BETA
Bureau d'économie théorique et appliquée

Documents de travail

« Macroepidemics and unconventional monetary policy: Coupling macroeconomics and epidemiology in a financial DSGE-SIR framework»

Auteurs

Verónica Acurio Vásconez, Olivier Damette, David W. Shanafelt

Document de Travail n° 2021 – 04

Février 2021

Bureau d'Économie Théorique et Appliquée
BETA

www.beta-umr7522.fr

@beta_economics

Contact :
jaoulgrammare@beta-cnrs.unistra.fr

Université de Strasbourg · CNRS · Université de Lorraine · INRAE · AgroParisTech

Macroepidemics and unconventional monetary policy: Coupling macroeconomics and epidemiology in a financial DSGE-SIR framework

Verónica ACURIO VÁSCONEZ*
Olivier DAMETTE†
David W. SHANAFELT‡

February 8, 2021§

Abstract

Despite the fact that the current COVID-19 pandemic was neither the first nor the last disease to threaten a pandemic, only recently have studies incorporated epidemiology into macroeconomic theory. In our paper, we use a dynamic stochastic general equilibrium (DSGE) model with a financial sector to study the economic impacts of epidemics and the potential for unconventional monetary policy to remedy those effects. By coupling a macroeconomic model to a traditional epidemiological model, we are able to evaluate the pathways by which an epidemic affects a national economy. We find that no unconventional monetary policy can completely remove the negative effects of an epidemic crisis, save perhaps an exogenous increase in the shares of claims coming from the Central Bank ("*epi loans*"). To the best of our knowledge, our paper is the first to incorporate disease dynamics into a DSGE-SIR model with a financial sector and examine the effects of unconventional monetary policy.

JEL codes: D58, E32, E52

Keywords: New-Keynesian model, DSGE, COVID-19, epidemiology

Running header: Macroepidemics and unconventional monetary policy

*Email: veronica.acurio-vasconez@univ-lorraine.fr,Université de Lorraine, Université de Strasbourg, Centre National de la Recherche Scientifique (CNRS), Bureau d'Economie Théorique et Appliquée (BETA), 13 Place Carnot, CO No.026, 54035 Nancy Cedex, France.

†Email: olivier.damette@univ-lorraine.fr,Université de Lorraine, Université de Strasbourg, CNRS, BETA, 13 Place Carnot, CO No.026, 54035 Nancy Cedex, France.

‡Email: david.shanafelt@inrae.fr,Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 14 Rue Girardet - CS 14216, 54042 Nancy Cedex, France.

§All remaining errors are ours.

1 Introduction

The economic effects of the COVID-19 pandemic are unprecedented, far-reaching, and extend to virtually every member of the global market. Global growth was projected at minus 4.9 percent in 2020, and at 6 percent to 7.6 percent depending on the emergence of a second wave (IMF (2020)). COVID-19 was not the first emerging zoonotic or epizoonic disease to threaten a pandemic (Boissay and Rungcharoenkitkul (2020), LePan (2020)), nor will it be the last (Daszak et al. (2001), Jones et al. (2008), Wu et al. (2017)).

Prior to the COVID-19 pandemic, few studies incorporated epidemiology into macroeconomic theory, though this was not the case in microeconomics (see Horan and Wolf (2005), Horan and Fenichel (2007), Fenichel et al. (2011), Lenhart and Workman (2007), Morin et al. (2014), and Morin et al. (2015) for examples). Recent studies have examined the potential economic impacts of pandemics on a macroeconomic scale using Susceptible-Infected-Recovered (SIR) epidemiological models in the line with the macro model developed by Eichenbaum et al. (2020b). However, the role of financial intermediaries in coupled epidemic-economic frameworks has yet to be studied. In addition, previous papers have not focused on the effect of economic remedies - in the form of monetary policies - to reduce the economic burden of epidemics.

In this paper, we use a dynamic stochastic general equilibrium (DSGE) model as in Smets and Wouters (2007), but with a financial sector as in Gertler and Karadi (2011) (GK hereafter), to study the economic effects of an epidemic and the ability of monetary policy to remedy the crisis. Thus, our model is a financial DSGE-SIR model. To the best of our knowledge, we are the first to incorporate SIR dynamics into a DSGE model with a financial sector. Using the GK framework enables us to account for the financial sector of the economy and to assess the efficiency of unconventional monetary policy to combat the economic burdens of an epidemic. It enables us to investigate different recovery paths of the economy following shocks to the system, including an epidemic crisis. For instance, the GK model was used to extensively examine the effects of unconventional monetary policy on macroeconomic outputs following the subprime crisis (Gertler and Karadi (2011), Dedola et al. (2013), Gelain and Ilbas (2017)). Gertler and Karadi (2011) showed that when there is a financial crisis (understood as a negative shock in the quality of capital), the stronger the reaction by the Central Bank, and the smaller the total losses in GDP. In comparison to a simpler model without financial frictions *à la Smet-Wouters*, our financial DSGE-SIR model enables us to study macro-financial feedback loops.

We evaluate the effects of unconventional monetary policy, in particular a form of quantitative easing (QE) or "*epi loans*" policy. We model "*epi loans*" as a Central Bank liquidity injection into the real sector in the form of claims that do not pass-through private banks, similar to those that followed the sub-prime crisis in Europe. This measure can be understood as a light form of "helicopter money" (Friedman (1969)), in the sense that the injected liquidity goes directly to the real sector without direct involvement of fiscal authorities or private banks. However, contrary to"helicopter money", our "*epi loans*" policy must be repaid, thus changing the Central Bank balance sheet by increasing its assets. Further, while "helicopter money" may be highly inflationist, there is no proof that QE policies are, at least not in developed countries (Qianying et al. (2016), Albertazzi et al. (2018), Baumeister and Benati (2013)). In this regard, the Central Bank behaves as last resort lender for the economy.

Our model incorporates six different agents: households, financial intermediates, non-financial goods producers, capital producers, retailers and a government. It also considers the existence of a Central Bank that conducts conventional and unconventional monetary policy. From a methodological point of view, this study goes further than Smets and Wouters (2007) and Gertler and Karadi (2011) by coupling the labor sector to an epidemiological SIR model rather than assuming that each household chooses the quantity of hours it wants to work in each period. We suppose that labor supply is given by the quantity of people in good health, and is exogenously driven by the SIR model. In addition, we suppose that the government may dispense unemployment benefits to those who can no longer work due to illness.

In general, we find significant GDP losses due to an epidemic shock, with the effect on the labor market echoing throughout the economy. We observe declines in household consumption, non-financial intermediary capital, and capital producer investment following the trajectories of labor and production, and financial intermediaries experiencing declines in the quantity and composition of expected discounted terminal wealth. The Central Bank increases its share of total credits that it finances to compensate for losses in investment and production. What is particularly interesting is that it is feasible to have a severe epidemic that does not result in a large economic loss, provided that the recovery rate is sufficiently high to allow workers to quickly return to the labor force. The nature of the epidemic thus has a strong impact on the macroeconomic response.

In terms of monetary policy, we find that no unconventional monetary policy can completely remove the negative economic effects of the crisis, besides perhaps an exogenous increase in the share of claims coming from the Central Bank. Our "*epi loans*" policy is a form of QE policy related to Friedman (1969) "helicopter money", in that the Central Bank takes savings from households and issues it as claims to be used to buy physical capital rather than re-financing private banks. The injected liquidity goes directly to the real sector.

Our framework is not directly targeted towards COVID-19, but instead models a representative epidemic. That being said, it can be tailored to any combination of epidemiological models or economic parameters, making it possible to calibrate the model to a specific disease or country. While we believe that our model is relevant to the current pandemic, we hope that its contribution extends to epidemics more generally.

The paper is structured as follows. Section 2 presents related literature. The model is presented in Section 3, whereas Section 4 describes the elements of the calibration and model simulation. Section 5 analyzes the response of the economy to the epidemic shock and investigates the effect of monetary policy. Finally, Section 6 concludes.

2 Related Literature

Since the beginning of the COVID-19 pandemic, there has been an explosion of literature investigating the macroeconomics of pandemics. In this section, we briefly survey the literature, presenting the main methodological choices and key results, and explain in more detail how we depart from those studies. We categorize the literature into two thematics: the economic impacts of a pandemic and the effects of policy response.

2.1 Economic impacts of a pandemic

A first line of literature outlines the channels through which the pandemic shock affects the economy. Carlsson-Szlezak et al. (2020a), Carlsson-Szlezak et al. (2020b), and Brodeur et al. (2020), identified three broad patterns that have emerged from the current pandemic. The first is a direct impact generated by a reduced consumption of goods and services (a demand shock), which is exacerbated by social distancing and pessimistic expectations in the short-run. The second is an indirect impact based on financial market shocks and their effects on the real side of the economy. Household wealth will likely fall (wealth effects) as precautionary savings increase (due to uncertainty), leading to declines in new consumption spending. The third set of effects consist of supply-side disruptions. Declines in production due to containment and mitigation policies negatively impact supply chains, labor demand, and global employment and, as a consequence, unemployment and GDP losses strongly increase. In addition, a negative supply shock can trigger a demand shortage that leads to a contraction in output and employment larger than the supply shock itself (Guerrieri et al. (2020)). The existence of "wait-and-see" attitudes adopted by economic agents (described by Baldwin and DiMauro (2020)) are likely to reinforce the previous effects by generating additional uncertainty. All in all, different types of recovery geometry - "V-shaped", "U-shaped", "WU-shaped", or "L-shaped"- are possible depending on the persistence of shocks and government interventions.

The basis for these findings are predominantly theoretical in nature, and can be seen as hypotheses to be tested and re-evaluated. Therefore, economists have empirically assessed the economic impacts of the pandemic, as well as delved deeper into their theoretical foundations. We divide them into three sub-groups based on their methodology.

Our first sub-group quantitatively assesses the potential response of the economy to a pandemic crisis, mostly from a macroeconometric perspective. Ludvigson et al. (2020) assessed the macroeconomic impact of COVID-19 in the United States from historical data using a vector auto-regression VAR model. They quantified the potential response of the economy by comparing the current pandemic shock to a series of large disaster shocks in US time series data. Using the costly disaster index, they found that a 60 standard deviations shock from the mean can generate a 12.75 percent drop in industrial production. Chudik et al. (2020) developed a threshold-augmented dynamic multi-country model (TGVAR) to estimate the global as well as country-specific macroeconomic effects of the identified COVID-19 shock. They showed that the most-developed economies will likely experience deeper, longer-lasting effects. For example, they found evidence of long-term, carry-over effects for countries like the United States and the United Kingdom, but not for developing Asian countries. Milani (2021) used a standard GVAR to investigate the importance of interconnections between countries. He found that the unemployment responses varied widely across countries after a health shock. Bonadio et al. (2020) developed a quantitative framework to simulate a negative global labor shock and examine the role of global supply chains in explaining the intensity of the real GDP downturn due to the COVID-19 shock. They found that "re-nationalization" of global supply chains would not make countries more resilient to pandemic-induced contractions in labor supply. Baqaee and Farhi (2020) stressed the role of non-linearities associated with complementarities in consumption and production in response to the COVID-19 shock using a multi-sector, neoclassical model.

Another set of studies relies on static or dynamic computable general equilibrium models, focusing on international spillovers and sectoral effects. A family of Computable General Equilibrium (CGE) were developed to study the macroeconomic impacts of pandemics on a global scale and trade. In particular, the popular CGE G-Cubed (Mckibbin and Fernando (2020)) and ENVISAGE (Maliszewska et al. (2020)) models have been extended to account for COVID-19. Both extensions focused on the importance of spillover effects in a globalized economy when assessing the GDP and macroeconomic losses. Mihailov (2020) implemented potential economics responses within a standard Galí-Smets-Wouters DSGE model (Galí et al. (2011)) calibrated to US, France, Germany, Italy and Spain. In all cases, the negative effects are quite damaging and last between one and two years on average. However, these papers treat epidemics as completely exogenous shocks without the integration of epidemic dynamics. Our work extends this literature by explicitly incorporating an epidemiological model into a macroeconomic framework, taking into account the dynamics of the economic patterns, incorporating a financial sector, and exploring the role of financial intermediaries and the use of unconventional monetary policies. The introduction of financial market disruptions, as in GK, allow us to analyze the effects of unconventional monetary policies.

Our work is more akin to the works of Bodenstein et al. (2020), Eichenbaum et al. (2020a,b,c), Angelini et al. (2020) or Krueger et al. (2020). These studies develop more-or-less simple macroeconomic neoclassical models, in which agents consume goods and work, combined with disease models that are standard in the epidemiology literature. However, they treat the labor market in a markedly different way than us. To be more specific, in those models agents choose the number of hours to work, with household consumption and labor changing the number of susceptible and infected individuals. The more a person consumes or works, the more s/he is in contact with others and the probability of infection is higher. Supply hours decrease not because people of getting sick, but because infected individuals are less productive (lower revenue) (Eichenbaum et al. (2020b)) and individuals know that if they work, they have a higher risk of infection. We do not follow this assumption, choosing to assume that sick individuals cannot or are not allowed to work. We believe that this assumption is reasonable, does not impact our results, and avoids introducing addition assumptions (such as homogenous mixing) into the model. Further, to the best of our knowledge, our paper is the first to directly consider the financial sector in this framework.

From a methodological point of view, our model is closest to Bodenstein et al. (2020), whom enlarge a ECB-BASE model with the dynamics of a SIR model with two distinct population groups. They embed a canonical epidemiology model (SIR) in a Real Business Cycle (RBC) type model. In contrast, we mix a financial DSGE *à la* GK and a SIR model and as a consequence, our model enables us to study the interplay between the real economy and the financial sector.

2.2 Economic Policies

A key challenge for policy makers is to identify suitable policies to mitigate the adverse economic effects of epidemics. Kaplan et al. (2020) demonstrated that the role of the government is not just to balance lives and livelihood (health versus economic output), but also over who should bear the burden of the economic crisis. This should be taken into account when investigating the optimality of lockdown and fiscal policies. Krueger et al. (2020) extended the Eichenbaum et al. (2020a,b,c) studies to analyze the "Swedish case". They found that a no government intervention with flexible resource allocation can lead to a substantial mitigation of economic and human costs of the COVID-19 crisis. Other papers have stressed the need for government intervention, particularly economic policies. Elenev et al. (2020) focused on the interrelationships between corporate and financial sectors and real macro-economy output. They found evidence that a no-intervention policy generates a negative feedback loop between corporate default and weakness in the financial intermediary sector and creates a macroeconomic disaster. They studied the role of corporate credit policies to mitigate this situation, and suggested the implementation of conventional or unconventional monetary policies, which we explicitly consider here. Faria-e Castro (2020) analyzed different types of discretionary fiscal policies to smooth household incomes in a simple DSGE model. Conditional and unconditional transfers to households were effective mitigation policies, with expansion of unemployment insurance as the best targeted measure.

In a theoretical model with multiple equilibria, Céspedes et al. (2020) demonstrated that traditional expansionary fiscal policy had no beneficial effects, while conventional monetary policy had a limited effect when the discount rate was low. Unconventional policies, including helicopter drops of liquid assets, equity injections and loan guarantees, were able to keep the economy at a higher equilibrium in terms of productivity and unemployment. In a similar fashion, Sharma et al. (2020) developed a so-called "Mark-0 Agent-Based Model" based on the model by Gualdi et al. (2015). They simulated several policies including giving easy credit to firms and "helicopter money", i.e. injecting new money into households savings. Here, we analyze similar policy questions but, in contrast to Sharma et al. (2020), we build a DSGE-SIR framework with microeconomic foundations. Kiley (2020) added exogenous shocks to a GK framework to mimic the COVID-19 recession. He found that the use of extraordinary policy actions, such as a QE program of government bonds, may support recovery. We also depart from the GK model, but contrary to Kiley (2020) we explicitly incorporate epidemic dynamics. Our main value added is that our model enables us to take into account interactions between an epidemic and the economy, as well as the financial and real economic sectors, and to study the potential for monetary policy (specifically unconventional monetary policy) to mitigate the effects of an epidemic.

3 The Model

In this paper, we construct a so-called financial DSGE model like the one developed in Gertler and Karadi (2011). However, in contrast to the usual financial DSGE models, we enlarge our model with a SIR block (see Atkeson (2020)).

Our DSGE model is a neo-keynesian micro-founded aggregate representation of a national economy, in which we assume that there is an infinite number of economic agents divided into households, financial intermediates, non-financial goods producers, capital producers, and retailers, which individually chooses quantities of goods, production factors, bonds and eventually prices in order to maximize their own well-being (e.g. preferences for households and profits for bankers, capital producers, non-financial firms, and retailers). The model also includes a government and a Central Bank that conducts conventional and unconventional monetary policy.

We couple the DSGE model to a classic epidemiological model of an epidemic

(F.Brauer and Castillo-Chavez (1994, 2012), Hethcote (2000)) and suppose that labor supply is directly tied to the proportion of healthy individuals. For the sake of simplicity, we do not impose stochastic shocks to the economy, and take the trajectory of labor supply, which is affected by the disease, as a deterministic, exogenous shock to the economy. In this way we isolate the effects of the epidemic on the model economy.

In this section, we first describe the epidemiological model and how it relates to households and labor supply. We then describe how households behave, the structure of financial, non-financial and capital producers, and retailers. Finally, we explain how the government intervenes in the economy and monetary policies conducted by the Central Bank. Variables, definitions, and parameters are summarized in Figures 1 and 2 and Tables 1 to 3. For details on the full derivation of the model, see the Appendix.

3.1 Epidemiological Model

In order to model the spread of an epidemic, we use a Susceptible-Infected-Recovered (SIR) model as in F.Brauer and Castillo-Chavez (1994, 2012), Hethcote (2000), and Lenhart and Workman (2007). The SIR model is a type of compartmental epidemiological model in which the total population, N_t, is divided into three classes or types of individuals: susceptible individuals, S_t, who can incur the disease but are not yet infected; infected individuals, $\widetilde{I}_t$, who have the disease and can spread it to susceptible individuals; and recovered individuals, $\widetilde{R}_t$, who have contracted the disease but have recovered and are immune to future infections (Figure 2). For simplicity, we assume a constant population size, abstracting from natural births and deaths[1], and

[1]The validity of this assumption depends on the timescale of the analysis and the nature of the disease in question. Take for example, a single, localized epidemic and a population such that the disease could reasonably circulate throughout the entire population. For diseases like the cold, flu, or measles, an epidemic may last weeks or months and accounting for births and deaths would not be appropriate; for diseases lasting years or a lifetime (AIDS/HIV, hepatitis C, or tuberculosis), including births and deaths is more reasonable (Hethcote (2000)).

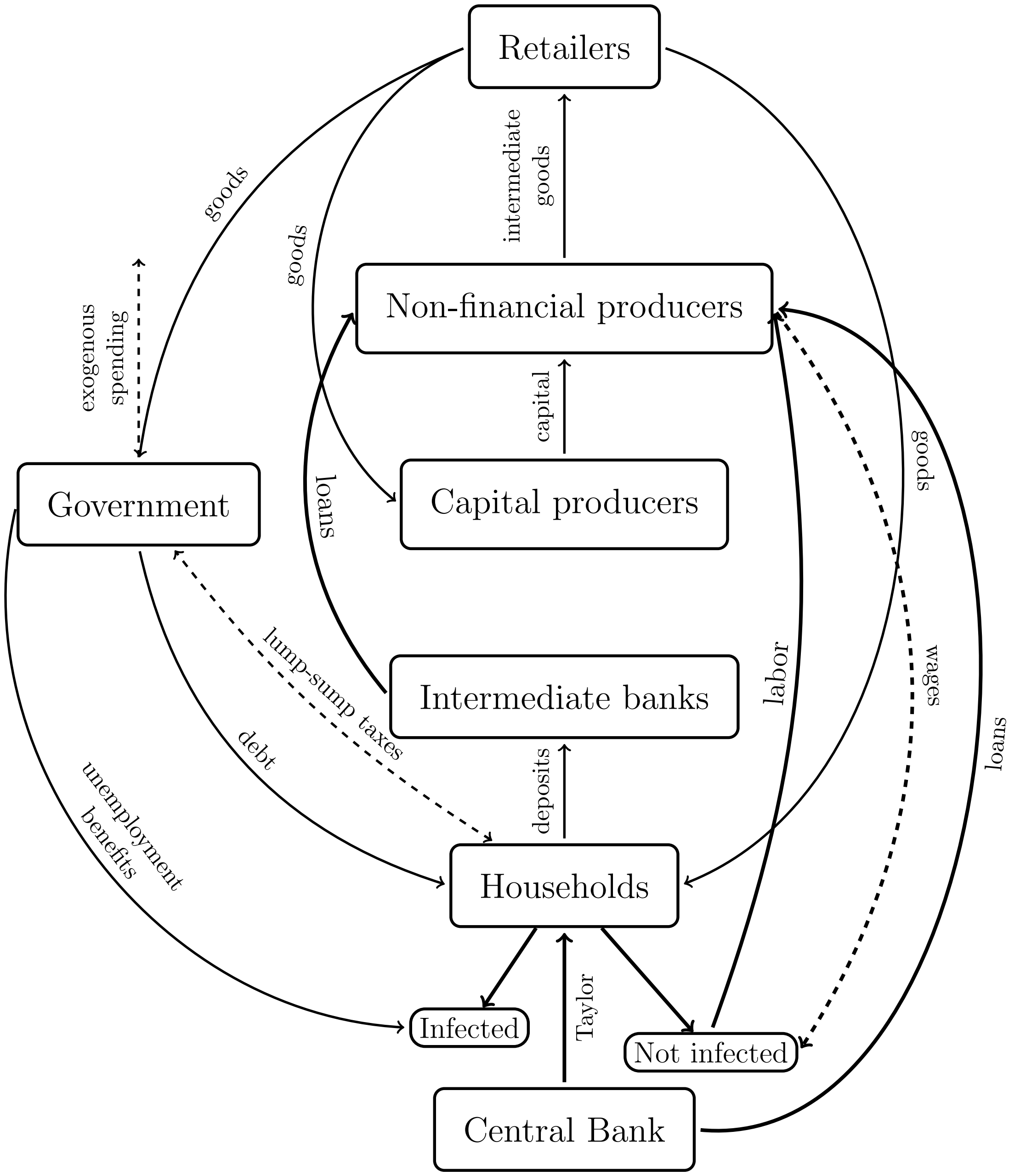

Figure 1: Economic Model Schema

normalize N_t to 1. Then S_t, $\widetilde{I}_t$ and $\widetilde{R}_t$ can be interpreted as shares or proportions of individuals of each class in the general population.

We can write the dynamics of the epidemic over time as:

$$S_{t+1} - S_t = -\,\alpha_v S_t \widetilde{I}_t \tag{1}$$

$$\widetilde{I}_{t+1} - \widetilde{I}_t = \alpha_v S_t \widetilde{I}_t - \gamma_v I_t \tag{2}$$

$$\widetilde{R}_{t+1} - \widetilde{R}_t = \gamma_v \widetilde{I}_t \tag{3}$$

where $1 = S_t + \widetilde{I}_t + \widetilde{R}_t$. The difference equations in (1)-(3) are equivalent to a system of ordinary differential equations solved via a Euler approximation. Susceptible and infected individuals make contact and transmit the disease with a constant probability α_v, and infected individuals recover at a rate γ_v. We assume that after recovery, individuals are immune from future infection.

Figure 2: SIR Schema

The model assumes a closed population (no immigration or emigration) with a constant population size (no births or deaths) and a well-mixed population. That is, each individual in the population has an equal probability of interacting with every other individual. Extensions of the basic SIR model relax these assumptions to take into account multiple populations of individuals (Bichara et al. (2015)), endemic disease (Hethcote (2000)), heterogeneous mixing (Morin et al. (2014), Morin et al. (2015), Toxvaerd (2020)), age structure (Hethcote (2000)), other classes of individuals such as exposed or asymptomatic, vaccinated or hospitalized (Chowell et al. (2003), Hethcote (2000), Lenhart and Workman (2007)), and management strategies such as treatment and vaccination (Hethcote (2000), Lenhart and Workman (2007), Toxvaerd and Rowthorn (2020)). However, relaxing our basic assumptions greatly complicates the analysis and is left for future work.

The epidemic affects the economy via the labor supply. Following Bodenstein et al. (2020), we assume that in absence of disease, labor supply L_t is equal to the total working force, $L_t = N_t$. However, as the epidemic spreads in the general population, we assume that infected individuals stay home and do not work, then the labor force is reduce by the quantity of infected people I_t. Thus, in each period, labor supply is given as $L_t = N_t$ - $\widetilde{I}_t$.

3.2 Households

We assume a continuum of perfectly competitive households in the economy indexed by $j \in [0, 1]$. Susceptible, infected, and recovered individuals are assumed to be evenly distributed among households. Each household consumes domestic goods, and, if healthy, supplies identical labor services to the non-financial production sector. Households pay/receive lump sum taxes, collect profits from all firms, have the option to lend funds to competitive financial intermediates or buy government bonds and, when infected, receive unemployment benefits.

At each time period t, a typical household j chooses consumption C_t to maximize the following lifetime expected utility function:

$$\mathbb{E}_t \left[\sum_{k=0}^{\infty} \beta^k U \left(C_{t+k}(j) \right) \right] \tag{4}$$

where $U(C_t(j))$ is the net utility of household consumption of non-financial goods and $\beta \in (0, 1)$ is the discount factor.

We allow for internal habit formation in consumption as in Christiano et al.

(2005). Thus, the instantaneous utility at time t is given by:

$$U(C_t(j)) = (log(C_t(j) - hC_{t-1}(j))) \tag{5}$$

where $h \in [0, 1)$ represents the internal habit formation parameter. The latter governs how household preferences for past consumption affects utility over time. A high value of h means that past consumption is important, so as to maintain the current level of utility, the household must consume at least the same quantity as the last time period. A low value of h implies that households only care about present consumption. Note that we do not introduce a trade-off between consumption and labor since labor supply is determined by the epidemic. With this formulation, we implicitly assume that all those who can work are willing to do it.

Within each household there may be a portion of infected people, whom do not work but receive unemployment compensation b_t. The remaining individuals - susceptible and/or recovered - may be divided in two groups: workers and bankers. Workers do so for non-financial intermediate firms and receive a real salary W_t in exchange for the total amount of labor provided L_t. Bankers manage financial intermediaries and gain earnings. We assume that each member of the household gives their respective revenues to the household and that there is perfect consumption insurance. That is, consumption is equally distributed within households regardless if everyone in them is able to work.

Each household consumes final goods produced by retailers at price P_t and invests/deposits an amount B_t in government bonds and intermediary deposits. We assume that investing in government bonds and depositing into intermediate banks are equivalent and perfectly substitutable, as both are risk-less and pay the same rate. Each are one-period real bonds, which pay a gross real rate of return R_t such that $R_{t+1} := \frac{1+i_t}{\Pi_{t+1}}$, where i_t is the nominal interest rate fixed by the Central Bank and $\Pi_{t+1} := \frac{P_{t+1}}{P_t}$ represents price inflation.

Share holders of retailers, capital firms, financial and non-financial firms receive real profits. We assume that each household owns an equal share of all firms and receives an aliquot share $D_t(j)$ of aggregate profits D_t, i.e. the sum of dividends of all retailers $D_{r,t}$, intermediate private banks $D_{b,t}$, intermediate non-financial firms $D_{m,t}$, and capital producers $D_{k,t}$. Thus $\int_0^1 D_t(j) = D_t := \int_0^1 (D_{r,t}(i) + D_{b,t}(i) + D_{m,t}(i) + D_{k,t}(i))di$ where i indexes an individual firm in each sector. Households pay/receive T_t lump-sum transfers.

For the sake of tractability, all households are identical and choose consumption and investment in the same manner. Then dropping the j subscript, we may write the real budget constraint for each household as:

$$C_t + B_{t+1} \leq b_t (1 - L_t) + W_t L_t + R_t B_t + T_t + D_t \tag{6}$$

Each household solves (4) under the budget constraint (6). The solution of this maximization problem gives us the following Euler equation that describes the evolution of consumption along an optimal path[2]:

$$1 = \beta \mathbb{E}_t \left[\frac{\lambda_{c,t+1}}{\lambda_{c,t}} R_{t+1} \right] \tag{7}$$

where $\lambda_{c,t}$ represents the marginal lifetime discounted utility function at t. Equation (7) says that, at the optimum, each consumer is indifferent to consuming one more unit today and saving that unit (by buying bonds) to consume in the future.

Assuming internal habit formation yields:

$$\lambda_{c,t} = \frac{1}{C_t - hC_{t-1}} - \beta h \mathbb{E}_t \left[\frac{1}{C_{t+1} - hC_t} \right] \tag{8}$$

Thus we define the stochastic real discount factor for the entire economy from

[2]Cf. Appendix for derivation.

period t to $t+i$ as:

$$\Lambda_{t,t+i} := \beta^i \frac{\lambda_{c,t+i}}{\lambda_{c,t}} \tag{9}$$

3.3 Financial Intermediates

For the time being we present the financial intermediate's problem assuming that the Central Bank does not apply unconventional monetary policy, i.e. it does not directly lend to non financial firms. We will relax this hypothesis in the next section.

We assume an infinite continuum of financial intermediates indexed by j. Each intermediate recovers a quantity $B_{t+1}(j)$ of deposits from households, which pays a gross interest rate R_{t+1}, and issues a quantity $Z_t(j)$ of financial claims to non-financial producers at a real price of Q_t per claim[3]. Denote $\Omega_t(j)$ as the net worth of banker j in period t such that:

$$\Omega_t(j) = Q_t Z_t(j) - B_{t+1}(j) \tag{10}$$

Given that assets acquired by bankers earn a rate of return $R_{k,t+1}$ on claims, then bankers' wealth at period $t+1$ is:

$$\Omega_{t+1}(j) = R_{k,t+1} Q_t Z_t(j) - R_{t+1} B_{t+1}(j) \tag{11}$$

And using equation (10) yields:

$$\Omega_{t+1}(j) = (R_{k,t+1} - R_{t+1}) Q_t Z_t(j) + R_{t+1} \Omega_t(j) \tag{12}$$

Note the difference in subscripts between the banker rate of return ($R_{k,t+1}$) and the

[3] In reality, the Central Bank also sells claims. Therefore, we should differentiate private claims $Z_{p,t}$ from government claims $Z_{g,t}$. However, for the sake of presentation, we abstract from this distinction in this section.

gross interest rate (R_{t+1}).

We assume that bankers cannot default on their loans. Then a banker j operates if and only if the following condition holds:

$$\mathbb{E}_t \Lambda_{t,t+1+i} \left(R_{k,t+1+i} - R_{t+1+i} \right) \geq 0, \quad i \geq 0 \tag{13}$$

where $\Lambda_{t,t+1+i}$ is defined as in (9). In other words, if a banker must borrow more than its income, then it will not remain a banker.

In each period t, a fraction f of household members are bankers; the remaining proportion are workers. We assume that a fraction θ of bankers in the current period remain bankers in the next time period. That is, $(1-\theta)f$ bankers become workers and a similar number of workers become bankers[4].

Accordingly, each banker has the following expected discounted terminal wealth:

$$\begin{aligned} V_t(j) &= \sum_{i=0}^{\infty} (1-\theta)\theta^i \Lambda_{t,t+1+i} \Omega_{t+1+i}(j) \\ &= \sum_{i=0}^{\infty} (1-\theta)\theta^i \Lambda_{t,t+1+i} \left((R_{k,t+1+i} - R_{t+1+i}) Q_{t+i} Z_{t+i}(j) + R_{t+1+i} \Omega_{t+i}(j) \right) \end{aligned} \tag{14}$$

Under condition (13), bankers may want to increase their assets indefinitely by borrowing more and more funds from households. Furthermore, a banker can decide to divert funds, i.e. transfer a fraction or even the totality of assets to its own household for personal gain. Creditors are aware of this possibility as they know that there may be a fraction λ of funds that will never be recovered. However, they can impose a borrowing constraint to ensure that bankers do not divert all funds. Therefore, households are willing to supply funds to a bank only if the banker's expected discounted terminal wealth $V_t(j)$ is at least as large as the banker's gain

[4] As explained in Gertler and Karadi (2011), this assertion implies that the average "survival time" for a banker at any period is $\frac{1}{1-\theta}$. This insures that bankers cannot fund all investments from their own capital and that the relative proportion of each type of household remains constant over time.

form diverting funds $\lambda Q_t Z_t(j)$[5]:

$$V_t(j) \geq \lambda Q_t Z_t(j) \tag{15}$$

where in each period t, banker j chooses $Z_t(j)$ in order to maximize (14) subject to constraint (15).

The leverage ratio is the value of total loans of a banker to non-financial producers divided by the net worth of that banker. It is a measure of the proportion of worth that a banker lends. Define $\phi_t(j)$ as the leverage ratio of banker j as:

$$\phi_t(j) := \frac{Q_t Z_t(j)}{\Omega_t(j)} \tag{16}$$

Note that the leverage ratio can be greater than one (e.g. bankers can lend more than they have), depending on interest rates.

As in Gertler and Karadi (2011), suppose that the solution of this problem has the following form:

$$V_t(j) = \nu_t Q_t Z_t(j) + \eta_t \Omega_t(j) \tag{17}$$

where ν represents the expected discounted marginal value that the banker gains by expanding claims, and η represents the expected marginal value of an extra unit of wealth. Equation (17) forms the initial guess of the solution, which is required in order to solve the problem. See the Appendix for details.

If constraint (15) is binding, then we arrive at an interior solution with:

$$\nu_t = \mathbb{E}_t \Lambda_{t,t+1} \Gamma_{t+1} \left(R_{k,t+1} - R_{t+1}\right), \quad \eta_t = \mathbb{E}_t \Lambda_{t,t+1} \Gamma_{t+1} R_{t+1} \tag{18}$$

$$\Gamma_{t+1} = 1 - \theta + \theta \left(\nu_{t+1} \phi_{t+1}(j) + \eta_{t+1}\right), \quad \phi_t(j) = \frac{\eta_t}{\lambda - \nu_t} \tag{19}$$

[5] See Gertler and Karadi (2011) for an extensive explanation of this condition.

If constraint (15) does not bind, then our solution is a corner with:

$$\nu_t = 0, \quad \eta_t = 1, \quad \Gamma_t = 1, \quad \phi_t(j) \text{ is undetermined} \tag{20}$$

As long as $0 < \nu_t < \lambda$, the incentive constraint holds and the banker will increase its assets. In contrast, when $\nu_t > \lambda$, the incentive constraint is not binding and the expected discounted value of the banker always exceeds gains from diverting funds.

Aggregating the wealth of all existing bankers, we have[6]:

$$\Omega_{t+1} = \left(\left(R_{k,t+1} - R_{t+1}\right)\phi_t + R_{t+1}\right)\Omega_t \tag{21}$$

Recall that, at each date t, not all bankers remain bankers to the next time period, and a portion of households become new bankers. We assume that bankers who exit give their earnings to their own household and the household gives the new banker startup funds, equal to a fraction $\frac{\epsilon}{1-\theta}$ of the value of assets that existing bankers had earned in their last operating period.

Accordingly, the total net worth of all bankers is the sum of the existing bankers and new bankers such that:

$$\Omega_t = \Omega_{e,t} + \Omega_{n,t} \tag{22}$$

Given that the probability of a banker at time t remaining a banker at time $t+1$ is equal to θ, then we may re-write (22) as:

$$\Omega_t = \theta\left(\left(R_{k,t} - R_t\right)\phi_{t-1} + R_t\right)\Omega_{t-1} + \epsilon Q_t Z_{t-1} \tag{23}$$

[6] Since all bankers are created equal and they choose the same quantity of claims, then their choice of $Z_t(j)$ will not depend upon j, neither deposits $B_t(j)$. Then ϕ_t is independent of j.

3.4 Central Bank and Public Loans

Until now, we have assumed that only private banks receive deposits from households (B_t) and lend funds to intermediate producers (Z_t). Here, we relax this assumption to consider a Central Bank which conducts unconventional monetary policy, managing the epidemic by issuing of bonds and lending money to non-financial firms.

As explained in Gertler and Kiyotaki (2010), there are many ways in which the Central Bank may behave. Since our objective is to study how the public authority may fight an epidemic crisis using public loans, we assume that the Central Bank issues government bonds $B_{g,t}$ to consumers at gross interest rate R_t and - using that income with respect to its budget constraint - issues financial claims $Z_{g,t}$ to intermediate non-financial producers at price Q_t, for which the government earns a stochastic rate of return $R_{k,t+1}$.

Let $Q_tZ_{p,t}$ be the value of assets coming from private banks, $Q_tZ_{g,t}$ the value of assets coming from the Central Bank, and Q_tZ_t the total value of intermediate assets (i.e. the sum of assets from private and Central banks). Note that in the eyes of borrowers and lenders in our model, private deposits/claims and government bonds/claims are equivalent in the sense that they have the same price and interest rates.

The Central Bank has both an advantage and a disadvantage with respect to private lenders. We assume that government assets come with an efficiency cost of τ per claim[7], but that, assuming the government can always honor its debts, there are no limitations in the number of bonds it can supply[8]. Therefore, it is not subject to an incentive constraint. As a consequence the Central Bank may also

[7] As explained in Gertler and Karadi (2011) and Gertler and Kiyotaki (2010), the government faces additional costs of evaluating and monitoring borrowers that privates banks do not have. This is because private banks possess specific knowledge of the market not readily available to the Central Bank.

[8] By abstracting from solvency problems, we are assuming that the government can always print money to pay its debts. In reality, solvency problems can emerge and be aggravated by sovereign debt and credit-rating agencies. We leave this for future work.

issue government debt to financial intermediates without constraint. Private banks fund government bonds by issuing households deposits at the same rate as they lend them from the Central Bank. Thus, only private assets financed with private banks face the incentive constraint.

Suppose that in each period the Central Bank lends a fraction ψ_t of total credit. Then, using equation (16), we write the total value of intermediate assets as:

$$Q_t Z_t = \phi_t \Omega_t + \psi_t Q_t Z_t = \Phi_t \Omega_t \tag{24}$$

where $\Phi_t := \frac{\phi_t}{1-\psi_t}$ is the leverage ratio for total intermediate funds (public and private). The choice of ψ_t will be explained in Section 3.8.

3.5 Intermediate Non-Financial Firms

Let there exist a continuum of perfectly competitive, homogenous intermediate goods producers that produce a differentiated non-financial good that is sold at real price $P_{m,t}$[9]. Each of them uses two inputs: labor L and capital K.

Following Gertler and Karadi (2011) we assume that at the end of period t, each intermediate producer acquires a quantity K_{t+1} of capital from the capital producers to be used in production in time $t+1$. After production in period $t+1$, the firm may sell capital back to the capital producer and/or refurbish depreciated capital. We assume that the cost of replacement is unity and that there are no adjustment costs. Thus, intermediate goods firms face a static problem, solving their profit maximization problem one period at a time rather than maximizing expected profit over the lifetime of the firm.

Goods producers finance physical capital by borrowing from financial intermediates[10]. Note that borrowers are not constrained by the quantity of claims Z_t they

[9]Following Gertler and Karadi (2011) we do not introduce price stickiness through intermediate goods producers, but rather do so by assuming that retailers are monopolistic.

[10]Private and public financial intermediaries are perfect substitutes in the eyes of the borrower.

want to purchase. However, as intermediate private banks are constrained by the quantity of funds they may obtain from households, there is an indirect effect of the interest rate $R_{k,t}$ on goods producer dynamics.

Each goods producer then purchases a quantity Z_t of capital claims, in which each claim equals one unit of capital $Z_t = K_{t+1}$ and that the price per unit capital is Q_t. It follows that $Q_t K_{t+1} = Q_t Z_t$.

Recall that goods producers are homogeneous and all behave in the same fashion. Then we can write the quantity of intermediate non-financial goods $Y_{m,t}$ produced by the representative physical goods producer at time t as a Cobb-Douglas production function involving capital and labor such that[11]:

$$Y_{m,t} := K_t^{\alpha} L_t^{1-\alpha} \tag{25}$$

where the subscript m differentiates intermediate goods ($Y_{m,t}$) from final goods (Y_t), and α is the elasticity of production with respect to capital. As we assume no stochastic shocks, we abstract here from quality capital shocks as in Merton (1973) and a total factor productivity shock as in classic DSGE models (Smets and Wouters (2007)).

Each goods producer chooses quantities of labor and capital in order to maximize its profit. The solution to this problem yields the following first order conditions:

$$W_t = (1-\alpha) P_{m,t} \frac{Y_{m,t}}{L_t} \tag{26}$$

$$R_{k,t} = \frac{\alpha P_{m,t} \frac{Y_{m,t}}{K_t} + (1-\delta) Q_t}{Q_{t-1}} \tag{27}$$

where δ is the capital depreciation rate. As we are in a perfect competitive frame-

[11]Since we assume that retailers are monopolistic, one unit of intermediate good $Y_{m,t}$ does not necessary equal one unit of final good Y_t. As shown in the Appendix, these quantities are related by the equation $Y_{m,t} = v_{p,t} Y_t$ at equilibrium, where $v_{p,t}$ is the price dispersion of the aggregated final good.

work, equations (26) and (27) establish that intermediate good producers choose the quantity of labor to equate real wages and the marginal product of labor, and quanty of capital such that the real price of capital equals the net return after depreciation.

3.6 Capital Producers

There exists a continuum of perfectly competitive, homogeneous capital production firms. At the end of each period t, capital producers may produce new capital by buying final goods from retailers $I_{n,t}$ (i.e. investing), purchase non-depreciated capital from intermediate good producers at price Q_t, repair depreciated capital at cost unity, and/or sell capital to intermediate goods producers at price Q_t. In doing so, total aggregate capital accumulates in the following fashion:

$$K_{t+1} := (1-\delta)\, K_t + I_{n,t} \tag{28}$$

where δ is the capital depreciation rate and $I_{n,t}$ is net/new capital investment.

Furthermore, we assume that there is no adjustment or investment cost associated with repairing capital. However, producing new capital does face an adjustment cost associated with changing the level of investment. Thus, capital producer profit can be written as[12]:

$$D_{k,t} = \left((Q_t - 1)I_{n,t} - f\left(\frac{I_{n,t}}{I_{n,t-1}}\right) I_{n,t}\right) \tag{29}$$

A representative capital producer chooses the quantity of net capital investment $I_{n,t}$ to maximize its discounted profits:

$$\mathbb{E}_t \sum_{i=0}^{\infty} \Lambda_{t,t+i} \left((Q_{t+i} - 1)I_{n,t+i} - f\left(\frac{I_{n,t+i}}{I_{n,t-1+i}}\right) I_{n,t+i}\right) \tag{30}$$

[12] See the Appendix for a detailed derivation.

where the adjustment cost function ($f(\cdot)$) depends on net capital investment at times t and $t-1$. Specifically, it is defined as:

$$f\left(\frac{I_{n,t}}{I_{n,t-1}}\right) = \frac{\kappa}{2}\left(\frac{I_{n,t}}{I_{n,t-1}} - 1\right)^2, \kappa > 0 \tag{31}$$

Remark that the adjustment cost is zero at the steady state, and that this cost is increasing with temporal changes in investment.

The first order condition for profit maximization yields:

$$Q_t = 1 + f\left(\frac{I_{n,t}}{I_{n,t-1}}\right) + f'\left(\frac{I_{n,t}}{I_{n,t-1}}\right)\frac{I_{n,t}}{I_{n,t-1}} - \mathbb{E}_t\Lambda_{t,t+1}f'\left(\frac{I_{n,t+1}}{I_{n,t}}\right)\left(\frac{I_{n,t+1}}{I_{n,t}}\right)^2 \tag{32}$$

This equation is the marginal Tobin's "Q" which, given asset prices, defines the optimal investment demand function. Remark that with no adjustment costs, $Q_t = 1$.

3.7 Retailers

Let there be a continuum of monopolistic *normal retailers* indexed by $h \in [0, 1]$, and a continuum of perfectly competitive *super retailers* that purchase and assemble final goods produced by *normal retailers* in order to produce an aggregate final good that will be sold at price P_t. We assume that *super retailers* are homogeneous and all behave in the same fashion (*normal retailers* are not treated as homogeneous).

The *super retailer* is characterized by the following CES production function:

$$Y_t := \left(\int_0^1 Y_t(h)^{\frac{\epsilon_p - 1}{\epsilon_p}} dh\right)^{\frac{\epsilon_p}{\epsilon_p - 1}} \tag{33}$$

where $Y_t(h)$ is final good produced by *normal retailer* h, and ϵ_p is the elasticity of substitution of choosing between *normal retailer* goods.

Given the prices of normal retailer goods $P_t(h)_{h\in[0,1]}$ and the final aggregated good price P_t, the *super retailer* chooses the quantities of *normal retailers* goods

$(Y_t(h))_{h\in[0,1]}$ in order to maximize its profit. The solution yields the following demand function for good h:

$$Y_t(h) = \left(\frac{P_t(h)}{P_t}\right)^{-\epsilon_p} Y_t \quad \forall h \tag{34}$$

Notice that the production function of the *super retailer* includes constant returns to scale and that firms are perfectly competitive, meaning that firms experience zero profits at equilibrium. We therefore obtain the following equation for the price of the final aggregate good:

$$P_t = \left(\int_0^1 P_t(h)^{1-\epsilon_p} dh\right)^{\frac{1}{1-\epsilon_p}}. \tag{35}$$

Each *normal retailer* h uses intermediate goods, produced by the intermediate goods firms, to "pack" the intermediate goods and sell them to the *super retailers* at price $P_t(h)$. We assume that it takes one unit of intermediate good to produce one unit of normal final output. Thus, the marginal cost for each *normal retailer* is the intermediate price $P_{m,t}$, which is the same for all *normal retailers*.

We introduce nominal price rigidity as in Calvo (1983). In each period t, a fraction $(1-\theta_p)$ of *normal retailers* can re-optimize their nominal price $(P_t(h) = P_t^*(h))$, while the remaining fraction can only partially adjust their prices according to past inflation. If firm h cannot change its price for i periods, then its normalized price after i periods is:

$$\prod_{s=1}^{i} \Pi_{t+s-1}^{\chi} \frac{P_t(h)}{P_{t+i}} \tag{36}$$

where $\chi \in (0,1)$ reflects the price response to inflation and $\Pi_t := \frac{P_t}{P_{t-1}}$ represents the level of inflation from period $t-1$ to t.

Profits for *normal retailer* h at date t is then given by:

$$\left(\prod_{s=1}^{i}\Pi_{t+s-1}^{\chi}\frac{P_t(h)}{P_t}-P_{m,t}\right)Y_t(h) \tag{37}$$

Given the option, each *normal retailer* firm will choose to readjust its price. The choice of $P_t^*(h)$ does not depend on the specific household h because all firms that are able to choose their prices will do so in the same fashion. Furthermore, firms only consider future states in which re-optimization is not possible thus each firm h chooses $P_t(h)$ to maximize expected discounted profits:

$$\mathbb{E}_t\sum_{k=0}^{\infty}\theta_p^i\Lambda_{t,t+i}\left(\prod_{s=1}^{i}\Pi_{t+s-1}^{\chi}\frac{P_t(h)}{P_{t+i}}-P_{m,t+i}\right)Y_{t+i}(h) \tag{38}$$

subject to equation (34).

The first order condition of this problem yields:

$$\mathbb{E}_t\sum_{i=0}^{+\infty}\theta_p^i\Lambda_{t,t+i}Y_{t+i}(h)\left(\frac{P_t^*}{P_{t+1}}\prod_{s=1}^{i}\Pi_{t+s-1}^{\chi}-\mathcal{M}P_{m,t+i}\right)=0 \tag{39}$$

where $\mathcal{M}=\frac{\epsilon_p}{\epsilon_p-1}$ is the desired price markup, absent from inflation. This equation gives the optimal price setting condition.

Finally, using the fact that a fraction $(1-\theta_p)$ of *normal retailers* can optimize prices while the rest index prices to past inflation, equation (35) can be written as:

$$P_t^{1-\epsilon}=\theta_p\left(\Pi_{t-1}^{\chi}P_{t-1}\right)^{1-\epsilon}+(1-\theta_p)\left(P_t^*\right)^{1-\epsilon} \tag{40}$$

3.8 Government, Monetary Policy and the Market Clearing Condition

The government distributes unemployment benefits b_t, issues public debt $B_{g,t}$ to households for which it pays a gross interest rate R_t, sells claims $Z_{g,t}$ to non-financial firms at price Q_t and gross interest rate of return of $R_{k,t}$, recovers/pays lump-sum taxes, and spends its own expenditures G_t.

As discussed previously, there is a portion of the population that is infected and is not part of the labor force. We assume that they receive at least partial unemployment benefits from the government. We define those benefits b_t as:

$$b_t = \zeta W_t, \quad \zeta \in [0, 1) \tag{41}$$

where ζ is the rate of unemployment compensation and W_t real wages. Thus, unemployment benefits are proportional to wages earned from working.

As explained in Subsection 3.4, in each period, the government via the Central Bank, lends a fraction ψ_t of total credit to financial intermediates. However, government assets come with an inefficiency cost of $\tau \in [0, 1]$ per claim. (Recall that private banks are more efficient in that they have better access to market information.) Then government expenditure on financial intermediates is given by $\tau\psi_t Q_t K_{t+1}$.

We assume as well that government consumption of final goods is always constant, $G_t := \omega_g Y_t$, where ω_g is the steady state share of GDP that the government uses for its own expenditures. Assuming that transfers automatically adjust at each date, the government faces the following budget constraint:

$$G_t + \tau\psi_t Q_t K_{t+1} + b_t(1 - L_t) + \psi_t Q_t Z_t = T_t + (R_{k,t} - R_t)\, B_{g,t} + B_{g,t+1} \tag{42}$$

Equation (42) equates all expenditures (final good consumption, expenditures to non-financial intermediaries, and unemployment benefits) to revenue (lump sum taxes, interest from debt).

Unconventional monetary policy ψ_t is set in the following manner:

$$\psi_t = \bar{\psi}_t + \omega \mathbb{E}_t \left[(logR_{k,t+1} - logR_{t+1}) - (logR_k - logR) \right] \tag{43}$$

where $\bar{\psi}_t$ is defined as our "*epi loans*", $\omega > 0$ is the Central Bank credit feedback parameter, and $logR_k - logR$ is the steady state risk-premium. The feedback parameter governs the intensity of the reaction of the Central Bank to changes in the spread relative to the steady state risk premium. When the risk-premium is larger than its steady state, the Central Bank expands its credit with the larger the ω, the greater the credit expansion. In our baseline simulations, we treat $\bar{\psi}_t$ as a constant equal to zero. We then relax this assumption, taking $\bar{\psi}_t$ as a deterministic, exogenous shock, to study the ability of our "*epi loans*" to alleviate the negative effects of the epidemic.

Suppose that the Central Bank also conducts conventional monetary policy by setting nominal interest rates, i_t, following a Taylor rule of the form:

$$1 + i_t = (1 + i_{t-1})^{\phi_i} \left(\frac{1}{\beta} \left(\frac{\Pi_t}{\Pi} \right)^{\phi_\pi} \left(\frac{Y_t}{Y_{ss}} \right)^{\phi_y} \right)^{1-\phi_i}, \tag{44}$$

where Π_t is the steady state of inflation and Y_{ss} is the steady state GDP in a scenario without disease. In this formulation the parameter ϕ_y measures the response of the Central Bank to the output gap, which contrary to other DSGE models, we define as the deviation of current GDP with respect to the steady state GDP without an epidemic[13].

Finally, we have the following Fisher relation that links nominal interest rates fixed by the Central Bank to the gross real interest rate fixed by the market:

$$1 + i_t = R_{t+1} \mathbb{E}_t \Pi_{t+1} \tag{45}$$

Market clearing conditions established that production is divided between consumption, net investment, government expenditures in goods, and government finan-

[13]Generally, in classic DSGE models, the output gap is defined as the deviation of current GDP with respect to its steady state. In our model, depending on the type of disease, it is possible to have different steady states values for Y. We believe that the real output gap should be measured as the deviation with respect to a fixed value of Y.

cial intervention.

$$Y_t = C_t + I_{n,t} + f\left(\frac{I_{n,t}}{I_{n,t-1}}\right) I_{n,t} + G + \tau\psi_t Q_t K_{t+1} \tag{46}$$

Equation (46) closes the model.

4 Parameter Calibration and Simulation Analysis

Details on model aggregation and calculation of the the steady state values are given in the Appendix. Each time period corresponds to a quarter. Baseline parameter values are summarized on Table 3. Calibration of our baseline parameters follows Smets and Wouters (2007) and Gertler and Karadi (2011) for the U.S. economy. Specifically, the discount factor β is set to ensure a 4% annual interest rate, with the elasticity of substitution among final goods taken to yield a steady-state price markup of 31%. The output of elasticity of capital α is calibrated assuming a "labor share" of approximately 2/3 and the bankers' survival rate is fixed at 0.975, which assumes that bankers remain bankers on average for 10 years. We fix the share of unemployment compensation ζ to 0.5. As in Gertler and Karadi (2011), the private banks' parameters λ and ϵ are fixed to meet the following targets: a risk-premium steady state of 100 basis points and a steady state leverage ratio of 4. Initial conditions and baseline epidemiological parameters were chosen to illustrate a full epidemic cycle, and are *not* meant to represent a specific disease.

Simulation of the model proceeds in two steps. First, we calculate the trajectories of the number of susceptible, infected, and recovered individuals given initial conditions and epidemic parameters. The dynamics of the epidemic were solved using a first-order Euler approximation for a time horizon of 150 periods, corresponding to the time scale of the economic model. We then used the trajectory of infected individuals as a deterministic, permanent shock to the real economy. In this way,

Table 1: State and control variables

Variable	Symbol	Type
Epidemic block		
Susceptible	S	State
Infected	$\tilde{I}$	State
Recovered	$\tilde{R}$	State
Households		
Labor	L	Control/State
Consumption	C	Control
Deposit = Government bonds	B	Control
Financial Intermediates		
Quantity of financial claims issued by private banks	Z_p	Control
Non-financial intermediates and capital producers		
Intermediate non-financial goods	Y_m	Control
Capital	K	Control/State
Labor	L	Control/State
Net capital investment	$I_{n,t}$	Control
Retailers and Capital Producers		
Normal retailed good price	$P(h)$	Control

Table 2: Model definitions and outcomes

Variable	Symbol
Households	
Total population	N
Real discount factor from date t to $t+1$	$\Lambda_{t,t+1}$
Good price = Aggregate retailer's price	P
Total real profits	D
Lump-sum taxes	T
Marginal lifetime discounted utility function	λ_c
Real wage	W
Financial Intermediates	
Total quantity of financial claims	Z
Bankers' net worth	Ω
Expected discounted terminal wealth	V
Leverage ratio of private banks	ϕ
Auxiliary variable	Γ
Risk-less gross real rate of return	R
Claims gross real rate of return = Capital rate of return	R_k
Financial claims price	Q
Total leverage ratio (public and private)	Φ
Marginal value of banker's gain w.r.t claim income	ν
Marginal value of banker's gain w.r.t wealth	η
Existing banker's net worth	Ω_e
New banker's net worth	Ω_n
Private deposits	B_p
Private bank profit	$D_{b,t}$
Non-financial intermediates and capital producers	
Intermediate non-financial good price	P_m
Intermediate non-financial profit	$D_{m,t}$
Capital producer profit	$D_{k,t}$
Adjustment cost function of investment	$f(\cdot)$
Retailers and Capital Producers	
Aggregate super retailed good	Y
Normal retailed good	$Y(h)$
Normal retailed good price	$P(h)$
Optimal normal retailed good price	P^*
Normal retailer profit	$D_{r,t}$
Price dispersion	$v_{p,t}$
Central Bank and Government	
Level of goods price inflation	Π
Fraction of total credits financed by the Central Bank	ψ
Quantity of financial claims issued by the Government	Z_g
Unemployment compensation	b
Government consumption	G
Nominal interest rate	i
GDP without disease	$\bar{Y}$
Inflation without disease	$\bar{\Pi}$
Government bonds	B_g
Exogenous fraction of publicly intermediate assets	$\bar{\psi}$

agents possess perfect foresight regarding the future states of the epidemic when computing their optimal solutions. We solve the economic block from a set of initial conditions to the steady-state of both economic and epidemic blocks[14].

In order to test the effectiveness of unconventional monetary policy to mitigate the epidemic crisis, we first establish a baseline model scenario with an epidemic and study the economic consequences of changes in the epidemic structure. We then implement unconventional monetary policy by testing the sensitivity of the model to the steady state leverage ratio for private banks, the intensity of the reaction of the Central Bank to changes in the spread, and our "*epi loans*" policy. All model simulations were conducted in Dynare 4.6.1. All source code and simulation data can be found on the Open Science Framework (osf.io/j7m65).

5 Results and Discussion

This section is divided in four parts. First, we present our baseline results of the model and the different pathways by which the epidemic affects the economy. Second, we describe the economic response to changes in epidemiological parameters (transmission and recovery rates). Third, we discuss the effects of unemployment compensation on the economy. Finally, we evaluate the potential of monetary policies to remedy the economic burden of the epidemic. For each of our results, we compare the trajectories of our economic variables to those in the absence of disease (or the "no-disease" case). When changing model parameters, we re-calculate the trajectories of the no-disease case to correspond to the new set of parameters.

[14]We solve the linearized version of the perfect foresight model with the Newton method, which uses sparse matrices to simultaneously solve all equations in every period.

Table 3: Parameter Calibration

Parameter	Symbol	Calibrated Value/Baseline
Epidemic block		
Initial condition of susceptible	S_0	0.9
Initial condition of infected	$\widetilde{I}_0$	0.1
Initial condition of recovered	$\widetilde{R}_0$	0
Transmission rate	α_v	0.4
Recovery rate	γ_v	0.1
Households		
Discount factor	β	0.99
Internal habit formation	h	0.71
Financial Intermediates		
Bankers' survival rate	θ	0.972
Fraction of claims income that can be diverted	λ	Function of risk premium at steady state, leverage ratio at steady state and θ
Proportional transfer to the new bankers	ϵ	Function of risk premium at steady state, leverage ratio at steady state, θ and $\bar{\psi}$
Risk premium at steady state	$R_k - R$	0.01/4
Leverage ratio at steady state	ϕ	4
Non-financial intermediates and capital producers		
Capital depreciation	δ	0.025
Price indexation to inflation	χ	0.24
Calvo price parameter	θ_p	0.66
Capital share	α	0.33
Retailers and Capital Producers		
Adjustment cost constant	κ	5.74
Elasticity of substitution between normal retailers	ϵ_p	4.167
Price markup	$\mathcal{M}$	Function of θ_p
Central Bank and Government		
Efficiency cost	τ	0.001
Unemployment rate compensation	ζ	0.5
Feedback parameter	ω	10
Taylor rule response to inflation	ϕ_π	2.04
Taylor rule response to output gap	ϕ_y	0.08
Taylor rule inertia	ϕ_i	0.81
Steady state share of GDP that Government expends	ω_g	0.18

5.1 Baseline Results

Our baseline results are summarized in Figures 3 and 4 . For brevity, we focus on a set of core variables of the model.

By assumption, the epidemic decreases the quantity of available labor (only healthy individuals are allowed to work), which at its maximum severity decreases the workforce by 45%. This effect on the labor market echoes throughout the economy, with declines in household consumption, non-financial intermediary capital, and capital producer investment following the trajectory of labor. The first is a consequence of lost wages and equality in the market clearing condition. The latter two follow declines in production due to a lower workforce.

Regarding financial intermediaries, the epidemic primarily affects their expected discounted terminal wealth (V). Both components of wealth - net worth (Ω) and claim selling (QZ) - are affected. This is because a decrease in capital translates to a decrease in claims demand ($K_{t+1} = Z_t$), which has a negative impact on claim prices (Q) compared to the no-disease case. We observe significant declines in GDP, reaching a maximum loss of 20% compared to the no-disease case.

What is particularly interesting is that as the crisis starts, the Central Bank increases its share of total credits that it finances (ψ) to compensate for losses in investment and production that follow declines in labor. This is because, while decreases in investment in capital and production of goods provoke decreases in interest rates (risk-less and capital rate of return), the observed spread in the interest rates is still higher than the steady-state.

Similarly, we observe an increase in inflation during the epidemic. In this model, the standard relationships between supply and demand and prices holds. If price increases (decreases), then the supply (demand) side dominates as the DSGE framework shifts back to equilibrium. In a perfectly competitive market, as overall production decreases with the epidemic, we would expect to see a larger than observed increase

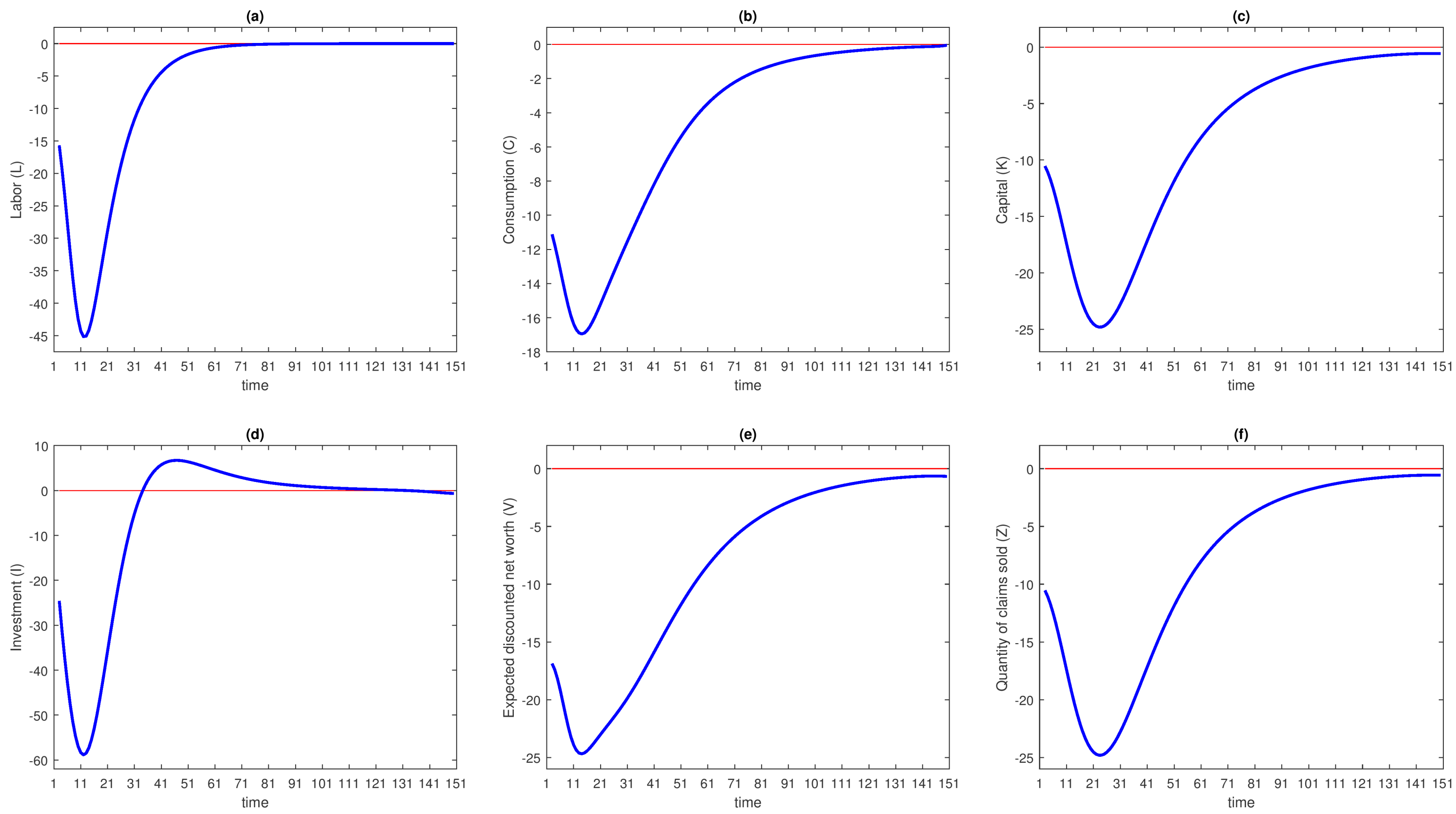

Figure 3: Baseline results for labor (a), consumption (b), capital (c), investment (d), expected discounted net worth (e), and the quantity of claims sold (f). Reported values are the percent deviation from the no-disease case. The red line corresponds to a zero percent change.

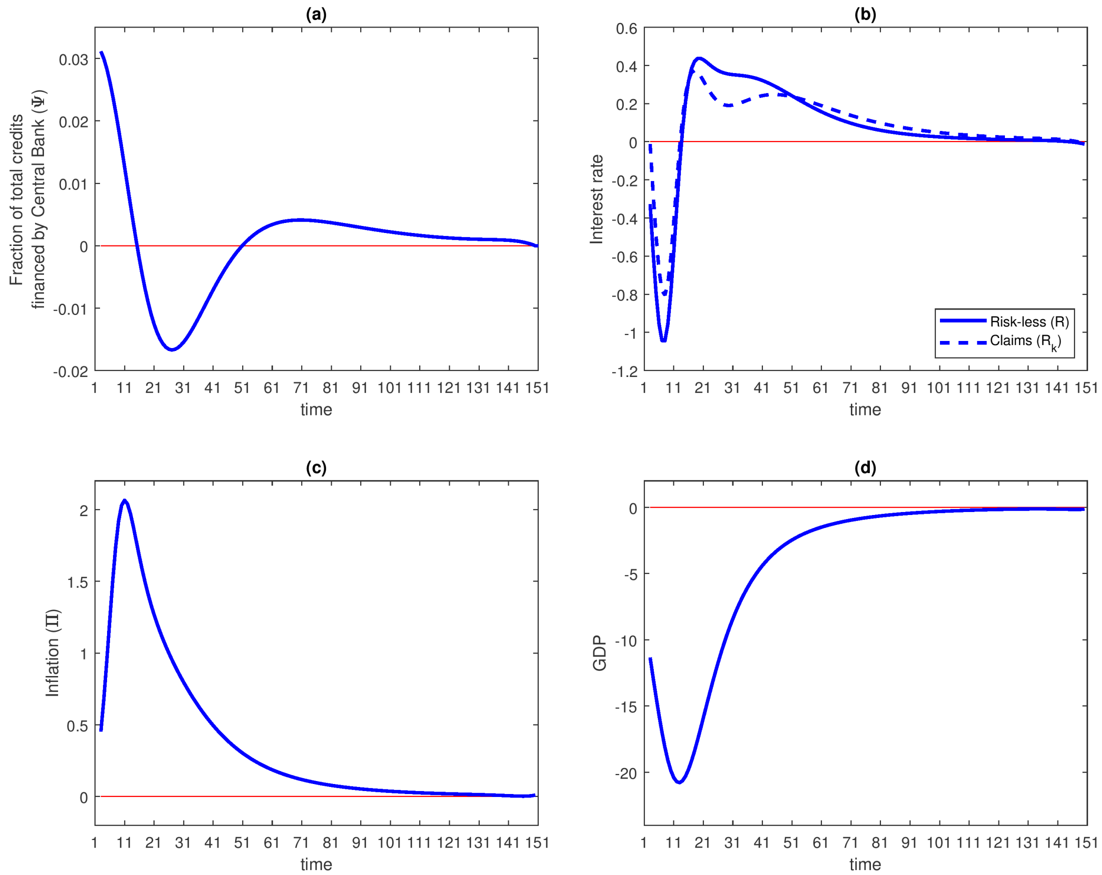

Figure 4: Baseline results for the fraction of total credits financed by the Central Bank (a), interest rates (b), inflation (c), and GDP (d). Reported values are the percent deviation from the no-disease case. For comparison, the red line corresponds to a zero percent change.

in prices (at least in the early stages of the epidemic). However, the increase in inflation is less than that of a perfectly competitive framework because of sticky prices.

5.2 Economic Response to Changes in Epidemic Structure

Holding all economic parameters constant, we vary the epidemiological parameters to understand how structural changes in the epidemic profile affect the economy. We find marked changes in cumulative GDP, with the recovery rate being the primary driver (Figure 5a). Indeed, at moderate to high recovery rates the model is relatively insensitive to the infection rate.

In our framework, the main burden of disease on the economy is in the labor supply: only healthy people are allowed to work. Therefore, an epidemic that persists for a long time in the population (low recovery rate) and, consequently, keeps people from working, will be the most costly. Even if we have a highly contagious epidemic (high infection rate), as long as it can pass through the population quickly (moderate or high recovery rate), then the overall burden in terms of GDP will be less.

This result has interesting implications for the relationship between disease's basic reproductive number (an epidemiological measure of the severity of a disease) and GDP (an economic measure of the well-being of an economy). The basic reproductive number (R_0) is defined as the average number of secondary infections that occur when a single individual is introduced into a population where everyone is susceptible (F.Brauer and Castillo-Chavez (2012), Hethcote (2000)). In general, if $R_0 > 1$ then the disease will spread through the population, and if $R_0 < 1$, then the disease will die out. The bigger the R_0, then the worse or more severe the disease. For a standard SIR model, it is defined as the ratio of the infection and recovery rates (α_v/γ_v) (Diekmann et al. (1990), Diekmann et al. (2010), Heffernan et al. (2005)).

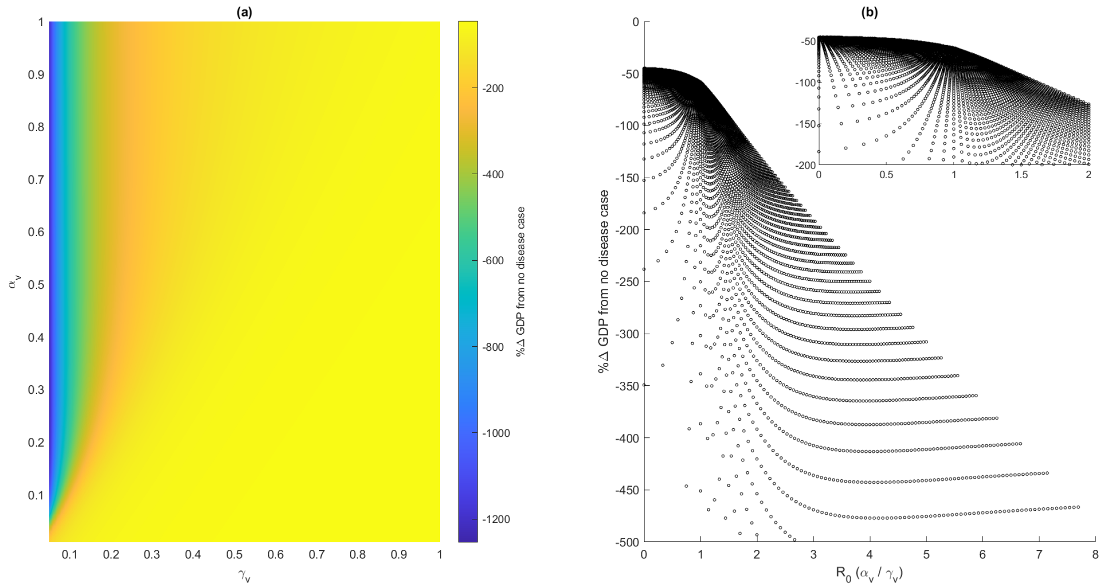

Figure 5: Sensitivity of GDP losses to epidemic parameters. Panel (a) presents the percent change in GDP for different combinations of disease transmission (α_v) and recovery (γ_v) rates. Color corresponds to the magnitude of GDP losses compared to the no-disease case. Dark blue (yellow) indicates greater (less) loss. Panel (b) relates the disease R_0 - generated from the epidemic parameters in panel (a) - to the percent change in GDP from the no-disease case. Though not tailored to a specific disease, for comparison the R_0 for COVID-19 is estimated to be between 1.4-6.5 (Cheng and Shan (2019)), 3.4 for H1N1 avian influenza (Chang et al. (2010)), 1.5-1.9 for Ebola (Khan et al. (2015)), and between 3.5-6 for smallpox (Hethcote (2000)).

Given the effects of the epidemiological parameters and GDP, a higher R_0 does not necessarily translate to greater GDP loss (Figure 5b). It is feasible to have a severe epidemic (in an epidemiological sense of the word) that does not result in a large economic loss, if the recovery rate is sufficiently high to allow workers to quickly return to the labor force. However, it is worth stressing that this result depends on a number of simplifying - albeit, we believe acceptable - assumptions. The model assumes a constant population size with homogeneous mixing, where the primary burden of disease is via the labor force. It does not account for deaths, vaccinations or treatments, nor quarantines or epidemic-related business closures. We leave further investigation to future work.

5.3 Unemployment Compensation

Next, we evaluate the quantity of unemployment benefits distributed to households who are unable to work due to infection. We find that, contrary to real-world expectations, distributing unemployment benefits generates no change in GDP compared to the baseline scenario. In a Keynesian framework, we would expect that compensating workers would help counterbalance the negative effects of the epidemic on GDP. The reason for this is that because households are Ricardian - a not unheard of phenomenon empirically (Evans and Hasan (1994)) - they are forward-looking and, in response to increases in government spending, choose to save today expecting to pay higher taxes later. This leads to no change in consumption. Ricardian consumer behavior is a common assumption in neoclassical models, which warrants future consideration when evaluating unemployment benefits as an economic policy.

5.4 Can monetary policy help fight the adverse effects of an epidemic?

In order to answer this research question, we individually vary a set of economic parameters, holding all the other parameters at their baseline values. We concentrate our analysis on financial parameters only, specifically focusing on three policy instruments. Remark that in this model, changing the economic parameters never provokes a change in labor. This is because we take labor as exogenously determined by the epidemic.

We start by first considering the steady-state leverage ratio for private banks (ϕ), defined as the total loans that a private bank can issue compared to its net worth (Figure 6). We find that the higher the leverage ratio, the higher the injection of funds from the Central Bank into the economy (ψ). This effect is observed because with a higher leverage ratio at the steady state, there is a greater probability of banks to sell claims. As this occurs, it causes the spread in the interest rates to increase, leading the Central Bank to further insert money into the economy. We also find a compositional shift in bankers' wealth, with income from selling claims (net worth) increasing (decreasing) with an increase in the steady-state leverage ratio. However, we do not observe a marked change in GDP compared to the baseline scenario.

Second, we test the sensitivity of Central Bank to a change in the spread via the feedback parameter ω (Figure 7). As the Central Bank responds more intensively to changes in the spread, it injects a higher quantity of funds into the economy during the beginning of the epidemic (when the difference in the spread is highest), and then drops off in the later stages. Volatility in the variation of the spread is greater with ω. This affects the quantity and composition of bankers' wealth, with higher wealth stemming from a smaller decrease in net worth. We find no effect on GDP losses. However, we observe that when the Central Bank reacts more intensively to changes in the spread, reductions in consumption are smaller than the baseline. This

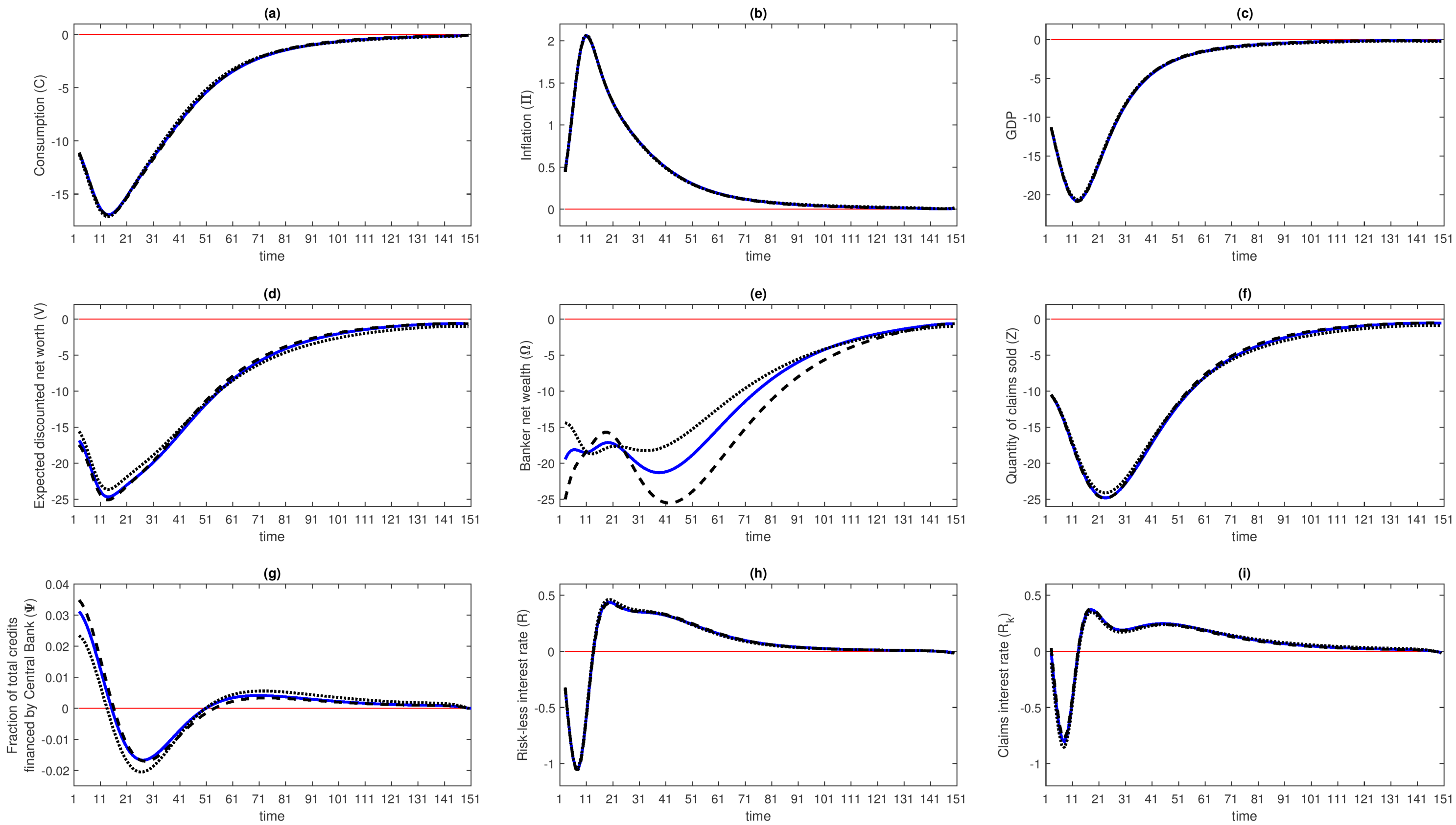

Figure 6: Model sensitivity to the steady state leverage ratio (ϕ). Recall that the results are reported as the percent change from the no-disease case. Line style and color indicates the value of the steady state leverage parameter: ϕ=2 (dotted, black), ϕ=4 (solid, blue; baseline), and ϕ=6 (dashed, black).

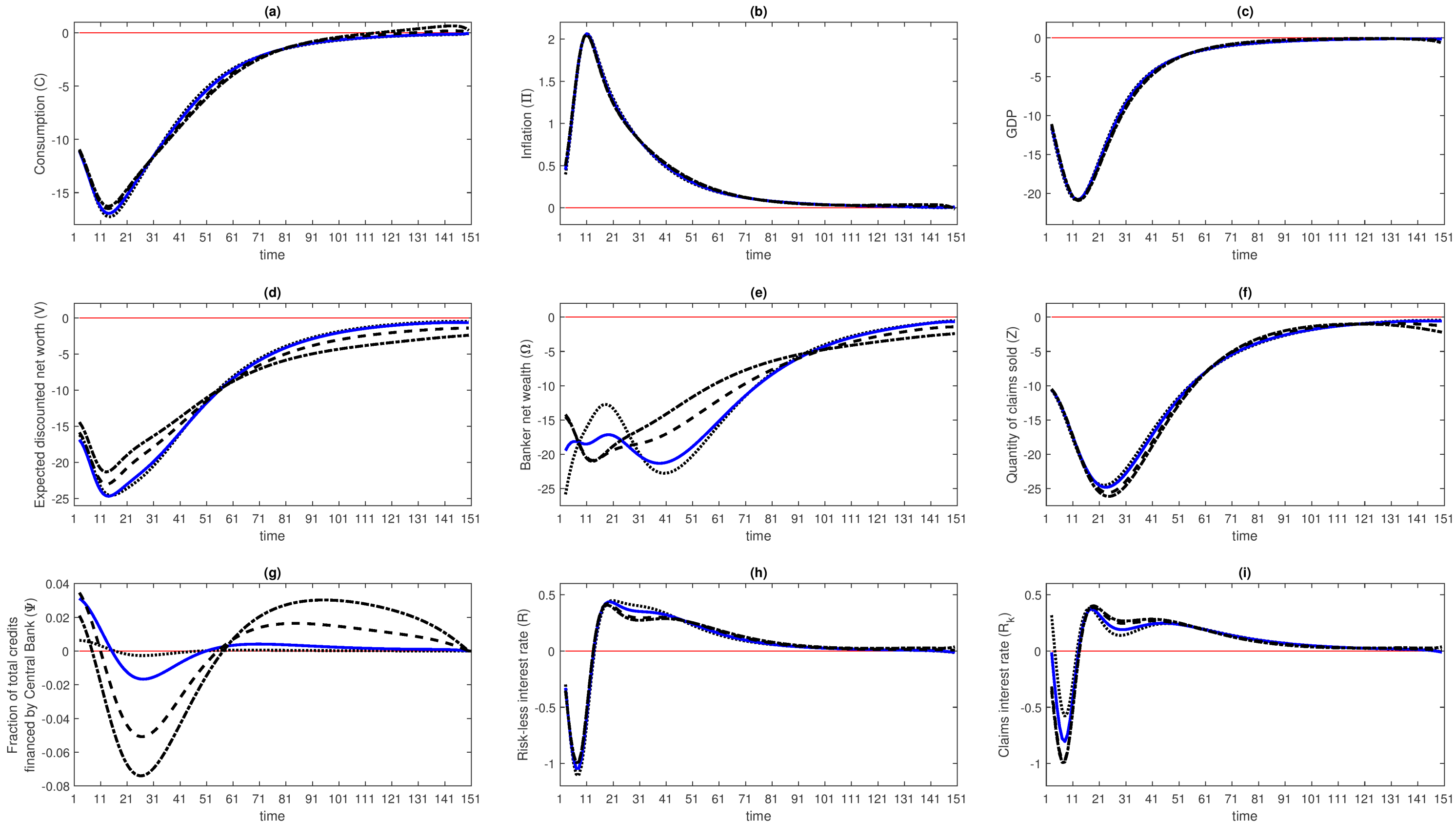

Figure 7: Model sensitivity to the feedback parameter (ω). Note that results are reported as the percent change from the no-disease case. Line style and color indicates the value of the feedback parameter: ω=1 (dotted, black), ω=10 (solid, blue; baseline), ω=100 (dashed, black), and ω=1000 (dot-dashed, black).

last result may suggest that, when talking about consumption, a stronger reaction to the spread is better for households.

Finally, we evaluate the use of "*epi loans*" to mitigate the effects of the epidemic (Figure 8). This takes the form of an exogenous shock on the steady state fraction of publicly intermediate assets $\bar{\psi}$, which affects the share of total claims the Central Bank finances (ψ). We assume that the Central Bank (with a cost) administers liquidity directly to the real economy in the form of claims that are transformed (one to one) into capital, and it does so from the beginning of the epidemic to its peak (in our case, this is about period 20).

Our definition of "*epi loans*" is an extreme form of a QE policy, but not exactly "helicopter money" as proposed by Friedman (1969). Instead of giving money directly to households with no expectation of being repaid, the Central Bank increases its share of total claims issued, and firms subsequently purchase capital without having to pass through private banks. Thus our "*epi loans*" directly affect demand by incentivizing investment, and should be thought of as expanding Central Bank intermediation rather than expanding the money supply.

With this policy we observe a smaller reduction in GDP compared to the baseline case. This should not come as a surprise given the fact that any increase in ψ will automatically increase GDP in the form of income obtained by the sale of claims. It is important to note, however, that although GDP loss is less than the baseline, the expected discounted terminal wealth of banks is reduced and the share of claims sold by private banks decreases. These are counterbalanced by an increase in the total quantity of claims sold such that the overall reduction of capital is smaller than the baseline. For households, this means that consumption is lower compared to the baseline case. An increase in claims reduces real rental interest rates and makes the acquisition of capital more attractive, incentivizing the investment in physical capital. As a side effect, we observe an expected increase in inflation. By reducing

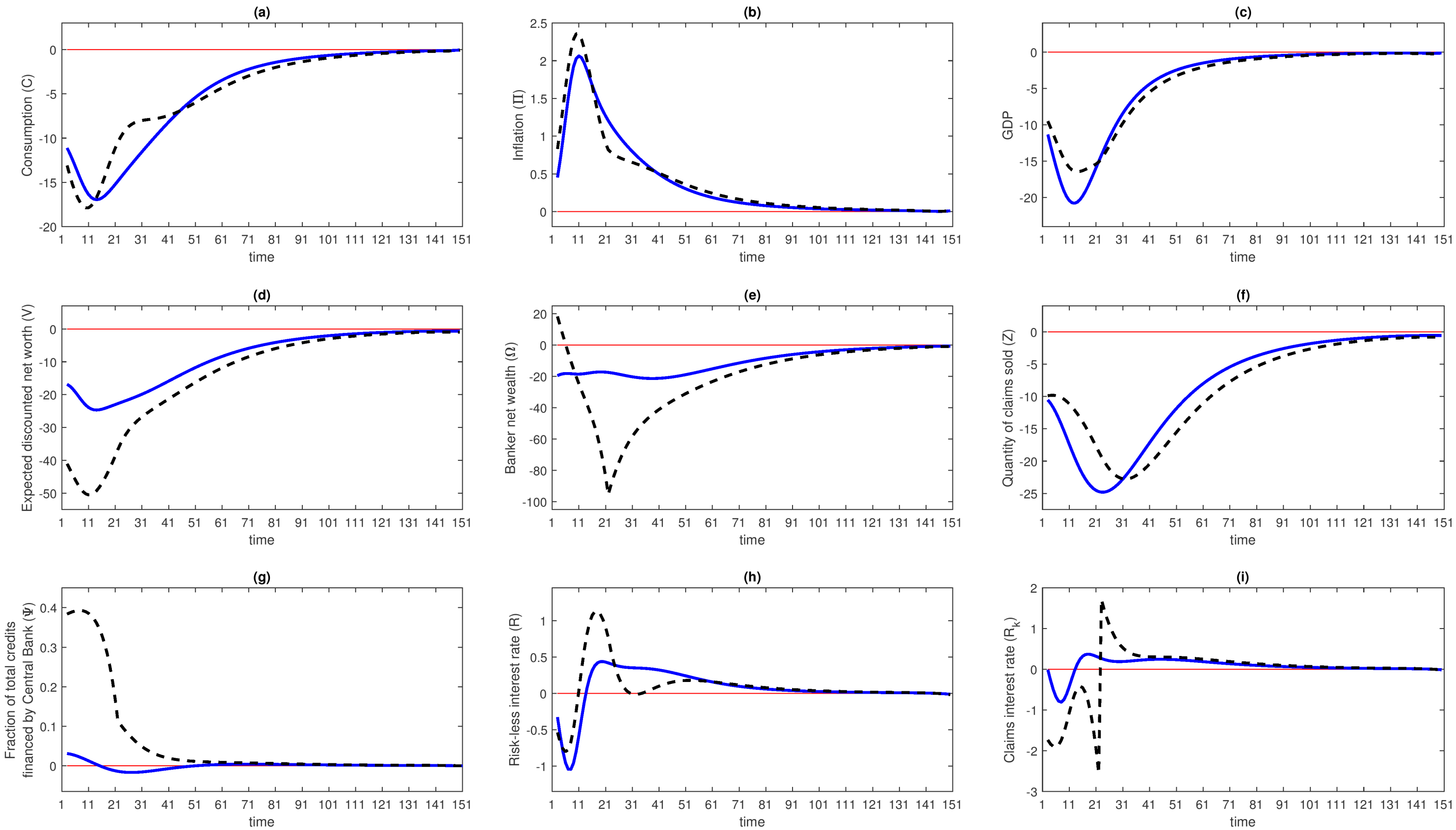

Figure 8: *Epi loans* ($\bar{\psi}$). Results are reported as the percent change from the no-disease case. The solid, blue line indicates the baseline model. The black, dotted line indicates a model implementing "*epi loans*" ($\bar{\psi}$=0.5). Note that the Central Bank administers "*epi loans*" from period 1 until peak of the epidemic (period 20).

demand, we drive up prices. However, it is important to remark that the increase in inflation, at its worst, is only 0.3% higher than that without an "*epi loans*" policy. Our results are in line with those proposed by Sharma et al. (2020), Céspedes et al. (2020), and Kiley (2020).

6 Conclusion

For the first time, we use a financial DSGE-SIR model to study the response of economy to an epidemic shock. We summarize our findings into three primary contributions.

First, due to the epidemic, the economy is likely to experience a deep recession. With our baseline calibration, we observe significant declines in GDP, reaching a maximum loss of 20% compared to the no-disease case. Although not directly comparable to other papers, for illustrative purposes Angelini et al. (2020), Chudik et al. (2020) and Bodenstein et al. (2020) found decreases in GDP post COVID-19 between 1.5% to 2.5%, 15%, and 20% to 30% respectively. However, our framework can be tailored to any combination of epidemiological models or economic parameters, making it possible to be calibrated to specific diseases and countries.[15]

Second, the profile of the epidemic has a significant effect on the shape of the recession. An epidemic that persists for a long time in the population (low recovery rate) and, consequently, keeps people from working, will be the most costly. Even if we have a highly contagious epidemic (high infection rate), as long as it can pass through the population quickly (moderate or high recovery rate), then the overall

[15] One could, for example, calibrate the epidemiological model to the COVID-19 epidemic. As COVID-19 is generally accepted to have an asymptomatic phase (Bi et al. (2020), He et al. (2020)), one would use a Susceptible-Asymptomatic-Infected-Recovered (SAIR) epidemiological model, which allows for asymptomatically-infectious individuals (F.Brauer and Castillo-Chavez (2012), Hethcote (2000)). Estimations of epidemiological model parameters have been conducted by Fanelli and Piazza (2020), Liangrong et al. (2020), Prem et al. (2020), and Yin et al. (2020), among others. However, it should be noted that there is uncertainty in estimations of these model parameters, as they will vary by country, the quality and timeframe of the data, the choice and timing of management strategies, accessibility to treatment and vaccines, as well as general assumptions inherent to disease models (such as homogeneous mixing or age structure).

recession will be less. This is because, in our model, as long as people are able to work, there should not be a reduction in production. We can infer that measures to decrease recovery time - such as treatments (which directly increases the recovery rate) and vaccination (which prevents individuals from getting sick) - could prove fruitful in minimizing economic losses of an epidemic. However, while straightforward to model in an epidemiological model (F.Brauer and Castillo-Chavez (2012), Hethcote (2000), Lenhart and Workman (2007)), these measures come with associated costs and the optimum usage is difficult to ascertain in a "macro-epidemic" framework (though see Lenhart and Workman (2007), Horan et al. (2010), and Toxvaerd and Rowthorn (2020) for examples in a microeconomics framework). We leave this for future work.

Finally, we found that, with the exception of increasing the share of claims from the Central Bank, our unconventional monetary policies cannot negate the negative economic effects of the crisis. However, as last resort lender, the Central Bank could use an unconventional monetary policy to exogenously increase its share of total claims issued ("*epi loans*"), which firms will then use to buy capital. This policy has the potential to lessen total losses in GDP, partially mitigating the economic recession, without being extremely inflationary, a side effect which has worried economists since the first use of unconventional monetary policies after the sub-prime crisis (e21 Staff (2010)). This is an encouraging thought as many industrialized countries have announced billions in stimulus to combat the COVID-19 crisis.

References

Albertazzi, U., B. Becker, and M. Boucinha (2018, January). Portfolio rebalancing and the transmission of large-scale asset programmes: evidence from the euro area. Working Paper Series 2125, European Central Bank.

Angelini, E., M. Darracq-Paries, S. Zimic, and M. Damjanovic (2020). Ecb-basir:

a primer on the macroeconomic implications of the covid-19 pandemic. Working Paper Series 2431, European Central Bank.

Atkeson, A. (2020, March). What will be the economic impact of covid-19 in the us? rough estimates of disease scenarios. Working Paper 26867, National Bureau of Economic Research.

Baldwin, R. and B. DiMauro (2020, July). *Mitigating the COVID Economic Crisis: Act Fast and Do Whatever It Takes A VoxEU.org Book*.

Baqaee, D. and E. Farhi (2020, May). Nonlinear production networks with an application to the covid-19 crisis. Working Paper 27281, National Bureau of Economic Research.

Baumeister, C. and L. Benati (2013, June). Unconventional Monetary Policy and the Great Recession: Estimating the Macroeconomic Effects of a Spread Compression at the Zero Lower Bound. *International Journal of Central Banking 9*(2), 165–212.

Bi, Q., Y. Wu, S. Mei, C. Ye, X. Zou, Z. Zhang, X. Liu, L. Wei, S. Truelove, T. Zhang, W. Gao, C. Cheng, X. Tang, X. Wu, Y. Wu, B. Sun, S. Huang, Y. Sun, J. Zhang, and T. Feng (2020, April). Epidemiology and transmission of covid-19 in 391 cases and 1286 of their close contacts in shenzhen, china: a retrospective cohort study. *The Lancet Infectious Diseases 20*.

Bichara, D., Y. Kang, C. Castillo-Chavez, R. Horan, and C. Perrings (2015). "SIS and SIR epidemic models under virtual dispersal". *Bulletin of Mathematical Biology 77*, 2004–2034.

Bodenstein, M., G. Corsetti, and L. Guerrieri (2020, April). Social Distancing and Supply Disruptions in a Pandemic. Finance and Economics Discussion Series 2020-031, Board of Governors of the Federal Reserve System (U.S.).

Boissay, F. and P. Rungcharoenkitkul (2020, April). Macroeconomic effects of Covid-19: an early review. BIS Bulletins 7, Bank for International Settlements.

Bonadio, B., Z. Huo, A. A. Levchenko, and N. Pandalai-Nayar (2020, May). Global supply chains in the pandemic. Working Paper 27224, National Bureau of Economic Research.

Brodeur, A., I. Grigoryeva, and L. Kattan (2020). Stay-at-Home Orders, Social Distancing and Trust. GLO Discussion Paper Series 553, Global Labor Organization (GLO).

Calvo, G. (1983). "Staggered Prices in a Utility-Maximizing Framework". *Journal of Monetary Economics 12*(3), 383–398.

Carlsson-Szlezak, P., M. Reeves, and P. Swartz (2020a). Understanding the Economic Shock of Coronavirus. *Harvard Business Review*.

Carlsson-Szlezak, P., M. Reeves, and P. Swartz (2020b). What Coronavirus Could Mean for the Global Economy. *Harvard Business Review*.

Céspedes, L. F., R. Chang, and A. Velasco (2020, May). The macroeconomics of a pandemic: A minimalist model. Working Paper 27228, National Bureau of Economic Research.

Chang, C., C. Cao, Q. Wang, Y. Chen, Z. Cao, H. Zhang, L. Dong, J. Zhao, M. Xu, M. Gao, S. Zhong, Q. He, J. Wang, and X. Li (2010). "The novel H1N1 Influenza A global airline transmission and early warning without travel containments". *Chinese Science Bulletin 55*, 3030–3036.

Cheng, Z. and J. Shan (2019). "Novel coronavirus: Where we are and what we know". *Infection 48*, 155–163.

Chowell, G., P. Fenimore, M. Castillo-Garsow, and C. Castillo-Chavez (2003). "SARS outbreaks in Ontario, Hong Kong, and Singapore: The role of diagnosis and isolation as a control mechanism". *Journal of Theoretical Biology 224*, 1–8.

Christiano, L. J., M. Eichenbaum, and C. L. Evans (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy 113*(1), 1–45.

Chudik, A., K. Mohaddes, M. H. Pesaran, M. Raissi, and A. Rebucci (2020, September). A counterfactual economic analysis of covid-19 using a threshold augmented multi-country model. Working Paper 27855, National Bureau of Economic Research.

Daszak, P., A. Cunningham, and A. Hyatt (2001). "Anthropogenic Environmental Change and the Emergence of Infectious Diseases in Wildlife". *Acta Tropica 78*, 103–116.

Dedola, L., P. Karadi, and G. Lombardo (2013). Global implications of national unconventional policies. *Journal of Monetary Economics 60*(1), 66–85.

Diekmann, O., J. Heesterbeek, and J. Metz (1990). "On the definition and the computation of the basic reproduction ratio R0 in models for infectious diseases in heterogeneous populations". *Journal of Mathematical Biology 28*, 365–382.

Diekmann, O., J. Heesterbeek, and M. Roberts (2010). "The construction of next-generation matrices for compartmental epidemic models". *Journal of the Royal Society Interface 7*, 873–885.

e21 Staff (2010). An Open Letter to Ben Bernanke. *Economics21.org*.

Eichenbaum, M. S., S. Rebelo, and M. Trabandt (2020a, June). Epidemics in the neoclassical and new keynesian models. Working Paper 27430, National Bureau of Economic Research.

Eichenbaum, M. S., S. Rebelo, and M. Trabandt (2020b, March). The macroeconomics of epidemics. Working Paper 26882, National Bureau of Economic Research.

Eichenbaum, M. S., S. Rebelo, and M. Trabandt (2020c, May). The macroeconomics of testing and quarantining. Working Paper 27104, National Bureau of Economic Research.

Elenev, V., T. Landvoigt, and S. VanNieuwerburgh (2020, May). Can the covid bailouts save the economy? Working Paper 27207, National Bureau of Economic Research.

Evans, P. and I. Hasan (1994). Are consumers ricardian? evidence for canada. *The Quarterly Review of Economics and Finance 34*(1), 25 – 40.

Fanelli, D. and F. Piazza (2020). Analysis and forecast of covid-19 spreading in china, italy and france. *Chaos, Solitons and Fractals 134*, 109761.

Faria-e Castro, M. (2020, March). Fiscal Policy during a Pandemic. Working Papers 2020-006, Federal Reserve Bank of St. Louis.

F.Brauer and C. Castillo-Chavez (1994). *"Ecological Time Series"*, Chapter "Basic Models in Epidemiology", pp. 410–477. New York: Raven Pressr.

F.Brauer and C. Castillo-Chavez (2012). *"Mathematical Models in Population Biology and Epidemiology"*. New York: Springer-Verlag.

Fenichel, E., C. Castillo-Chavez, M. Ceddia, G. Chowell, P. G. P. G. Hickling, G. Holloway, R. Horan, B. Morin, C. Perrings, M. Springborn, L. Velazquez, and C. Villalobosi (2011). "Adaptive human behavior in epidemiological models". *Proceedings of the National Academy of the Sciences 108*, 6306–6311.

Friedman, M. (1969). *"The Optimum Quantity of Money and Other Essays"*, Chapter "The Optimum Quantity of Money", pp. 1–50. Chicago: Adline Publishing Company.

Galí, J., F. Smets, and R. Wouters (2011, May). Unemployment in an estimated new keynesian model. Working Paper 17084, National Bureau of Economic Research.

Gelain, P. and P. Ilbas (2017). Monetary and macroprudential policies in an estimated model with financial intermediation. *Journal of Economic Dynamics and Control 78*(C), 164–189.

Gertler, M. and P. Karadi (2011). A model of unconventional monetary policy. *Journal of Monetary Economics 58*(1), 17 – 34. Carnegie-Rochester Conference Series on Public Policy: The Future of Central Banking April 16-17, 2010.

Gertler, M. and N. Kiyotaki (2010). Chapter 11 - financial intermediation and credit policy in business cycle analysis. Volume 3 of *Handbook of Monetary Economics*, pp. 547 – 599. Elsevier.

Gualdi, S., M. Tarzia, F. Zamponi, and J.-P. Bouchaud (2015). Tipping points in macroeconomic agent-based models. *Journal of Economic Dynamics and Control 50*, 29 – 61. Crises and Complexity.

Guerrieri, V., G. Lorenzoni, L. Straub, and I. Werning (2020, April). Macroeconomic implications of covid-19: Can negative supply shocks cause demand shortages? Working Paper 26918, National Bureau of Economic Research.

He, D., S. Zhao, Q. Lin, Z. Zhuang, P. Cao, M. H. Wang, and L. Yang (2020). The relative transmissibility of asymptomatic covid-19 infections among close contacts. *International Journal of Infectious Diseases 94*, 145 – 147.

Heffernan, J., R. Smith, and L. Wahl (2005). "Perspectives on the basic reproductive ratio". *Journal of the Royal Society Interface 2*, 281–293.

Hethcote, H. (2000). "The Mathematics of Infectious Diseases". *SIAM Review 42*(4), 599–653.

Horan, R. and E. Fenichel (2007). "Economics and ecology of managing emerging infectious animal diseases". *American Journal of Agricultural Economics 89*, 1232–1238.

Horan, R. and C. Wolf (2005). "The economics of managing infectious wildlife disease". *American Journal of Agricultural Economics 87*, 537–551.

Horan, R. D., E. P. Fenichel, C. A. Wolf, and B. M. Gramig (2010). Managing infectious animal disease systems. *Annual Review of Resource Economics 2*(1), 101–124.

IMF (2020). World Economic Outlook: A Long and Difficult Ascent. World Economic Outlook 1, International Monetary Fund.

Jones, K., N. Patel, M. Levy, A. Storeygard, D. Balk, and P. D. J.L. Gittleman (2008). "Global trends in emerging infectious diseases". *Nature 451*, 990–993.

Kaplan, G., B. Moll, and G. L. Violante (2020, September). The great lockdown and the big stimulus: Tracing the pandemic possibility frontier for the u.s. Working Paper 27794, National Bureau of Economic Research.

Khan, A., M. Naveed, M. Dur-E-Ahmad, and M. Imran (2015). "Estimating the basic reproductive ratio for the Ebola outbreak in Liberia and Sierra Leone". *Infectious Diseases of Poverty 4*, 13.

Kiley, M. T. (2020, Oct). Pandemic Recession Dynamics: The Role of Monetary Policy in Shifting a U-Shaped Recession to a V-Shaped Rebound. Finance and Economics Discussion Series 2020-083, Board of Governors of the Federal Reserve System (U.S.).

Krueger, D., H. Uhlig, and T. Xie (2020, April). Macroeconomic dynamics and reallocation in an epidemic: Evaluating the "swedish solution. Working Paper 27047, National Bureau of Economic Research.

Lenhart, S. and J. Workman (2007). *"Optimal Control Applied to Biological Models"*. London: Chapman and Hall.

LePan, N. (2020). A visual history of pandemics.

Liangrong, P., W. Yang, D. Zhang, C. Zhuge, and L. Hong (2020, February). Epidemic analysis of covid-19 in china by dynamical modeling.

Ludvigson, S. C., S. Ma, and S. Ng (2020, April). Covid-19 and the macroeconomic effects of costly disasters. Working Paper 26987, National Bureau of Economic Research.

Maliszewska, M., A. Mattoo, and D. Mensbrugghe (2020, April). *The Potential Impact of COVID-19 on GDP and Trade: A Preliminary Assessment.*

Mckibbin, W. and R. Fernando (2020, April). The global macroeconomic impacts of covid-19: Seven scenarios. *SSRN Electronic Journal*.

Merton, R. C. (1973). An intertemporal capital asset pricing model. *Econometrica 41*(5), 867–887.

Mihailov, A. (2020, April). Quantifying the Macroeconomic Effects of the COVID-19 Lockdown: Comparative Simulations of the Estimated Galí-Smets-Wouters Model. Economics Discussion Papers em-dp2020-07, Department of Economics, Reading University.

Milani, F. (2021). Covid-19 outbreak, social response, and early economic effects: a global var analysis of cross-country interdependencies. *Journal of Population Economics 34*(1), 223–252.

Morin, B., C. Perrings, A. Kinzig, and S. Levin (2015). "The social benefits of private infectious disease-risk mitigation". *Theoretical Ecology 8*, 467–479.

Morin, B., C. Perrings, S. Levin, and A. Kinzig (2014). "Disease risk mitigation: The equivalence of two selective mixing strategies on aggregate contact patterns and resulting epidemic spread". *Journal of Theoretical Biology 363*, 262–270.

Prem, K., Y. Liu, T. Russell, A. Kucharski, R. Eggo, N. Davies, M. Jit, P. Klepac, S. Flasche, S. Clifford, C. Pearson, J. Munday, S. Abbott, H. Gibbs, A. Rosello, B. Quilty, T. Jombart, F. Sun, C. Diamond, and J. Hellewell (2020, March). The effect of control strategies to reduce social mixing on outcomes of the covid-19 epidemic in wuhan, china: a modelling study. *The Lancet Public Health 5*.

Qianying, C., F. Andrew, H. Dong, and Z. Feng (2016). Financial crisis, us unconventional monetary policy and international spillovers. *Journal of International Money and Finance 67*, 62 – 81.

Sharma, D., J.-P. Bouchaud, S. Gualdi, M. Tarzia, and F. Zamponi (2020, June). V-, U-, L-, or W-shaped recovery after COVID: Insights from an Agent Based Model. Papers 2006.08469, arXiv.org.

Smets, F. and R. Wouters (2007). "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach". *American Economic Review 97*(3), 586–606.

Toxvaerd, F. (2020). Equilibrium social distancing. Cambridge working papers in economics, Faculty of Economics, University of Cambridge.

Toxvaerd, F. and R. Rowthorn (2020). On the management of population immunity. Cambridge working papers in economics, Faculty of Economics, University of Cambridge.

Wu, T., C. P. A. Kinzig, J. Collins, B. Minteer, and P. Daszak (2017). "Economic growth, urbanization, globalization, and the risks of emerging infectious diseases in China: A review". *Ambio 46*, 18–29.

Yin, Z., H. An, and D. W. Shanafelt (2020, Oct). Best-fit epidemiological models for covid-19: New cases in korea.