individuals, the equity and real balance of those who died cannot be transferred within households, and they have to be reallocated across households through other mechanisms. Now two situations would happen. First, there is no insurance market for real balance (further discussed below), and Proposition 2 would hold. Second, if the insurance contract is written on total wealth (i.e., (27) holds), then it would relax the CIA constraint on consumption to $c_t \leq m_t + pm_t$. Relaxing the CIA constraint would end up increasing growth.

In summary, in the monetary economy, the increase in the probability of death would impact negatively or positively (depending on the institutional arrangements) on growth. By contrast, it would have no effect on long-run growth in models without money. We believe the negative effect is more plausible. When the real balance from those who died is collected by the government, the government uses a lump-sum transfer mechanism. Concerning seigniorage, the government treats each individual alive equally. This differs from the proportional pricing mechanism of the insurance market for equity. Additionally, it is much easier to enforce. The government does not need to collect the real balance of those who died, and it simply prints more fiat money in the same amount.

3.5 Quantitative Analysis

Our model has the following set of structural parameters $\{\rho, p, \theta, \varphi, \gamma\}$. We set the discount rate ρ to a conventional value of 0.04. The expected life expectancy is $1/p$. Therefore, we follow Prettner and Trimborn (2012) to set $p = 0.0128$ (life expectancy is 78 years) to be the benchmark. We need three conditions to pin down the values of $\{\theta, \varphi, \gamma\}$. The first condition is the long-run GDP per capita growth of 1.8% in advanced countries. Second, we follow Chu, Cozzi and Liao (2013) to set the equilibrium R&D share of GDP to 0.03 for the US. Third, the standard moment of $l = 0.3$ is used. Now we pin down the values of $\{\theta, \varphi, \gamma\}$ by solving the following three equations:

$$g = \varphi (\ln \gamma) l_r = 0.018, \tag{28}$$

$$w_t L_r / y_t = l_r / (\gamma l_x) = 0.03, \tag{29}$$

$$l_r + l_x = 0.3. \tag{30}$$

We calibrate the annual nominal interest as $i = 0.099$ for the US (which is calculated as $i = \pi + \rho + g = \pi + 0.04 + 0.02$, and the sample mean of annual inflation in the US is 3.92% during 1960-2014 in the Penn World Table 9.0). Now solving equations (28)-(30) yields the values of $\{\theta, \varphi, \gamma\}$ to be $\{2.09, 61.01, 1.033\}$.

Barro et al. (2020) show that flu-related deaths in 1918-1920 were 2.1 percent of world population. The WHO (World Health Organization) data shows that the COVID-19 pandemic caused a death rate of 4.3% of infected population for the World (585,727 deaths and 13,616,593 confirmed cases as of July 18, 2020) and 5.4% for China (4,651 deaths and

85,775 confirmed cases as of July 18, 2020).[1] As discussed in the introduction, Manski and Molinari (2020) find that the upper bounds of cumulative infection rates as of April 24, 2020, for Illinois, New York, and Italy are, respectively, 0.525, 0.618, and 0.471. Therefore, we consider an increase in the probability of death by 0.021 as the worst-case scenario. Barro et al. state: "Other influenza outbreaks with global reach had much lower mortality rates as a share of the global population, including by first place of registry: Siberia (1889-90) at 0.08%, East Asia (1957-58) at 0.07%, and Hong Kong (1968-69) at 0.03%." Therefore, we consider a range of values for the probability of death $p \in \{0.0136, 0.0208, 0.0338\}$, corresponding to an increase in mortality of 0.08%, 0.8% and 2.1%, respectively. The calibration results are presented in Table 1.

First, the effects of the probability of death p on welfare are larger compared to those on growth. For instance, when the nominal interest rate is fixed at 9.9% annually, Columns 1.1, 1.3, 1.5 and 1.7 illustrate that, as p increases from 0.0128 to 0.0136, 0.0208 and 0.0338, the annual growth rate would decrease from 1.80% (the benchmark) to 1.80%, 1.79% and 1.77%, respectively. The growth effects are not very large. However, because of the change in units, the welfare for different p is not comparable. Nevertheless, as the growth rates and initial consumption levels do not decrease much as p increase, we can simply use the life expectancy for comparison. As p increases from 0.0128 to 0.0136, 0.0208 and 0.0338, the decrease in initial consumption is 0.05%, 0.34%, and 1.37%, respectively, and the life expectancy decreases from 78 years to 73.5, 48 and 29.6 years, respectively. Therefore, the welfare loss mainly comes from the substantial decrease in life expectancy when the probability of death increases tenfold, despite that the decrease in initial consumption also increases tenfold. In sum, the welfare losses are substantial if the pandemic does not disappear. Therefore, despite of the small growth loss and moderate consumption decrease, the shortened life expectancy indicates that we need to fight the pandemic.

Second, for a given p, there are significant growth and welfare gains when reducing the nominal interest rate from 9.9% to zero. Columns 1.1 and 1.2 (our benchmark) indicate that reducing the nominal interest rate from 9.9% to zero, the annual growth rate would increase from 1.8% to 1.93%, and the welfare gain ΔU is equivalent to a permanent increase in consumption of 2.84%. The growth and welfare gains from the same amount of monetary contraction remain very similar for p of very different magnitudes.

[1] For details, please see https://covid19.who.int/.

Table 1: Calibration results

	Column number							
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
	$\{\rho, \theta, \gamma, \varphi\} = \{0.04, 2.09, 1.033, 61.01\}$							
$p =$	0.0128		0.0136		0.0208		0.0338	
	benchmark							
i	9.9%	0%	9.9%	0%	9.9%	0%	9.9%	0%
l_x	0.291	0.310	0.291	0.310	0.290	0.309	0.287	0.306
l_r	0.0090	0.0097	0.0090	0.0097	0.0090	0.0096	0.0089	0.0095
g	1.80%	1.93%	1.80%	1.93%	1.79%	1.92%	1.77%	1.90%
Δc			-0.05%		-0.34%		-1.37%	
$\frac{1}{p}$	78.1		73.5		48.1		29.6	
ΔU	n/a	2.84%	n/a	2.80%	n/a	2.53%	n/a	3.67%

Note: i is the nominal interest rate; l_x and l_r are manufacturing labor and R&D labor, respectively; g is the growth rate of per capita output; Δc is the percentage change in initial consumption. $1/p$ is the life expectancy. ΔU is the welfare gain (equivalent to a permanent increase in consumption).

4 Conclusion

The COVID-19 pandemic has greatly changed our life and the way we organize economic activities (e.g., online meetings and teaching become popular). Additionally, it has caused more than a half million deaths (and the number is still increasing, see https://covid19.who.int/ for updated data). In this paper, we take a first step to evaluate the potential economic outcome of the pandemic.

Specifically, we investigate how the presence of the COVID-19 pandemic—the increase in the probability of death, following Blanchard and Fischer (1989)—may affect growth and welfare in a scale-invariant R&D-based Schumpeterian model. Our results are as follows. Without money, the increase in the probability of death has no effect on long-run growth and a negative effect on welfare. By contrast, when money is introduced via the CIA constraint on consumption, the increase in the probability of death decreases long-run growth and welfare under elastic labor supply. Calibration shows that the quantitative effect of an increase in the probability of death on welfare is much larger compared to that on growth.

We study the case where the pandemic will not disappear. If the pandemic disappears, the model becomes the standard Schumpeterian model and there are no long-run growth effects of the pandemic. Our model may be too simple to capture the necessary elements of the COVID-19 pandemic. We follow Blanchard and Fischer (1989) to assume the probability of death is independent of age for tractability, but the old cohorts are hit the hardest. Additionally, we do not consider health expenditures and time spent fighting the pandemic. Obviously, the time spent fighting the pandemic would decrease total labor supplied to R&D and production, decreasing long-run growth and welfare. Moreover, the short-run effects of lockdown should also deserve attention. We leave these to future research.

APPENDIX I: HOUSEHOLD'S DYNAMIC OPTIMIZATION

Household's Hamiltonian function is

$$H_t = \ln c_t + \theta \ln (1 - l_t) + \mu_t \left[(r_t + p) a_t + w_t l_t - c_t - \pi_t m_t + \tau_t \right] + v_t (m_t - c_t),$$

where μ_t is the co-state variable on (2); v_t is the Lagrangian multiplier for the CIA constraint. The first-order conditions include

$$\frac{\partial H_t}{\partial c_t} = \frac{1}{c_t} - \mu_t - v_t = 0, \tag{31}$$

$$\frac{\partial H_t}{\partial l_t} = -\frac{\theta}{1 - l_t} + \mu_t w_t = 0, \tag{32}$$

$$\frac{\partial H_t}{\partial a_t} = \mu_t (r_t + p) = (\rho + p) \mu_t - \dot{\mu}_t, \tag{33}$$

$$\frac{\partial H_t}{\partial m_t} = -\mu_t \pi_t + v_t = (\rho + p) \mu_t - \dot{\mu}_t, \tag{34}$$

Combining (33) and (34) yields $v_t = \mu_t (r_t + \pi_t + p) = \mu_t (i_t + p)$, where we define $i_t = r_t + \pi_t$. Plugging this condition into (31) yields

$$\frac{1}{c_t} = \mu_t (1 + i_t + p), \tag{35}$$

which is (22) in the main text. Rewriting (32) yields the optimal condition for labor supply

$$\frac{\theta}{1 - l_t} = w_t \mu_t, \tag{36}$$

which combines with (35) yields (23) in the main text. Rewriting (33) as

$$-\frac{\dot{\mu}_t}{\mu_t} = r_t - \rho \tag{37}$$

yields the intertemporal optimality condition.

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