

Central Bank of Armenia

Working Paper 21/4/08



Macroeconomic Policy during COVID-19

Vahagn Davtyan
Haykaz Igityan
Hovhannes Manukyan

April 2021

CBA Working Paper
Monetary Policy Department

Macroeconomic Policy during COVID-19

Vahagn Davtyan
Haykaz Igityan
Hovhannes Manukyan

April 2021

Abstract

The coronavirus pandemic can already be considered as one of the major humanitarian and economic disasters happened for the last hundred years. The consequences of the crisis are numerous starting from psychological effects and ending with significant economic recession. This paper investigates the economic side of pandemic by constructing a DSGE model for closed economy and incorporating health block into it. We explicitly model the reproduction rate without using a SIR model. As a result, we get endogenously determined supply and demand sides of the pandemic in the model. We do different policy experiments to understand the best policies during this shock and show that sector specific policies can bring better results compared to aggregate macroeconomic policies. Further, we introduce uncertainty into the model and show that if agents have partial information about the spread of virus, the policy should be stricter to achieve similar results of the full information case.

JEL classification: D81, E12, E52, E6, I10, I14

Keywords: COVID-19, DSGE, Health, Inequality, Monetary Policy, Macroeconomic Policy, Uncertainty

The views expressed in this paper are those of the authors and do not necessarily represent the views or policies of the Central Bank of Armenia.

Authors are grateful to Martin Galstyan, Vahagn Grigoryan, Armen Nurbekyan, Hayk Avetisyan and Gevorg Minasyan for valuable comments and constructive discussions.

Authors' E-mail Address: vahagn.davtyan@cba.am; haykaz.igityan@cba.am; hovhannes.manukyan@cba.am.

Contents

1	Introduction	3
2	Literature Review	5
3	The Model	8
3.1	Reproduction Rate and Infected	9
3.2	Households	10
3.3	Labor Market	13
3.4	Firms	14
3.5	Market clearing	15
3.6	Monetary policy	16
4	Calibration	16
5	Transmission mechanism of the health shock	17
6	Monetary Policy	19
7	Optimal Policy	19
7.1	Tax/Subsidy to Aggregate Consumption	20
7.2	Optimal Policy and Early Exit during COVID-19	21
7.3	Tax/Subsidy to Other Sector	21
7.4	Tax/Subsidy to Social Sector	22
7.5	Expanding Health Sector	23
8	Uncertainty	24
8.1	Full and Partial Information Sets	24
8.2	Optimal Policy during Uncertainty	25
9	Conclusion	27
10	Appendix	32

1 Introduction

The outbreak and the spread of coronavirus (COVID - 19) have serious world-wide impact. The crisis, like any pandemic occurred during the human history, is, first of all, humanitarian: almost 3 million deaths throughout the world were recorded by the time this paper is being written. The pandemic also has huge economic impact, (the drop in world GDP was 3.3 for 2020) coming from both production and aggregate demand sides. Public health objectives necessitate people staying home from consuming and working and, thus, production and spending must decline for a time. In order to stop the spread of the virus, many advanced and developing countries implement containment measures, including quarantine for infected people, closure of public places for gathering, restrictions to movement and travel, mandatory use of masks and so on. As a result, the economic activity declined all over the world and governments implement different kind of policies to mitigate the effects of the shock.

The pandemic, like any global shock, for example Global Financial Crisis, creates a lot of room for research and the vast and rapidly growing literature concerning the coronavirus and its economic impact serves as proof. The ongoing research is aimed to answer different policy and research questions related to pandemic. What is the nature of the shock in economic terms? Can it be considered as purely supply side shock or it also has demand components? Does the shock have permanent effects or they are only temporary? What kind of policies are more effective during the pandemic?

To answer these questions, researchers construct economic models and try to somehow incorporate health components in the model either explicitly or implicitly. In the next section we briefly present some of the papers, trying to answer the aforementioned questions.

This paper develops closed economy DSGE model by incorporating the spread of the virus into the model. The model economy is populated by Ricardian and Non Ricardian households. We divide the production into three sectors: social, health and other. To the best of our knowledge, we are the first modelling the reproduction rate as a function of economic activity without linking SIR (Susceptible, Infectious and Recovered) to the DSGE model. Because the interaction of people is intense in the social sector and, as a result, the probability of getting infected is high, consuming social good and working in social sector have more impact on the reproduction rate compared to the other sector's activity. To have the adverse effect of the pandemic on the decision of economic agents, we incorporate the spread of the virus into the utility functions of households. Infections alter the decision rules of the households, which represent both demand and supply sides effects of the pandemic. Further, we endogenize the productivity of different sectors, assuming that it depends on the number of infected people. This assumption is motivated by the fact that people, who has lost jobs due to the crisis, can disrupt their skills.

Simulations show, that health shock leads to the huge decline of the output and creates modest deflation. The response of the sectors is different and the shock results in an increase of inequality. Additional expansionary mone-

tary policy mitigates decline in output but worsens the health situation. So, monetary policy creates the trade-off between output and infections. Then the paper introduces the social planner, which tries to minimize the output loss and the number of infected. Planner has aggregate consumption tax/subsidy and a number of sector specific tools.

We show that, depending on which policy tool is used, the results can be very different. When the planner has the aggregate consumption tax, he or she is unable to solve the trade-off between output and health, similar to monetary policy. When the policy instrument is the tax rate of other or social sector, planner can achieve less decline in output and less number of infected, but inequality increases. Further, we discuss the case when the planner uses the tax rates of health sector and aggregate consumption tax as policy tools but she is constrained with the possibility of expanding the health sector. In this case, we have improvements in terms of GDP loss, number of infected and inequality. Thus, the results tell us that having a right policy tool the Ramsey planner can implement policies which are more effective in terms of less output loss and fewer number of infected people. As a final step, we incorporate the model with uncertainty, meaning that economic agents (both households and firms as well as the social planner) do not know the true number of infected people when making their decisions, particularly, their information is incomplete and they use adaptive learning to overcome this inefficiency. In this case we show that by choosing the right amount of taxation it is possible to deal with this problem effectively. Introducing uncertainty in this way is also, to our knowledge, a novelty in economic literature regarding coronavirus.

The rest of the paper is organized as follows. Section 2 presents the literature discussing the economic consequences of COVID-19. Section 3 introduces the model. Section 4 briefly presents the calibration of the model. Sections 5 - 8 discuss the results, namely, section 5 discusses the effect of the health shock, section 6 shows how expansionary monetary policy alters the results of the health shock. section 7 illustrates optimal policies and in section 8 we introduce uncertainty into the our model. Finally, section 9 concludes.

2 Literature Review

The literature on the macroeconomic implications of COVID-19 is already vast and still growing. Existing literature has addressed many aspects of the interaction between the epidemic and the economy, such as effects of COVID-19 on households and firms; COVID-19 and labor markets; aggregate macroeconomic effects of COVID-19; health, mortality, and pandemic modeling for COVID-19; social distancing and other policy responses.

Krueger et al. (2020) introduce a SIR epidemiological model into a neoclassical economy in which goods are distinguished by the degree to which they can be consumed at home rather than in a social, possibly contagious context. They demonstrate that within the model the “Swedish solution” of letting the epidemic play out without government intervention and allowing agents to shift their consumption behavior towards relatively safe sectors can lead to substantial mitigation of the economic and human costs of the COVID-19 crisis. Coibion et al. (2020a) use surveys to estimate the macroeconomic expectations of U.S. households. They find that lockdowns rather than COVID-19 infections are driving down consumption, employment, lower inflation expectations and increased uncertainty. Elenev et al. (2020) model the impact of COVID-19 as a decrease in productivity and a decline in labor supply which ultimately adversely affect firm revenue. The fall in revenue and the subsequent non-repayment of debt service obligations create corporate defaults, which might bring down financial intermediaries. Bartik et al. (2020) survey a small number of firms in the US and document that several of them have temporarily closed shop and reduced their number of employees compared to January 2020. The surveyed firms were not optimistic about the efficiency of the fiscal stimulus implemented by the government.

Kahn et al. (2020) show that firms in the US have dramatically reduced job vacancies from the second week of March 2020. The authors find, that the job vacancy declines occurred at the same time when unemployment insurance (UI) claims increased. Coibion et al. (2020b) find that the unemployment/job loss in the US is more severe than one might judge based on the rise in UI claims, which is to be expected given the low coverage rate for UI regimes in the US. Campello et al. (2020) find, that job losses have been more severe for industries with highly concentrated labor markets (where hiring is concentrated within few employers) and non-tradable sectors (construction, health services). Barrero et al. (2020) measure the reallocation of labor in response to the pandemic-induced demand response (increased hiring in delivery companies, delivery-oriented restaurant/fast food chains, technology companies).

Fernández-Villaverde and Jones (2020) analyze the data for the first two quarters of 2020. They situate different countries and US states in a two-by-two matrix, with COVID-19 deaths (high or low) on one axis and GDP loss (high or low) on the other. They show that most countries fall along the diagonal – high for both or low for both. For example, Korea, Japan, Germany, and Norway have comparatively few deaths and low macroeconomic losses, on the other hand, New York City, Lombardy, the United Kingdom, and Madrid have many

deaths and large macroeconomic losses. This illustrates the well-known point that without successful containment of the virus, there can be no sustained economic recovery. Without containment, consumers will be reluctant to go shopping. Families will be reluctant to eat out. Businesses will be reluctant to invest given this subdued consumer spending and virus-related uncertainty.

Eichenbaum et al. (2020a) study the effects of an epidemic in three standard macroeconomic models by embedding SIR model into them. They find that the neoclassical model does not rationalize the positive comovement of consumption and investment observed in recessions associated with an epidemic. Introducing monopolistic competition into the neoclassical model remedies this shortcoming even when prices are completely flexible. Finally, sticky prices lead to a larger recession, but do not fundamentally alter the predictions of the monopolistic competition model.

The pandemic-related shock inevitably entails a reduction in the consumption and output of non-health goods. However, expansionary monetary and fiscal policies in these conditions involve specific risks. Asoyan et al. (2020) find, that stimulating policy supports consumption and overall economic activity that might simultaneously be connected with the spread of virus. In other words, as stressed by the authors, government authorities should seek a balance between supporting economic activity and protecting people's health.

According to Baker et al. (2020), COVID-19 has led to massive spikes in uncertainty, and there are no close historical parallels. Because of the speed of evolution and timely requirements of data, the authors suggest that one should utilize forward-looking uncertainty measures to ascertain its impact on the economy. Using a real business cycle (RBC) model, the authors find that a COVID-19 shock leads to year-on-year contraction of GDP by 11 percent in 4th quarter of 2020. According to the authors, more than half of the contraction is caused by COVID-19-induced uncertainty.

Bianchi et al. (2020), using a VAR model, try to investigate the historical relation between unemployment, life expectancy, and mortality rates for US population. They find that shocks to unemployment are followed by statistically significant increases in mortality rates and declines in life expectancy. Using model results, they assess the long-run effects of the COVID-19 economic recession on mortality and life expectancy. Their estimates show that the size of the COVID-19-related unemployment to be between 2 and 5 times larger than the typical unemployment shock, depending on race/gender, resulting in a 3.0% increase in mortality rate and a 0.5% drop in life expectancy over the next 15 years for the overall American population.

Ellison (2020) provides a quick survey of results on the classic SIR model and variants allowing for heterogeneity in contact rates. The paper notes, that calibrating the classic model to data generated by a heterogeneous model can lead to forecasts that are biased in several ways and to understatement of the forecast uncertainty. Among the biases are that we may underestimate how quickly herd immunity might be reached, underestimate differences across regions, and have biased estimates of the impact of endogenous and policy-driven social distancing.

Acemoglu et al. (2020) introduce the feature of heterogeneity of risks across sub-populations. The different sub-populations (young, middle-aged, and old) have different infection, morbidity, and fatality rates, as well as different levels of interaction with others. These conditions give rise to targeted quarantine measures. This is because a differential lockdown between different risk groups (aggressive lockdown of older groups compared to younger ones) can reduce the number of lives lost and negative economic outcomes to a greater extent compared to uniform lockdown measures for all age groups. The authors find that with a uniform lockdown lasting 434 days, the total number of fatalities reaches 1.8 percent of the population, with economic costs of about 24.3 percent of annual GDP. On the other hand, a targeted lockdown policy lasting 230 days reduces fatalities to 1 percent of the population and the economic cost to 10 percent of annual GDP.

Berger et al. (2020) extend the baseline SIR epidemiology model to understand the role of testing and case-dependent quarantine. They bring forward the idea of increasing testing of susceptible populations to identify infected-asymptomatic patients and quarantining this segment of the population. The authors find that the targeted quarantine policy would have a lower negative impact on the economy compared to the standard uniform quarantine policy. Eichenbaum et al. (2020b) develop a SIR-based macroeconomic model where people do not know their true health state. In this environment, testing allows the government to identify infected people and quarantine them. They conclude that smart containment policies, which are a combination of testing and quarantining of infected people, would give more favorable trade-off between economic activity and public health. Chiou and Tucker (2020) try to understand the role of income inequality in moderating the effectiveness of social distancing measures taken in wake of the spread of coronavirus. They show that Americans living in higher-income regions with access to high-speed internet are more likely to comply with social distancing directives. Barrios et al. (2020) provide evidence that regions with stronger higher civic culture engaged in more voluntary social distancing.

3 The Model

This section develops three sector and two agent DSGE model, allowing to take into account COVID-19 shock and its economic implications. The basic structure of the model is as follows. There are two different types of households: Ricardian households, who can trade in asset markets and, thus, are able to smooth consumption, and non-Ricardian households, who do not hold any assets and therefore consume their disposable income every period. Households consume health and non-health goods. The latter is divided into social and other goods. Households have some monopoly power, which allows them to set the wage for the differentiated labor services they supply. Ricardian and non-Ricardian households solve the following optimization problems. Firstly, they minimize their total expenditures and decide how much consume health, social and other goods. Secondly, they maximize their utility function subject to the budget constraints. Firms in each sector use labor of Ricardian and Non-Ricardian households to produce specific type of good. We endogenize technological progress in a way to be negatively dependent on infected people. Infected is a function of reproduction number, which positively depends on social and other goods consumption, as well as working in social and other sector. Government has many tools to subsidize (tax) households and firms. The monetary authority sets the nominal interest rate via Taylor rule. The schematic representation of the model is captured in Figure 1.

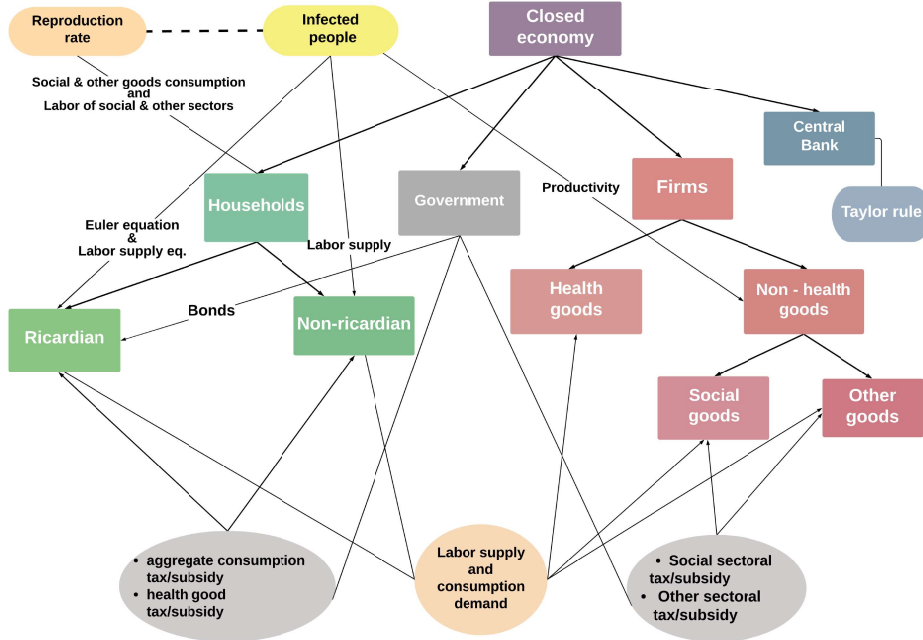


Figure 1: Model Environment

3.1 Reproduction Rate and Infected

Our model demonstrates the interaction between the behaviour of economic agents operating in the economy and the dynamics of the virus. To model the feedback from economic behavior to infections, we assume that reproduction rate (R_t) is given by the following equation:

$$\frac{R_t}{R} = \left(\frac{C_{S,t}}{C_S} \right)^{\kappa_{C,S}} \left(\frac{C_{O,t}}{C_O} \right)^{\kappa_{C,O}} \left(\frac{N_t^S}{N^S} \right)^{\kappa_{N,S}} \left(\frac{N_t^O}{N^O} \right)^{\kappa_{N,O}} \varepsilon_t^{covid-19} \quad (3.1.1)$$

where $C_{S,t}$ is social good consumption, $C_{O,t}$ is other good consumption, N_t^S is employment of social sector and N_t^O is employment of other sector. Parameters $\kappa_{C,S}$, $\kappa_{C,O}$, $\kappa_{N,S}$ and $\kappa_{N,O}$ measure elasticities of the reproduction rate to changes in social good consumption, other good consumption, employment of social sector and employment of other sector, respectively. Variables without time subscript denote their values in steady state. Reproduction rate is increasing function in its arguments because consuming and working in these sectors translate into higher transmission of the disease. The Cobb-Douglas specification captures the idea that there is a complementarity between the reduction in workplace and retail activities in containing the spread of the virus.

The law of motion of infections in the economy is given by the following function:

$$Inf_t = (1 - \delta_{rec})Inf_{t-1} + R_t^\mu \quad (3.1.2)$$

where Inf_t are infections at time t and δ_{rec} is recovery rate. R_t^μ represents the new infected and μ is the parameter linking reproduction rate to the infections. The schematic representation of the spread of the virus is captured in Figure 2.

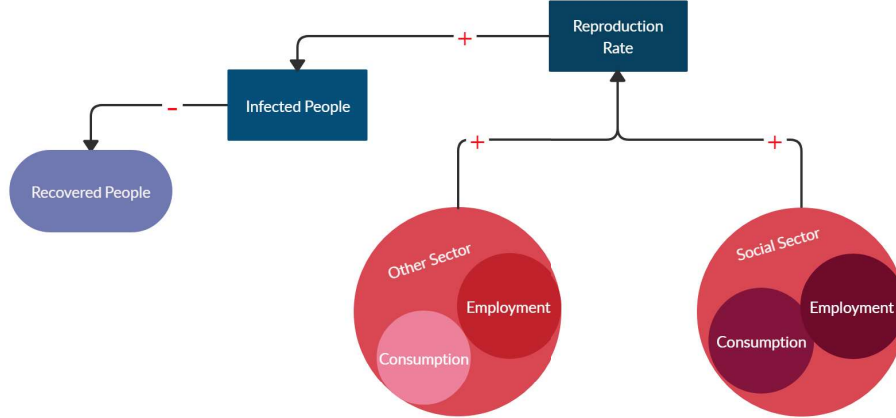


Figure 2: Reproduction Rate and Infected

3.2 Households

Consumption basket of the representative Ricardian and non-Ricardian households consists of health and non-health goods. The consumption index is represented by the following constant elasticity of substitution function.

$$C_t^R = \left[(1 - \gamma_1)^{\frac{1}{\eta_1}} (C_{H,t}^R)^{\frac{\eta_1-1}{\eta_1}} + (\gamma_1)^{\frac{1}{\eta_1}} (C_{N,t}^R)^{\frac{\eta_1-1}{\eta_1}} \right]^{\frac{\eta_1}{\eta_1-1}} \quad (3.2.1)$$

$$C_t^{NR} = \left[(1 - \gamma_2)^{\frac{1}{\eta_2}} (C_{H,t}^{NR})^{\frac{\eta_2-1}{\eta_2}} + (\gamma_2)^{\frac{1}{\eta_2}} (C_{N,t}^{NR})^{\frac{\eta_2-1}{\eta_2}} \right]^{\frac{\eta_2}{\eta_2-1}} \quad (3.2.2)$$

where, $C_{H,t}^i$ is consumption of health goods, $C_{N,t}^i$ is consumption of non-health goods ($i = R, NR$), γ_1 and γ_2 are the shares of non-health goods for Ricardian and non-Ricardian households respectively, η_1 and η_2 are the elasticity of substitution between these two types of goods. By maximizing (3.2.1) and (3.2.2) subject to the budget constraints $P_{H,t}C_{H,t}^R + P_{N,t}C_{N,t}^R = P_t^R C_t^R$ and $P_{H,t}C_{H,t}^{NR} + P_{N,t}C_{N,t}^{NR} = P_t^{NR} C_t^{NR}$, we obtain the following consumption demand functions

$$C_{H,t}^R = (1 - \gamma_1) \left(\frac{P_{H,t}}{P_t^R} \right)^{-\eta_1} C_t^R \quad (3.2.3)$$

$$C_{N,t}^R = \gamma_1 \left(\frac{P_{N,t}}{P_t^R} \right)^{-\eta_1} C_t^R \quad (3.2.4)$$

$$C_{H,t}^{NR} = (1 - \gamma_2) \left(\frac{P_{H,t}}{P_t^{NR}} \right)^{-\eta_2} C_t^{NR} \quad (3.2.5)$$

$$C_{N,t}^{NR} = \gamma_2 \left(\frac{P_{N,t}}{P_t^{NR}} \right)^{-\eta_2} C_t^{NR} \quad (3.2.6)$$

Equations (3.2.3) - (3.2.6) show that the demands for both health and non-health goods depend on the relative prices of each good. The CPI (defined as the minimum expenditure required to buy one unit of C_t^i) is given by the following functions:

$$P_t^R = \left[(1 - \gamma_1) P_{H,t}^{1-\eta_1} + \gamma_1 P_{N,t}^{1-\eta_1} \right]^{\frac{1}{1-\eta_1}} \quad (3.2.7)$$

$$P_t^{NR} = \left[(1 - \gamma_2) P_{H,t}^{1-\eta_2} + \gamma_2 P_{N,t}^{1-\eta_2} \right]^{\frac{1}{1-\eta_2}} \quad (3.2.8)$$

where, $P_{N,t}$ is the aggregate price index of non-health goods and $P_{H,t}$ is the aggregate price index of health goods.

Consumption baskets of non-health goods are given by a composite consumption index defined as follows:

$$C_{N,t}^R = \left[(1 - \gamma_3)^{\frac{1}{\eta_3}} (C_{S,t}^R)^{\frac{\eta_3-1}{\eta_3}} + (\gamma_3)^{\frac{1}{\eta_3}} (C_{Other,t}^R)^{\frac{\eta_3-1}{\eta_3}} \right]^{\frac{\eta_3}{\eta_3-1}} \quad (3.2.9)$$

$$C_{N,t}^{NR} = \left[(1 - \gamma_4)^{\frac{1}{\eta_4}} (C_{S,t}^{NR})^{\frac{\eta_4-1}{\eta_4}} + (\gamma_4)^{\frac{1}{\eta_4}} (C_{Other,t}^{NR})^{\frac{\eta_4-1}{\eta_4}} \right]^{\frac{\eta_4}{\eta_4-1}} \quad (3.2.10)$$

where, $C_{S,t}^i$ and $C_{Other,t}^i$ are respectively consumption of social and other goods. Demand functions of social and other goods are derived by maximizing (3.2.9) and (3.2.10) subject to following budget constraints $P_{S,t}C_{S,t}^R + P_{Other,t}C_{Other,t}^R = P_{N,t}^R C_{N,t}^R$ and $P_{S,t}C_{S,t}^{NR} + P_{Other,t}C_{Other,t}^{NR} = P_{N,t}^{NR} C_{N,t}^{NR}$. Demand functions get the following forms.

$$C_{S,t}^R = (1 - \gamma_3) \left(\frac{P_{S,t}}{P_{N,t}^R} \right)^{-\eta_3} C_{N,t}^R \quad (3.2.11)$$

$$C_{Other,t}^R = \gamma_3 \left(\frac{P_{Other,t}}{P_{N,t}^R} \right)^{-\eta_3} C_{N,t}^R \quad (3.2.12)$$

$$C_{S,t}^{NR} = (1 - \gamma_4) \left(\frac{P_{S,t}}{P_{N,t}^{NR}} \right)^{-\eta_4} C_{N,t}^{NR} \quad (3.2.13)$$

$$C_{Other,t}^{NR} = \gamma_4 \left(\frac{P_{Other,t}}{P_{N,t}^{NR}} \right)^{-\eta_4} C_{N,t}^{NR} \quad (3.2.14)$$

The price indexes of non-health goods are given by

$$P_{N,t}^R = \left[(1 - \gamma_3) P_{S,t}^{1-\eta_3} + \gamma_3 P_{Other,t}^{1-\eta_3} \right]^{\frac{1}{1-\eta_3}} \quad (3.2.15)$$

$$P_{N,t}^{NR} = \left[(1 - \gamma_4) P_{S,t}^{1-\eta_4} + \gamma_4 P_{Other,t}^{1-\eta_4} \right]^{\frac{1}{1-\eta_4}} \quad (3.2.16)$$

where, $P_{S,t}$ and $P_{Other,t}$ are price indexes of social and other goods.

We assume, that domestic economy consists of infinitely lived households, which maximize their lifetime utility subject to a budget constraint. We distinguish between Ricardian and non-Ricardian types of households, which is important for capturing proper dynamics in the model. Non-Ricardians do not have an access to the bond market and they consume all the received income in each period. Ricardians, on the other hand, smooth their consumption by changing their stock of assets.

Ricardian household maximizes it's utility function.

$$\max_{\{C_{R,t}, N_{R,t}, B_t\}} E_0 \sum_{t=0}^{\infty} \beta^t \left(\ln f_t^{\omega_R} \frac{C_{R,t}^{1-\sigma_R}}{1-\sigma_R} - \ln f_t^{\nu_R} \chi_R \frac{N_{R,t}^{1+\varphi_R}}{1+\varphi_R} \right) \quad (3.2.17)$$

subject to the budget constraint of the following form:

$$\frac{P_{R,t}}{P_t} (1 - \tau_{1,t}) C_{R,t} + \frac{B_t}{P_t} = \frac{W_{R,t}}{P_t} N_{R,t} + \frac{1 + r_{t-1}}{P_t} B_{t-1} + \frac{\Pi_t}{P_t}, \quad (3.2.18)$$

where, E_0 is the expectation operator conditional on information available at the current time, $C_{R,t}$ is the real consumption of Ricardian household, $N_{R,t}$ is the working hours of Ricardian household, B_t is domestic one period bond held by the household, r_t is the risk free nominal interest rate, $W_{R,t}$ is the nominal wage of Ricardian household, $\tau_{1,t}$ is the consumption subsidy. Π_t is the profits of firms owned by households, β is the discount factor, σ_1 is the elasticity of intertemporal substitution for consumption, φ_1 is the inverse of the Frisch elasticity of labor supply and χ_R is the disutility from working. Infections, defined above, is presented in the utility function as a consumption preference and labor supply shifts, which represents both the demand and supply sides of the pandemic.

Non-Ricardian households maximize similar utility function:

$$\max_{\{C_{NR,t}, N_{NR,t}\}} E_0 \sum_{t=0}^{\infty} \beta^t \left(\ln f_t^{\omega_{NR}} \frac{C_{NR,t}^{1-\sigma_{NR}}}{1-\sigma_{NR}} - \ln f_t^{\nu_{NR}} \chi_{NR} \frac{N_{NR,t}^{1+\varphi_{NR}}}{1+\varphi_{NR}} \right) \quad (3.2.19)$$

However, they have budget constraint of different form represented by:

$$\frac{P_{NR,t}}{P_t} (1 - \tau_{1,t}) C_{NR,t} = \frac{W_{NR,t}}{P_t} N_{NR,t} \quad (3.2.20)$$

Solving the optimization problems of the households and combining first order conditions, we get the following optimality conditions:

$$C_{R,t}^{\sigma} = \frac{1}{\beta} \left(\frac{\ln f_{t+1}}{\ln f_t} \right)^{-\omega_R} C_{R,t+1}^{\sigma} \pi_{t+1} i_t^{-1} \frac{1 - \tau_{1,t+1}}{1 - \tau_{1,t}} \quad (3.2.21)$$

$$\chi_R N_{R,t}^{\varphi_1} C_{R,t}^{\sigma_1} (1 - \tau_{1,t}) = MRS_{R,t} \frac{1}{\ln f_t^{\nu_R - \omega_R}} \quad (3.2.22)$$

$$\chi_{NR} N_{NR,t}^{\varphi_2} C_{NR,t}^{\sigma_2} (1 - \tau_{1,t}) = MRS_{NR,t} \frac{1}{\ln f_t^{\nu_{NR} - \omega_{NR}}} \quad (3.2.23)$$

where π_t is the inflation rate, $MRS_{R,t}$ and $MRS_{NR,t}$ are the marginal rate of substitution between consumption and hours for Ricardian and non-Ricardian households respectively. The Euler equation (3.2.21) shows that consumption depends negatively on the number of infected at time t and positively on the expected number infected people $\left(\frac{\ln f_{t+1}}{\ln f_t} \right)^{-\omega_R}$ ($\omega_R < 0$). People reduce their consumption in order to decrease the spread of the virus affecting reproduction

rate. In labor supply equations the presence of the rate of infected dictates the same intuition as the reduction of consumption ($\nu_R - \omega_R > 0$, $\nu_{NR} - \omega_{NR} > 0$). Thus, the presence of infections in (3.2.21)-(3.2.23) illustrates both demand and supply side effects of the pandemic.

3.3 Labor Market

Households have some monopoly power, which allows them to set the wage for the differentiated labor services they supply to labor organizations. The latter combine differentiated labor services to homogeneous labor and supply to firms according to the following Dixit-Stiglitz CES function:

$$N_{i,t} = \left[\int_{j=0}^{\infty} N(j)_{i,t}^{1-\frac{1}{\varepsilon_i^w}} dj \right]^{\frac{\varepsilon_i^w}{\varepsilon_i^w-1}} \quad (3.3.1)$$

where ε_i^w is the elasticity of substitution between varieties of supplied labor, $i = \{R, NR\}$.

Labor organization seeks to minimize expenditures associated with hiring each type of labor:

$$W_{i,t}N_{i,t} - W(j)_tN(j)_t \rightarrow \min \quad (3.3.2)$$

subject to (3.3.1). Solving labor organization's optimization problem, we are left with demand equation for j -th type of labor:

$$N(j)_{i,t} = \left(\frac{W(j)_{i,t}}{W_{i,t}} \right)^{-\varepsilon_i^w} N_{i,t} \quad (3.3.3)$$

where the aggregate wage index is given by:

$$W_{i,t} = \left[\int_{j=0}^{\infty} W(j)_{i,t}^{1-\varepsilon_i^w} dj \right]^{\frac{1}{1-\varepsilon_i^w}} \quad (3.3.4)$$

According to Calvo (1983), it is assumed that in a given period only a $(1 - \theta_i^w)$ fraction of households can reset new wages. Parameter θ_i^w shows wage stickiness. So, households set optimal wage in a way that they cannot change it in the future. Solving wage setting problem, Phillips curve for wage inflation gets the form:

$$\pi_{i,t}^w = \beta \pi_{i,t+1}^w + \lambda_i^w (mrs_{i,t} - (w_{i,t} - p_{i,t})) \quad (3.3.5)$$

where

$$\lambda_i^w = \frac{(1 - \beta \theta_i^w)(1 - \theta_i^w)}{\theta_i^w (1 + \varepsilon_i^w \varphi_i)} \quad (3.3.6)$$

Equation (3.3.5) makes it clear, that when the average wage in the economy is below the desired markup, households, readjusting their nominal wage, tend to increase the latter, thus generating positive wage inflation.

Taking the identity that $\pi_{i,t}^w = W_{i,t} - W_{i,t-1}$, real wage can be defined by the following equation:

$$w_{i,t}^r = w_{i,t-1}^r + \pi_{i,t}^w - \pi_t \quad (3.3.7)$$

3.4 Firms

On the production side, there are three sectors: health good sector, social good sector and other good sector. Intermediate goods producers in each sector use Ricardian and Non-Ricardian households' labor to produce the specific type of good. They operate in a monopolistic competitive environment and use the production function given as follows:

$$Y_{i,t} = A_{i,t} N_{i,t} \quad (3.4.1)$$

where $A_{i,t}$ is the cyclical technological process and $N_{i,t}$ is labor hours represented by CES function, $i = \{H, S, O\}$:

$$N_{i,t} = \left[(1 - \gamma_i)^{\frac{1}{\eta_i}} N_{i,R,t}^{\frac{\eta_i-1}{\eta_i}} + \gamma_i^{\frac{1}{\eta_i}} N_{i,NR,t}^{\frac{\eta_i-1}{\eta_i}} \right]^{\frac{\eta_i}{\eta_i-1}} \quad (3.4.2)$$

The COVID-19 pandemic has seriously disrupted skills across sectors of the economy, because due to a coronavirus the number of people lost their jobs. For modeling skill disruption, we endogenize technological process of social sector and other sector, which negatively depend on infections:

$$A_{j,t} = A_j^* + (1 - \delta_j) A_{j,t-1} - g_j Inf_t^{\zeta_j} \quad j = \{S, O\} \quad (3.4.3)$$

where A_j^* is the steady state value of productivity, δ_j is the depreciation rate of productivity stock and g_j, ζ_j are parameters linking infections to productivity process. Schematic representation of productivity process is represented in Figure 3.

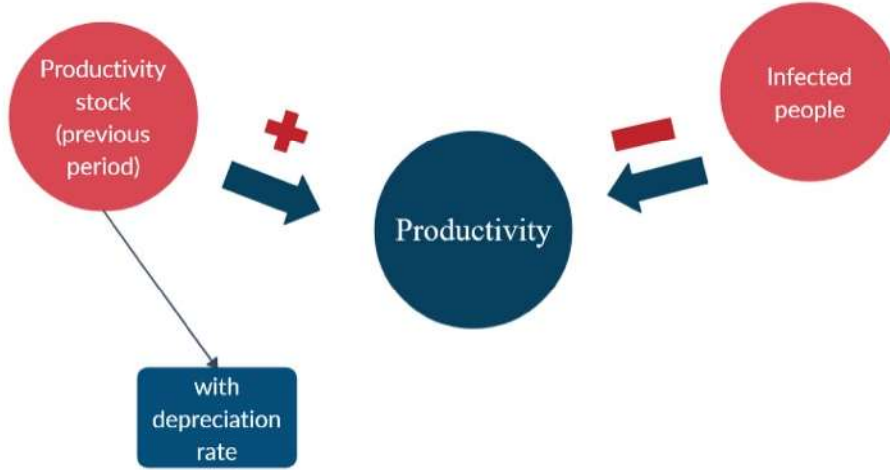


Figure 3: Endogenous technology

Firms in each sector solve cost minimization problem:

$$W_t^R N_{i,t}^R + W_t^{NR} N_{i,t}^{NR} \rightarrow \min \quad (3.4.4)$$

subject to

$$Y_{i,t} = A_{i,t} N_{i,t} \quad (3.4.5)$$

$$N_{i,t} = \left[(1 - \gamma_i)^{\frac{1}{\eta_i}} N_{i,R,t}^{\frac{\eta_i-1}{\eta_i}} + \gamma_i^{\frac{1}{\eta_i}} N_{i,NR,t}^{\frac{\eta_i-1}{\eta_i}} \right]^{\frac{\eta_i}{\eta_i-1}} \quad (3.4.6)$$

FOCs of the problem are represented by the followings:

$$W_t^R - \mu_{i,t} P_{i,t} A_{i,t} \left[(1 - \gamma_i)^{\frac{1}{\eta_i}} N_{i,R,t}^{\frac{\eta_i-1}{\eta_i}} + \gamma_i^{\frac{1}{\eta_i}} N_{i,NR,t}^{\frac{\eta_i-1}{\eta_i}} \right]^{\frac{1}{\eta_i-1}} (1 - \gamma_i)^{\frac{1}{\eta_i}} N_{i,R,t}^{-\frac{1}{\eta_i}} = 0 \quad (3.4.7)$$

$$W_t^{NR} - \mu_{i,t} P_{i,t} A_{i,t} \left[(1 - \gamma_i)^{\frac{1}{\eta_i}} N_{i,R,t}^{\frac{\eta_i-1}{\eta_i}} + \gamma_i^{\frac{1}{\eta_i}} N_{i,NR,t}^{\frac{\eta_i-1}{\eta_i}} \right]^{\frac{1}{\eta_i-1}} (\gamma_i)^{\frac{1}{\eta_i}} N_{i,NR,t}^{-\frac{1}{\eta_i}} = 0 \quad (3.4.8)$$

where $\mu_{i,t} = mc_{i,t}$ is marginal cost in each sector. In marginal cost equations we include subsidies that firms get from the government. Intuition dictates, that when the government subsidizes the one sector, this enables firms operating in the sector to reduce prices and become more competitive compared to the other sectors' firms.

Combining (3.2.7) with (3.2.8), we have:

$$\frac{W_t^R}{W_t^{NR}} = \left(\frac{1 - \gamma_i}{\gamma_i} \right)^{\frac{1}{\eta_i}} \left(\frac{N_{i,R,t}}{N_{i,NR,t}} \right)^{-\frac{1}{\eta_i}} \quad (3.4.9)$$

Firms set prices following Calvo (1983): in a given period only a $(1 - \theta)$ fraction of intermediate firms can re-optimize their prices. Solving the price setting problem, we derive Phillips curve in each sector:

$$\pi_{i,t} = \beta \pi_{i,t+1} + \lambda_i mc_{i,t} \quad (3.4.10)$$

where

$$\lambda_i = \frac{(1 - \beta \theta_i)(1 - \theta_i)}{\theta_i} \quad (3.4.11)$$

3.5 Market clearing

Goods market clearing requires the aggregate output to be equal to aggregate demand, i.e. to the sum of Ricardian and non-Ricardian households consumption:

$$Y_t = C_t^R + C_t^{NR} \quad (3.5.1)$$

where

$$Y_t = \frac{P_{S,t}}{P_t} Y_{S,t} + \frac{P_{H,t}}{P_t} Y_{H,t} + \frac{P_{O,t}}{P_t} Y_{O,t} \quad (3.5.2)$$

The labor market is in equilibrium when the labor demanded by intermediate goods firms is satisfied by the labor supplied by Ricardian and non-Ricardian households:

$$N_t^R = N_{H,t}^R + N_{S,t}^R + N_{O,t}^R \quad (3.5.3)$$

$$N_t^{NR} = N_{H,t}^{NR} + N_{S,t}^{NR} + N_{O,t}^{NR} \quad (3.5.4)$$

3.6 Monetary policy

To complete the model, we add an equation for interest rate determined as a monetary policy rule. Monetary authority operates with a Taylor (1993) type interest rate rule, which is expressed by following equation

$$\frac{R_t}{R^{ss}} = \left(\frac{R_{t-1}}{R^{ss}} \right)^{\rho_r} \left\{ \left(\frac{\Pi_{t+1}}{\Pi_{ss}} \right)^{\mu_\pi} \left(\frac{Y_{t+1}}{Y_{ss}} \right)^{\mu_y} \right\}^{(1-\rho_r)}. \quad (3.6.1)$$

The Central bank is forward looking with an interest rate persistence component and responds to inflation expectations and the future output gap.

4 Calibration

In this section we report our choice of parameters. The model is calibrated on a weekly basis. The calibration of the model is general and most of the parameter values are taken from DSGE literature. First, we discuss the parameters related to reproduction rate. Parameters $\kappa_{C,S}$, $\kappa_{N,S}$, $\kappa_{C,O}$ and $\kappa_{N,O}$, which are the elasticities of the reproduction rate to changes in social good consumption, employment of social sector, other good consumption and employment of other sector, are taken 1, 1.2, 0.5 and 0.8, respectively. This calibration is very close to values used in Kaplan et al (2020). These parameter values are set in a way that working and consuming in social sector leads to more infected cases. Recovery rate $\delta_{rec} = 0.4$, representing the average duration of infection of 2.5 weeks (Eichenbaum et al., 2020b).

The values of parameters in the utility function relating to the epidemics $\omega_R, \nu_R, \omega_{NR}, \nu_{NR}$ are all negative demonstrating that the increase of infected people leads to a decrease of consumption and labor supply. Thus, we set the following values: $\omega_R = -9.5$, $\nu_R = -5.9$, $\omega_{NR} = -4.5$ and $\nu_{NR} = -3$. Indeed, we don't know true values of these parameters, but we set these values in a way that $\nu_R - \omega_R > \nu_{NR} - \omega_{NR} > 0$ showing that the increase of infected people decreases labor supply more in Ricardian than non-Ricardian households, because poor households are not able to smooth their consumption.

For the rest of the parameters presented in the model we set following values. Risk aversion parameters σ_R and σ_{NR} for Ricardian and non-Ricardian households are 1.5 and 1, respectively, implying that Ricardians are more risk averse. Labor supply elasticity parameters are set $\varphi_R = 2$ and $\varphi_{NR} = 1.5$. Here we assume that non-Ricardian households are more sensitive to wage rate changes. Weekly discount factor is set to $\beta = 0.99^{1/13}$. Price stickiness parameters are equal $\theta_H = 0.94$, $\theta_S = 0.96$ and $\theta_O = 0.92$ (prices change on average once a year). Wage stickiness parameters for Ricardian and non-Ricardian households are set $\theta_R^w = 0.25$ and $\theta_{NR}^w = 0.23$ ¹. Following wide range of literature (Gali and Monacelli (2005), Christiano et al. (2011), etc.), we set ε_S , ε_H and ε_O (the elasticity of substitution among intermediate goods for social, health and

¹We could have fully flexible labor market and still obtain our main results. Simulations are available upon request.

other sector, respectively) to 6 implying 20% mark-up in steady state. The elasticities of substitution between varieties of supplied labor for Ricardian and non-Ricardian households are equal $\varepsilon_w^R = 3$ and $\varepsilon_w^{NR} = 12$, respectively. The intuition behind these values is that Ricardian households are more skilled and their supplied labor is less substitutable compared to non-Ricardian labor services.

Share of non-Ricardian labor in social sector is $\alpha_s^{NR} = 0.7$, indicating the fact that low skilled workers are mostly employed in the social sector. On the contrary, Ricardian labor predominates in the other sector ($\alpha_o^{NR} = 0.4$). Equal weights are given to the Ricardian and non-Ricardian labor forces in the health sector, $\alpha_h^{NR} = 0.5$. The choice of these parameter values is consistent with empirical evidence (see Table 2 in Appendix). Depreciation rates of productivity stocks for social and other sectors are equal $\delta_S = 0.2$ and $\delta_O = 0.05$. Here the assumption is made that skill disruption existing in social sector has a lower persistence than in other sector, because on average workers in other sector, who have lost their job due to a coronavirus, regain their skills much later than social sector employers ².

The coefficients of the reaction of interest rate to inflation expectations μ_π and output gap μ_y are set to 1.2 and 0.125, respectively. The value of the smoothing parameter in Taylor type rule ρ_r is calibrated to 0.75. This calibration is very close to values used in the literature. Table 1 in Appendix presents the calibration of all the parameters.

5 Transmission mechanism of the health shock

This section discusses the dynamics of the main variables of the model in response to health shock. As many countries subsidize health consumption during Covid-19, we apply subsidies to non-Ricardian and Ricardian health consumption simultaneously with health shock. All the graphs of impulse responses represent time in weeks (horizontal axis) and vertical axis shows percentage deviation of variables from their steady states³.

Figure 4 displays the impulse response functions to a health shock. This case forms a useful benchmark with which to compare alternative scenarios and policy interventions. Health shock increases reproduction rate which translates into higher transmission of the disease. That leads to an increase in the number of infected people. To reduce the reproduction rate Ricardian and non-Ricardian households decrease both their labor supply and consumption in social and other sectors. On the contrary, households increase their demand for health goods. To meet the additional demand, firms in health sector hire more labor. As a result, increase of production factors in health sector entails an increase of production itself. Share of health sector in total GDP is small, which results in a decline of total production due to high decrease in social and other sec-

²For example, a waiter who has lost his job due to a coronavirus can regain his skills much earlier than an engineer.

³The simulations are implemented within the Dynare software platform.

tors. Aggregate output falls, with the majority of the drop concentrated in the social sector, because we assume that probability of getting infected is higher in social sector. According to the model structure, non-Ricardian household decreases labor supply less than Ricardian one but a greater decline of demand in social sector leads to a further reduction in non-Ricardian employment. The presence of higher price stickiness in social and other sectors prevents inflation and emerges a deflation. Monetary authority reacts to deflation and negative output by decreasing interest rate modestly.

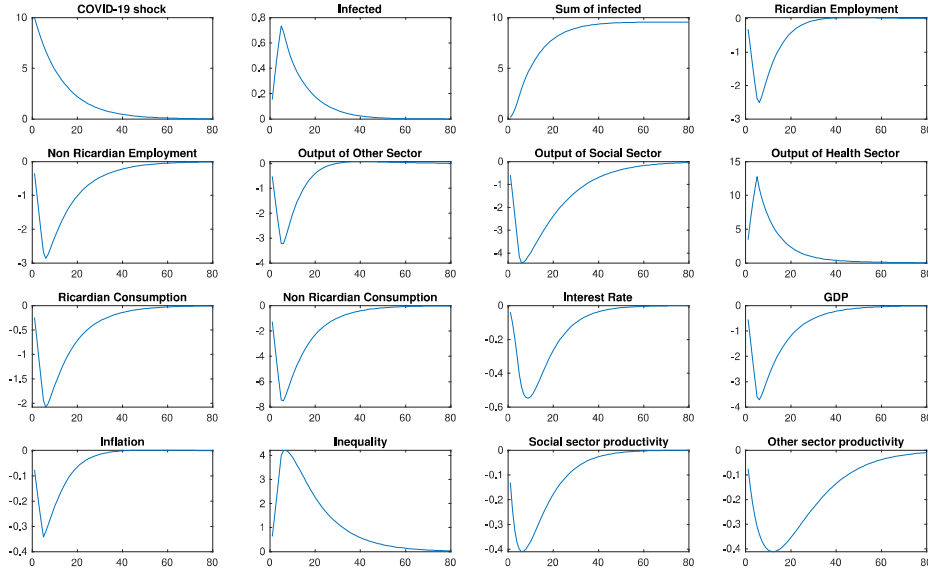


Figure 4: Impulse responses to health shock

As we mentioned above, pandemic has seriously disrupted skills across sectors of the economy, which directly affects productivity of social and other sectors. Other sector productivity requires much time to converge its steady state value compared to social sector because on average workers in other sector regain their skills much later than social sector employers. Covid-19 shock increases inequality⁴ between households for two reasons: firstly, non-Ricardian employment decreases more than Ricardian employment because of our assumption that poor households work mostly in social sector and, secondly, non-Ricardian

⁴We construct an inequality index by the wage income gap and consumption difference between Ricardian and non-Ricardian households, which is given by:

$$IN_t = \left(\frac{C_t^R}{C_t^{NR}} \right)^{\frac{1}{2}} \left(\frac{W_t^R N_t^R}{W_t^{NR} N_t^{NR}} \right)^{\frac{1}{2}}$$

households do not have savings.

6 Monetary Policy

In this section, we discuss the case, when monetary authority deviates from the previously announced interest rate rule by further decreasing nominal interest rate in response to health shock (see Figure 5). Expansionary monetary policy affects the economy through consumption/saving channel. Ricardian households increase their demand for all types of goods. Additional demand forces firms to hire both Ricardian and non-Ricardian labor. As a result, compared to the baseline case, both output and overall employment decrease less. However, higher economic activity comes with the cost of worse health conditions: the number of infected people increases. Hence, we get a trade-off between the recession severity and the health status of the epidemic. Similar phenomenon was reported in Eichenbaum et al. (2020c) and Asoyan et al. (2020).

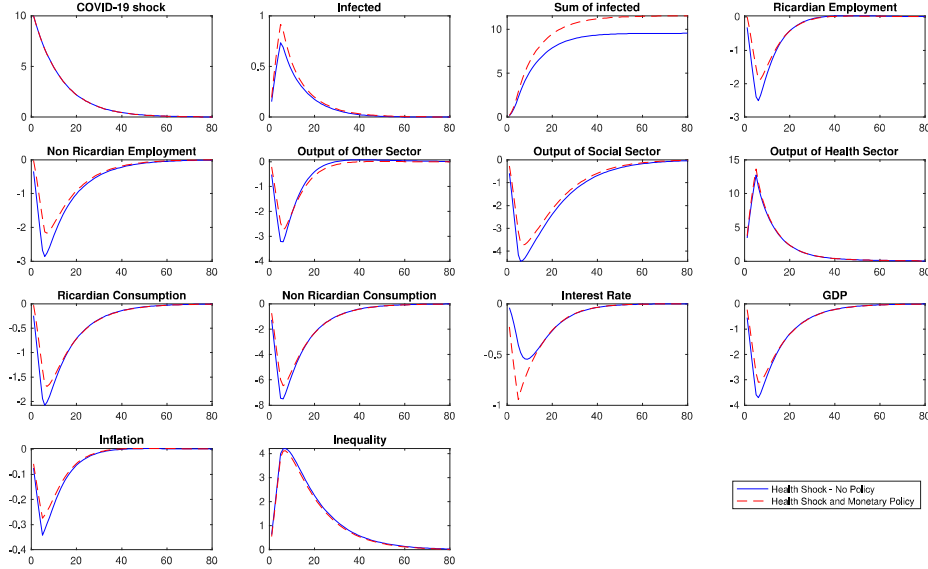


Figure 5: Expansionary monetary policy during pandemic

7 Optimal Policy

Here, we define a social planner, who seeks to minimize its objective function defined below, using both aggregate and sectoral policy tools available to him.

Particularly, in this setup as a social planner we have the government, whose objective function is to minimize the output loss and the number of infected people:

$$E_t \sum_{j=0}^{\infty} \beta^j (y_{t+j}^2 + w \times Inf_{t+j}^2) \rightarrow \min \quad (7.0.1)$$

where w is the weight of infected people in social planner's objective function.

7.1 Tax/Subsidy to Aggregate Consumption

Figure 6 presents the results of optimal Ramsey policy when the social planner uses the aggregate consumption tax as a policy tool. Blue solid line represents the baseline simulation. In the first case, Ramsey planner puts less weight on health ($w = 25$, red dotted line) in her objective function and vice versa when she cares more about health situation ($w = 100$, green dash-dotted line). In the latter case, she increases tax rate substantially compared to the case when she is more concerned with economic conditions. As a result, we have bigger output loss and less infected people. Similar to monetary policy, aggregate tax tool does not improve both GDP and health outcome leading to the creation of trade-off.

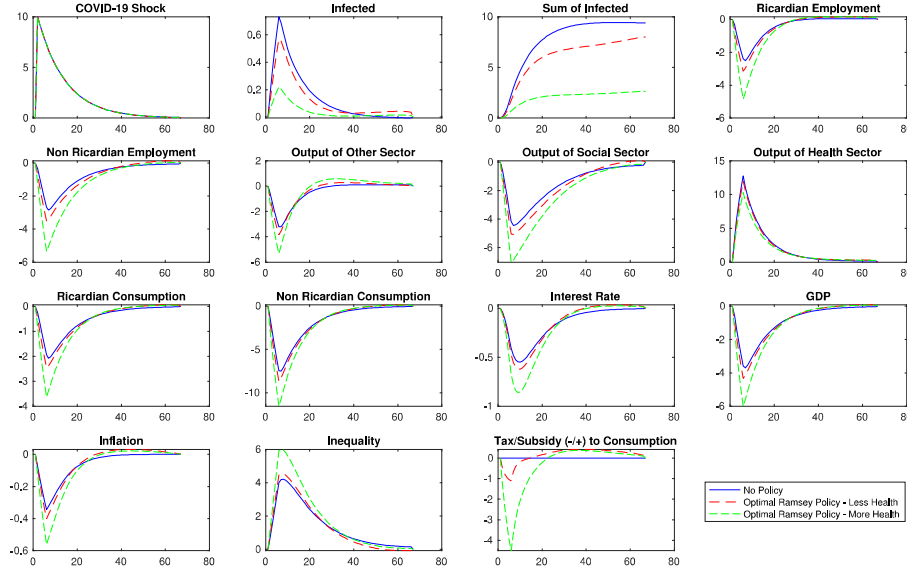


Figure 6: Optimal policy during COVID-19 - tax/subsidy to aggregate consumption

7.2 Optimal Policy and Early Exit during COVID-19

This subsection discusses the case, when Ramsey planner deviates from optimal policy path and exits earlier. Ramsey planner has tax/subsidy to aggregate consumption as a policy instrument. Saying early exit we mean that the planner after some periods stops using his policy instrument and turns it off. Figure 7 compares the simulation of early exit with baseline one and when social planner completely follows optimal policy path. In the case of early exit, the planner is able to save some decline in GDP but the increase in the number of infected people is very sharp. When planner deviates from optimal policy path, he contributes to the increase in inequality.

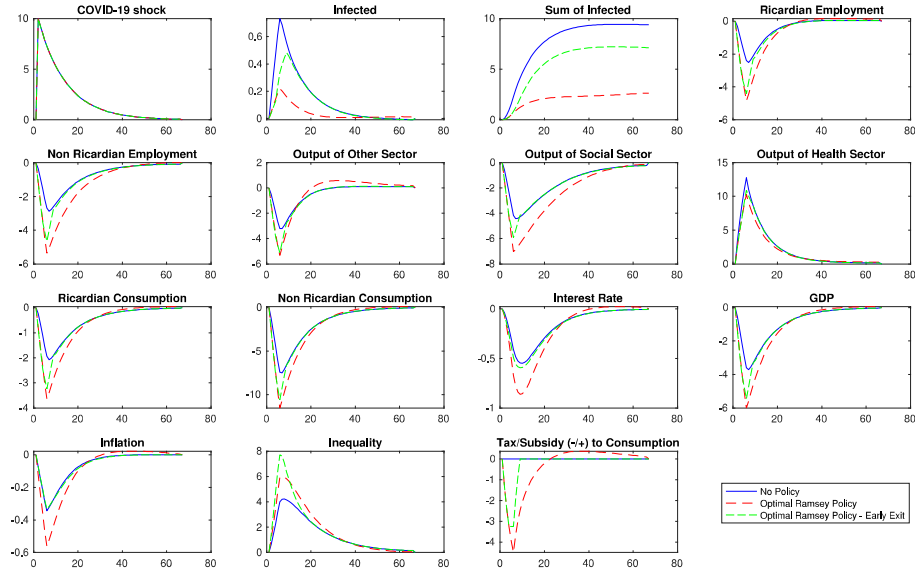


Figure 7: Optimal Ramsey policy and early exit during COVID-19

7.3 Tax/Subsidy to Other Sector

This subsection applies sectoral policy to minimize welfare losses created by health shock. Ramsey planner has tax/subsidy to other sector as a policy instrument. Figure 8 compares the mentioned simulation with the baseline one when there are no any policy interventions. Ramsey planner subsidizes and boosts other sector. As a result, planner kills social sector. The expansion of other sector means the increase of demand for Ricardian employment. On the contrary, the reduction of social sector leads to more decline in non-Ricardian employment. When the planner subsidizes other sector, it becomes more competitive

which brings on deflation in this sector. As a result, the number of infections decreases. Use of this tool results in an improvement of both economic and health conditions, which could not be achieved with aggregate macroeconomic policies. What refers to inequality, this policy always leads to the increase in inequality, because the reduction of the social sector means shrinking of non-Ricardian employment.

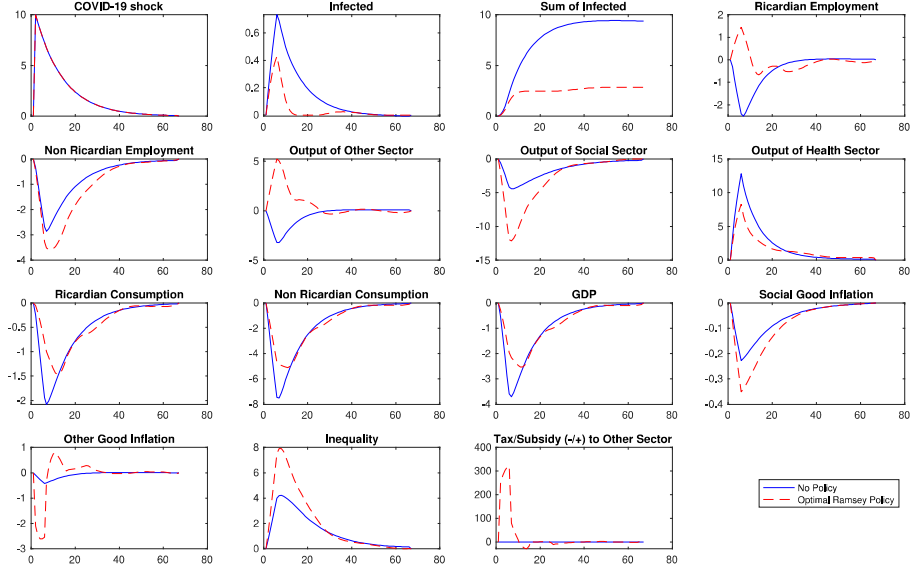


Figure 8: Optimal policy during COVID-19 - tax/subsidy to other sector

7.4 Tax/Subsidy to Social Sector

Figure 9 presents the case, when social planner changes the tax/subsidy rate imposed on social sector as a policy tool. The results are similar to the ones presented in subsection 7.3, when Ramsey planner has a tax/subsidy rate for other sector as a tool. Here, the optimal policy for planner is to tax rather than subsidize the social sector firms making them to reduce their production. Other sector becomes relatively more competitive, since higher tax rate for social sector means higher marginal costs. The transmission channel and results are similar to the previous case. Thus, though we get lower output loss and infected rate, the inequality increases since more Ricardian households are employed in the other sector.

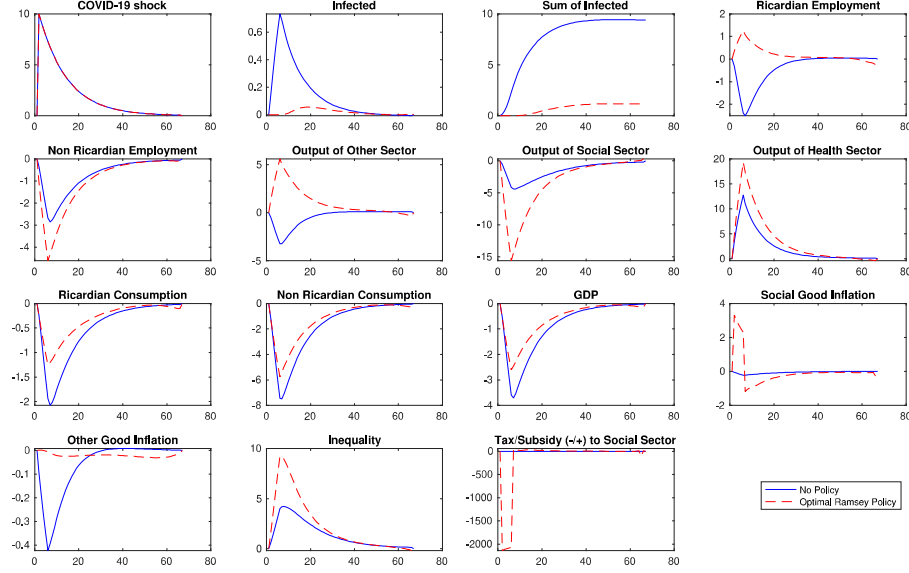


Figure 9: Optimal policy during COVID-19 - tax/subsidy to social sector

7.5 Expanding Health Sector

Here we allow Ramsey planner to have two instruments: aggregate consumption tax and tax/subsidy to health sector. In reality, countries have restricted financial resources and capacities for expanding the health sector. Therefore, we also set restrictions on how much the government can subsidize the health sector. We consider three cases: firstly, when government has few financial resources and capacities for subsidizing health sector. In the second case, government has moderate resources for health sector. And finally, government can subsidize the health sector to a large extent. Figure 10 compares aforementioned scenarios with baseline one. Simulation results show that the planner can fight the epidemic by expanding the health sector and providing aggregate consumption subsidy to households. In case of government with less resources, the planner initially keeps economic restrictions then starts to subsidize the consumption. This policy has a negative impact on GDP. Compared to the baseline scenario, there are improvements in terms of health situation in all three cases. What refers to inequality, this combination of policies leads to the decline in inequality caused by COVID-19 shock.

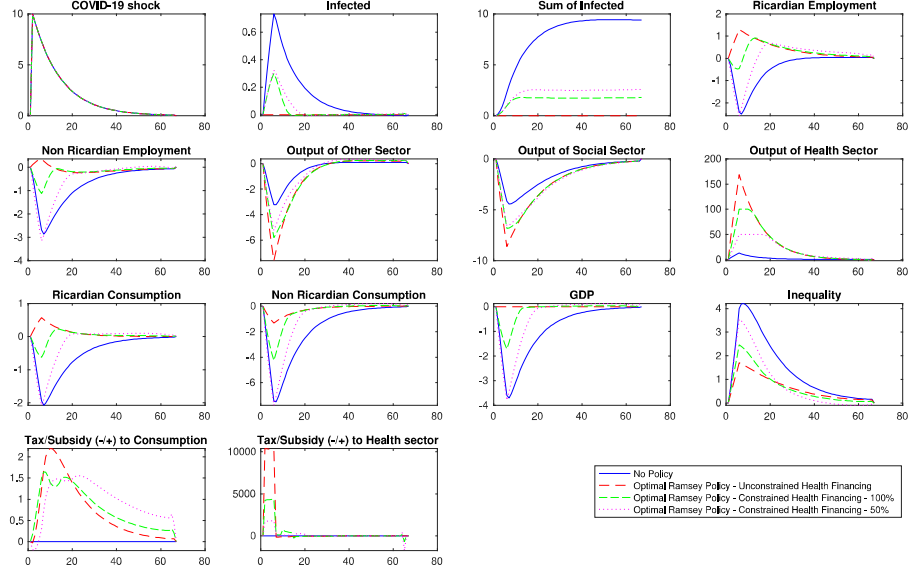


Figure 10: Optimal policy during COVID-19 - tax/subsidy to health sector

8 Uncertainty

In all our previous simulations we assume that economic agents, when making their decisions, have full information about the health situation, particularly, they always know the exact number of infected people. However, this assumption can be too strong and in reality, both economic agents and policy makers could have the incomplete picture of the pandemic. This section presents the results of model's simulations, when either only economic agents or both economic agents and social planner have partial or incomplete information about the spread of the virus. After the shock hits the economy, they use adaptive learning mechanisms⁵ to update their information sets and expectations.

8.1 Full and Partial Information Sets

First, we compare our baseline (agents have complete information about pandemic) case with the case, when economic agents have partial or incomplete information about the spread of virus. Figure 11 plots the IRFs. Size of the shock is the same in both cases. However, since in the second case people cannot observe the true situation of pandemic, they make decisions which differ from

⁵See, for example, Slobodyan and Wouters (2012a,b) and Rychalovska (2016)

the benchmark case. Particularly, since in our setup economic agents underestimate the number of infected people, they do not reduce their labor supply and consumption demand. As a result, the economy doesn't contract during the first periods following the shock and the virus spreads more rapidly. But since the time passes, agents realize the true epidemic situation and they cut consumption demand and labor supply even more to stabilize and reduce the number of infected people. To conclude, we see that under partial information setup with adaptive learning mechanisms, the effects of the shock are stronger compared to the benchmark case.

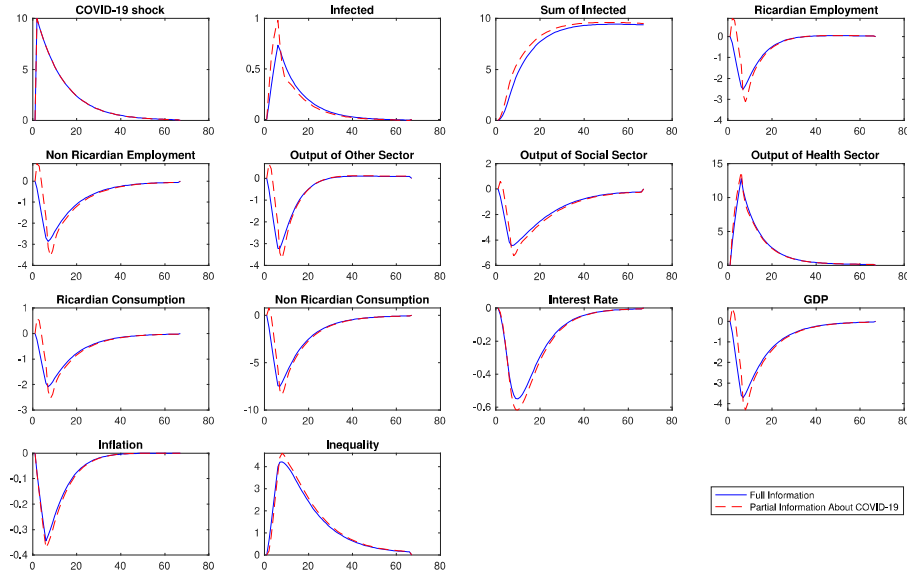


Figure 11: Full and partial information sets

8.2 Optimal Policy during Uncertainty

Having established the uncertainty we know discuss the optimal policies, when the social planner has full information in contrast to households and firms. Also we discuss the case when the social planner doesn't know the true number of infected people. In both cases, as a policy tool, the Ramsey planner has the consumption tax.

Figure 12 illustrates the first case. The graphs show that because agents' decisions deviate from the optimality, the social planner having full information and therefore, knowing exactly, what's going on in the economy should be more aggressive and impose stricter restrictions in order not to allow the number of

infected to rise more compared to the case, when all agents have full information. Moreover, by imposing higher taxes, all variables behave similar to the case with full information setup. Thus, Ramsey planner can overcome the inefficiency created by information bias with higher tax rate.

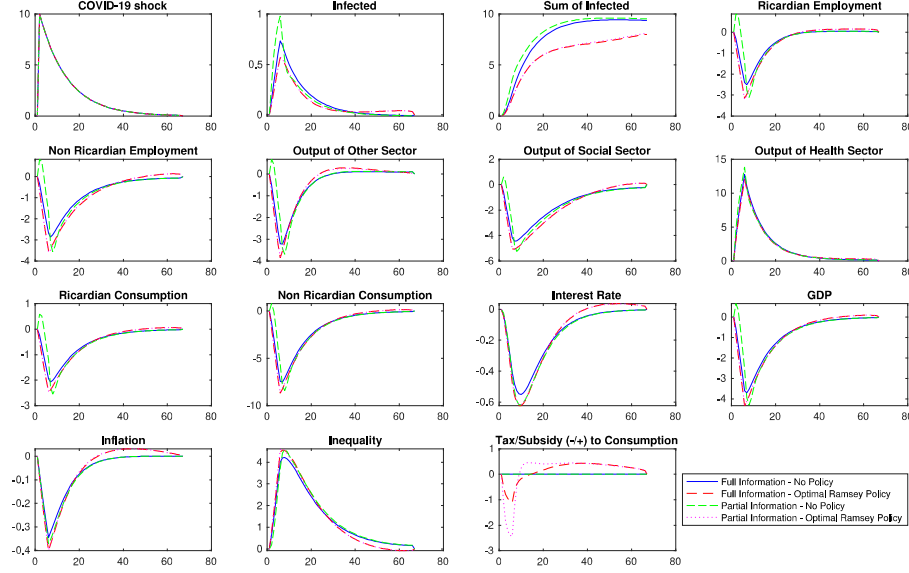


Figure 12: Optimal Ramsey policy during COVID-19 - full and partial information setup

As a last simulation, we illustrate the case when social planner has a partial information as well. Figure 13 depicts this case. As one can see, when the planner has partial information about the spread of COVID-19, it is optimal to employ stricter restrictions compared to the case with full information. Then he should significantly subsidize the economy. Nevertheless, as far as Ramsey planner doesn't have complete information about the virus, the actual realization of infected is always higher compared to the case when planner has complete information. To sum up, here, as well as in the previous case the planner can almost solve the problem of partial information by introducing the right size of restrictions.

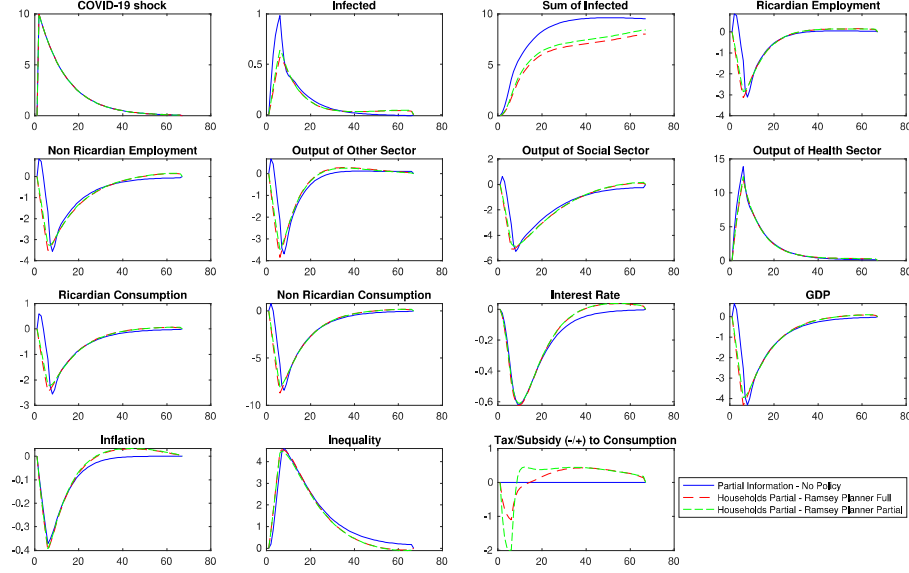


Figure 13: Optimal Ramsey policy during COVID-19 - full and partial information setup case 2

9 Conclusion

This paper incorporates the spread of the virus into New Keynesian DSGE framework. To model the interaction between the behaviour of economic agents operating in the economy and the pandemic, we model the reproduction rate varying over the course of pandemic and allowing four behavioural channels: working and consuming in social and other sectors increase reproduction rate and, hence, the number of infected people. We study the effects of the health shock on the economy. We find that an epidemic shock leads to a decrease in the consumption and production of social and other goods. The epidemic is accompanied by a moderate decline in the inflation rate and monetary authorities, following Taylor rule, decreases interest rate.

The paper analyzes the consequences of the expansionary macroeconomic policy pursued by the central bank. While the interest rate cut mitigates the loss of total output, it increases the number of infected cases demonstrating trade-off between economic activity and health consequences caused by the epidemic.

Then the paper discusses optimal policy in times of pandemic. When social planner uses aggregate consumption tax as a policy tool, he increases tax rate or, in other words, sets economic restriction in order to prevent the spread of the virus. Then we discuss the case when Ramsey planner deviates from optimal policy path and exits earlier. As a result, the planner saves some

decline in GDP but he contributes to the increase in inequality and the number of infected people. Having tax/subsidy to other sector as a policy instrument, planner boosts other sector and kills social one. In case of tax/subsidy to social sector as a policy tool, we have the similar results. What refers to inequality, these types of policies always lead to the increase in inequality, because the reduction of the social sector means shrinking of non-Ricardian employment. Furthermore, we introduce different types of health constraints and studies the behavior of optimal policy under these constraints. As a result, the more the government expands the health sector, the more improvements we obtain in terms of health situation, economic activity and inequality.

Finally, we introduce uncertainty assuming that economic agents and policy makers have partial information about true health state. Having partial information about the situation of Covid-19, agents do not react rationally, which results in a high peak of infected. After some period of time economic agents realize the size of infected and cut the consumption and employment dramatically compared to the full information case, which leads to the high level of infected number and high drop in GDP. Simulation of optimal policy shows, that social planner should be more aggressive and apply a twice higher economic restrictions. Finally, we discuss the case when Ramsey planner has a partial information as well. In this context, it is optimal to set initially strict economic restrictions then subsidize the economy more compared to the case with full information. What refers to infections, social planner with partial information brings on the higher infected cases compared to the case when planner has complete information.

References

- [1] Acemoglu, D., Chernozhukov, V., Werning, I., & Whinston, M. D. (2020). A Multi-Risk SIR Model with Optimally Targeted Lockdown (Working Paper No. 27102; Working Paper Series). National Bureau of Economic Research.
- [2] Asoyan, A., Davtyan, V., Igityan, H., Kartashyan, H. and Manukyan, H. (2020). Modelling the Effects of a Health Shock on the Armenian Economy. *Russian Journal of Money and Finance*, 79(4), pp. 18–44.
- [3] Baker, S. R., Bloom, N., Davis, S. J., & Terry, S. J. (2020). COVID-Induced Economic Uncertainty (Working Paper No. 26983; Working Paper Series). National Bureau of Economic Research.
- [4] Barrero, J. M., Bloom, N., & Davis, S. J. (2020). COVID-19 Is Also a Reallocation Shock (Working Paper No. 27137; Working Paper Series). National Bureau of Economic Research.
- [5] Barrios, John M. & Yael Hochberg, (2020). Risk Perception Through the Lens of Politics in the Time of the COVID-19 Pandemic (Working Paper No. 27008; Working Paper Series). National Bureau of Economic Research.
- [6] Bartik, A. W., Bertrand, M., Cullen, Z. B., Glaeser, E. L., Luca, M., & Stanton, C. T. (2020). How Are Small Businesses Adjusting to COVID-19? Early Evidence from a Survey (Working Paper No. 26989; Working Paper Series). National Bureau of Economic Research.
- [7] Berger, D. W., Herkenhoff, K. F., & Mongey, S. (2020). An SEIR Infectious Disease Model with Testing and Conditional Quarantine (Working Paper No. 26901; Working Paper Series). National Bureau of Economic Research.
- [8] Bianchi, F., Faccini, R., & Melosi, L. (2020). Monetary and Fiscal Policies in Times of Large Debt: Unity is Strength (Working Paper No. 27112; Working Paper Series). National Bureau of Economic Research.
- [9] Calvo Guillermo A., (1983). "Staggered prices in a utility-maximizing framework," *Journal of Monetary Economics*, Elsevier, vol. 12(3), pages 383-398, September.
- [10] Campello, M., Kankanhalli, G., & Muthukrishnan, P. (2020). Corporate Hiring under COVID19: Labor Market Concentration, Downskilling, and Income Inequality (Working Paper No. 27208; Working Paper Series). National Bureau of Economic Research.
- [11] Chiou, L., & Tucker, C. (2020). Social Distancing, Internet Access and Inequality (Working Paper No. 26982; Working Paper Series). National Bureau of Economic Research.

- [12] Christiano, Lawrence J., Mathias Trabandt & Karl Walentin, (2011), "Introducing financial frictions and unemployment into a small open economy model," *Journal of Economic Dynamics and Control*, Elsevier, vol. 35(12), pages 1999-2041.
- [13] Coibion, O., Gorodnichenko, Y., & Weber, M. (2020a). The Cost of the Covid-19 Crisis: Lockdowns, Macroeconomic Expectations, and Consumer Spending (Working Paper No. 27141; Working Paper Series). National Bureau of Economic Research.
- [14] Coibion, O., Gorodnichenko, Y., & Weber, M. (2020b). Labor Markets During the COVID-19 Crisis: A Preliminary View (Working Paper No. 27017; Working Paper Series). National Bureau of Economic Research.
- [15] Eichenbaum, M. S., Rebelo, S., & Trabandt, M. (2020a). "Epidemics in the Neoclassical and New Keynesian Models". NBER Working Paper No. 27430. National Bureau of Economic Research.
- [16] Eichenbaum, M. S., Rebelo, S., & Trabandt, M. (2020b). "The Macroeconomics of Testing and Quarantining," NBER Working Papers 27104, National Bureau of Economic Research, Inc.
- [17] Eichenbaum, M. S., Rebelo, S., & Trabandt, M. (2020c). The Macroeconomics of Epidemics (Working Paper No. 26882; Working Paper Series). National Bureau of Economic Research.
- [18] Elenev, V., Landvoigt, T., & Van Nieuwerburgh, S. (2020). Can the Covid Bailouts Save the Economy? (Working Paper No. 27207; Working Paper Series). National Bureau of Economic Research.
- [19] Ellison, G. (2020). Implications of Heterogeneous SIR Models for Analyses of COVID-19 (Working Paper No. 27373; Working Paper Series). National Bureau of Economic Research.
- [20] Fernández-Villaverde, J., & Jones, C. I. (2020). Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities (Working Paper No. 27128; Working Paper Series). National Bureau of Economic Research.
- [21] Galí Jordi & Tommaso Monacelli, (2005). "Monetary Policy and Exchange Rate Volatility in a Small Open Economy," *Review of Economic Studies*, Oxford University Press, vol. 72(3), pages 707-734.
- [22] Kahn, L. B., Lange, F., & Wiczer, D. G. (2020). Labor Demand in the Time of COVID-19: Evidence from Vacancy Postings and UI Claims (Working Paper No. 27061; Working Paper Series). National Bureau of Economic Research.

- [23] Kaplan G. & Moll B. & Violante G. L., (2020), "The Great Lockdown and the Big Stimulus: Tracing the Pandemic Possibility Frontier for the U.S," NBER Working Papers 27794, National Bureau of Economic Research, Inc.
- [24] Krueger, D., Uhlig, H., & Xie, T. (2020). Macroeconomic Dynamics and Reallocation in an Epidemic (Working Paper No. 27047; Working Paper Series). National Bureau of Economic Research.
- [25] Rychalovska, Y., (2016), "The implications of financial frictions and imperfect knowledge in the estimated DSGE model of the US economy," *Journal of Economic Dynamics and Control*, 73, 259–282.
- [26] Slobodyan, S. & Wouters, R., (2012a) "Learning in an estimated medium-scale DSGE model," *Journal of Economic Dynamics and control*, 26–46.
- [27] Slobodyan, S. & Wouters, R., (2012b), "Learning in a Medium-Scale DSGE Model with Expectations Based on Small Forecasting Models," *American Economic Journal: Macroeconomics*, 65–101.

10 Appendix

Parameter	Description	Calibration
$\kappa_{C,S}$	The elasticity of the reproduction rate to changes in social good consumption	1
$\kappa_{N,S}$	The elasticity of the reproduction rate to changes in employment of social sector	1.2
$\kappa_{C,O}$	The elasticity of the reproduction rate to changes in other good consumption	0.5
$\kappa_{N,O}$	The elasticity of the reproduction rate to changes in employment of other sector	0.8
δ_{rec}	Recovery rate	0.4
ω_R	Parameter in utility function of Ricardian households	-9.5
ν_R	Parameter in utility function of Ricardian households	-5.9
ω_{NR}	Parameter in utility function of non-Ricardian households	-4.5
ν_{NR}	Parameter in utility function of non-Ricardian households	-3
σ_R	Risk aversion parameter for Ricardian households	1.5
σ_{NR}	Risk aversion parameter for non-Ricardian households	1
φ_R	Labor supply elasticity for Ricardian households	2
φ_{NR}	Labor supply elasticity for non-Ricardian households	1.5
β	Discount factor	$0.99^{1/13}$
θ_H	Price stickiness parameter for health sector	0.94
θ_S	Price stickiness parameter for social sector	0.96
θ_O	Price stickiness parameter for other sector	0.92
θ_R^w	Wage stickiness parameters for Ricardian households	0.25
θ_{NR}^w	Wage stickiness parameters for non-Ricardian households	0.23
ε_S	The elasticity of substitution among intermediate goods for social sector	6
ε_H	The elasticity of substitution among intermediate goods for health sector	6
ε_O	The elasticity of substitution among intermediate goods for other sector	6
ε_w^R	The elasticity of substitution between varieties of supplied labor for Ricardian households	3
ε_w^{NR}	The elasticity of substitution between varieties of supplied labor for non-Ricardian households	12
δ_S	Depreciation rate of productivity stock for social sector	0.2
δ_O	Depreciation rate of productivity stock for other sector	0.05
μ_π	Reaction to inflation expectations	1.2
μ_y	Reaction to output gap	0.125
ρ_r	Persistence parameter	0.75
g_S	Parameter in endogenous productivity for social sector	1
g_O	Parameter in endogenous productivity for other sector	2
g_H	Parameter in endogenous productivity for health sector	1
ζ_S	The elasticity of social sector productivity to changes in number of infected	0.2
ζ_O	The elasticity of other sector productivity to changes in number of infected	0.1
μ	The elasticity of infected to changes in reproduction rate	0.02
γ_1^i	Share of non-health goods in total consumption	0.95
γ_2^i	Share of other goods in non-health consumption	0.6
c_R	Ricardian consumption share in total consumption	0.7
c_{NR}	Non-ricardian consumption share in total consumption	0.3
y_s	Share of social output in GDP	0.4
y_o	Share of other output in GDP	0.55
y_h	Share of health output in GDP	0.5
n_s^R	Share of social workers in Ricardian labor	0.25
n_o^R	Share of other workers in Ricardian labor	0.7
n_h^R	Share of health workers in Ricardian labor	0.05
n_s^{NR}	Share of social workers in Non-ricardian labor	0.5
n_o^{NR}	Share of other workers in Non-ricardian labor	0.45
n_h^{NR}	Share of health workers in Non-ricardian labor	0.05
α_s^{NR}	Share of non-Ricardian labor in social sector	0.7
α_o^{NR}	Share of non-Ricardian labor in other sector	0.4
α_h^{NR}	Share of non-Ricardian labor in health sector	0.5
η_1	The elasticity of substitution between health and non-health goods for Ricardians	1
η_2	The elasticity of substitution between health and non-health goods for non-Ricardians	1.1
η_3	The elasticity of substitution between social and other goods for Ricardians	1.5
η_4	The elasticity of substitution between social and other goods for non-Ricardians	1.6

Table 1: Calibration

Classification of economic activities	Less than primary, primary and lower secondary education	Upper secondary and post-secondary non-tertiary education	Tertiary education
Transportation and storage (social sector)	22%	61.8%	16.2%
Accommodation and food service activities (social sector)	32.7%	54.6%	12.7%
Information and communication (other sector)	5.6%	36%	58.4%
Professional, scientific and technical activities (other sector)	5.5%	36%	58.6%
Human health and social work activities (health sector)	14.4%	48.3%	37.4%

Source: Eurostat, EU - 27 countries

Table 2: Employees by educational attainment level