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Abstract

The COVID-19 pandemic is producing a global health and economic crisis. The entire globe is facing the trade-off between health and recessionary effects. This paper investigates this trade-off according to a macro-dynamic perspective. We set up and simulate a Dynamic Stochastic General Equilibrium model to analyze the COVID-19 contagion within an economy with endogenous dynamics for the pandemic. There are three main results. First, the macroeconomic effects of the epidemic containment measures are much severe. The negative peak in aggregate production range from 11 percent with a soft containment measure to 35 percent with a strong containment measure; second, recovery from recession emerges when the lockdown policy is relaxed. On that basis, the output would return to its pre-lockdown level by the end of 2021; third, a return infection is expected after 36 weeks from the fist contagion contributing to exacerbates the size and duration of the economic crisis.

JEL-Codes: E320, I120.

Keywords: business cycle, COVID-2019 pandemic, DSGE.

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1 Introduction

The COVID-19 (or SARS-CoV-2) outbreak is arisen in China at the start of December 2019 and spread out widely all over the world in the next weeks. The epidemic propagation is bringing considerable human losses and suffering. On the other hand, the actions to prevent infection propagation are producing economic disruption. There are several direct channels through which the virus is affecting economies: quarantines, restrictions on travel, factory closures, and a sharp decline in many service sector activities (Boone, 2020). From an economic perspective, these closures and travel bans reduce productivity directly in a way that is akin to temporary drops in employment (OECD, 2020). In addition, the decline in hours worked reduces the income entailing an additional damper on households' demand (OECD, 2020). The COVID-19 pandemic can be considered as an unprecedented shock to labor markets (Fujita et al., 2020). The epidemic has caused the economic slowdown in many economies, and the precise dimension of the recession will depend on what proportion of the population that gets infected or locked down (Simon Wren-Lewis, 2020). Therefore, policymakers face a severe trade-off between preventing deaths from COVID-19 and GDP slowdown. This paper proposes a model in which economic activity and disease progression are jointly determined and contributes to the growing literature in examining this trade-off. In particular, we ask the following questions: what are the macroeconomic effects of the epidemic containment measures? Under what conditions could it be possible to think about the recovery phase emerges? What about these recessive effects in the presence of any return infections?

In order to investigate the macroeconomic impacts of lockdown policies, this paper proposes and simulates a Dynamic Stochastic General Equilibrium (DSGE) model that is embedding a pandemic shock, a temporary lockdown policy, and variable labor utilization. We consider three lockdown policies with different degrees of size and duration of the containment measures. In our model, the pandemic is modeled as an exogenous shock, triggering a but contact-intensive activities contagions supporting affect its propagation. Besides, we provide a range of epidemiological assumptions and create a mechanism that converts the pandemic into supply and demand effects on the labor force. The transmission occurs through the epidemic containment measures that prevent the full utilization of the available labor force.

So, in our model, we use a sort of "indiscriminate quarantine" as a tool to deal with the pandemic to evaluate its costs. This need we assume (realistically) the policymaker's inability to distinguish the asymptomatic infected from the susceptible but still unaffected. So the governments cannot quarantine only those affected, letting the unaffected population continue their normal activities. Moreover, we assume (again realistically) also that there exists a capacity constraint of the health system to deal with the massive inflow of patients (see, for instance, Piguillem and Shi 2020). Finally, in this paper, we do not consider other mitigation mechanisms such as endogenous shifts in private consumption behavior across sectors of the economy during an epidemic or after a temporary lockdown (see Krueger at al. 2020).

The model is calibrated for Italy, being a case leading, from a temporal perspective, the infection in Europe, and the rest of the world. We employ the epidemic data from February 23 to April 25, 2020, to calibrate the stochastic process for the COVID-19 disease. Moreover, we focus on the dynamic response of the economic variables after a single wave of COVID-19 infections and the case of a new infection wave after the slacking of social distancing measures at work.

Our results are summarized as follows. First, we show that a temporary lockdown policy reduces the size of the epidemic but exacerbates the severity of the recession caused by the pandemic shock. The intensity of the economic crisis depends on the type of lockdown policy adopted: output reaches a negative peak of 11 percent with a soft containment measure and 35 percent with a strong containment measure. Second, recovery from recession emerges when the lockdown policy is relaxed. However, the pre-lockdown conditions are reached approximately only after two years. The recovery phase is more lasting for investments. Third, the returns infection triggers more stringent containment measures than the first wave. The new lockdown policy aggravates the economic crisis triggering a much severe recession.

The rest of the paper is organized as follows. Section 2 presents a brief review of the literature related to the pandemic and its effect on the economy. Section 3 describes the model and carries out a brief time series analysis of the epidemic in Italy. Section 4 discusses the calibration of the model. Section 5 displays the dynamic properties of the model with one wave of contagions and the case of a return infection. Section 6 concludes.

2 Related Literature

Although the COVID-19 pandemic only came out a few weeks ago, it deeply questioned ways of living and economic systems all over the world. This attracted the attention of many scholars starting the investigate the impact of the COVID19 crisis along with different perspectives. A growing literature attempts to analyze the economic impact of the COVID19 crisis employing several modeling techniques.

Following Atkenson (2020) and Berger et al. (2020), among others, it is possible to classify the studies addressing the effects of the COVID 19 pandemic on the economy into two main categories. First, a part of the literature extends the Susceptible-Infected-Recovered (SIR and SEIR exposed infectious recovered) model to consider the pandemic effects on the economy. Among the many, Eichenbaum et al. (2020) is one of the first works that combine an epidemiological model with macroeconomic issues. The authors extend the canonical epidemiology model to study the interaction between economic decisions and epidemics. They find that people's choices cut back on consumption, and work reduces the severity of the pandemic, but exacerbate the size of the recession. Krueger et al. (2020) extend the previous theoretical framework assuming an economy composed of several heterogeneous sectors that differ in technology and infection probabilities. The authors find that a model with heterogeneous agents produces a different economic outcome. In detail, they demonstrate it is possible to mitigate the economic and human costs of the COVID-19 crisis without government intervention and allowing agents to shift their sectoral behavior.

The second strand of research focuses on the economic response after the epidemic shock and how traditional policy instruments might mitigate its adverse effects. In particular, Faria-e-Castro (2020) characterizes the outbreak as a negative shock to the propensity to consume. The authors test different fiscal policies and find that unemployment insurance is the most effective tool to stabilize income for borrowers, whereas savers may favor unconditional transfers. Fornaro and Wolf (2020) use a New-Keynesian framework to analyze the possibility that the recent SARS-CoV-2 outbreak could result in an expectation-driven stagnation trap. Fernando and McKibbin (2020) present a global hybrid DSGE/CGE general equilibrium model in which the COVID-19 shock induces a negative labor supply shock, disruption of production networks, and a shift of consumer preferences towards domestic goods, and a rise in equity and country risk premia. The authors analyze three pandemic scenarios with different contagion (mortality) rates. They demonstrate that even a contained outbreak could significantly impact the global economy in the short run.

This paper is related to the strand of the literature that focuses on the economic response after the pandemic shock. Ongoing discussions on the optimal policy responses to the pandemic COVID shock are in Guerrieri et al. (2020), Jordà et al. (2020), Hall et al. (2020), Dewatripont et al. (2020), Jones et al. (2020), Piguellem and Shi (2020), McKibbing and Fernando (2020) and the papers in Baldwin and Weder (2020).

Our work considers epidemiological issues, as in Eichenbaum et al. 2020, in order to investigate the trade-off between economy and deaths from the COVID19 disease.

3 The Model

This section presents a parsimonious DSGE model with endogenous labor effective utilization, endogenous dynamics for the pandemic, and the lockdown policy[1]. This section presents a parsimonious DSGE model with endogenous labor effective utilization, endogenous dynamics for the pandemic, and the lockdown policy. The economy is populated by a representative household, a representative final-good-producing firm, and a government that decides the containment measures. Technically, government contrasts virus contamination choosing a partial lockdown policy (Moser and Yared 2020 and Alvarez et al. 2020 present various characteristics and strategic aspects of the lockdown). The model simulates a pandemic shock that affects labor demand and supply and propagates through to the economy. Nevertheless, the contact-intensive activities, as labor and consumption, amplify the size of disease propagation. Shock intensity and duration are calibrated using the most recent epidemic data in Italy and propose a simple Auto-Regressive Integrated Moving Average (ARIMA) model. Eventually, we discuss the possibility and consequences of a new wave of COVID-19 infections in autumn 2020. Time is discrete, weekly, and infinite[2].

3.1 Households

The representative household derives utility from consumption and disutility from labor. The household's preferences are described by the following utility function:

$$U_t = u\left(c_t, n_t\right) = E_t \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-q}}{1-q} - \theta \frac{n_t^{1+\psi}}{1+\psi} \right) \tag{1}$$

where $\beta \in (0,1)$ denotes the discount factor, θ is the disutility from labor,ψ is the inverse of Frish elasticity, q denotes risk aversion parameter and c_t and n_t denote consumption and hours

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[1] Certainly, the aspects relating to the frictions of the economy and policy are the subject of future research.

[2] The competitive equilibrium is not Pareto optimal because the agents do not fully internalize the effect of their decisions because it takes the virus's spread as given.

worked, respectively. The representative households maximize the utility function subject to the following inter-temporal budget constraint:

$$c_t + i_t = w_t \kappa_t n_t + r_t k_t \tag{2}$$

where w_t is the wage per unit of effective labor, k_t is capital, r_t is the rate of rent for capital and i_t are the investments. In details, $\kappa_t \in (0,1)$ denotes labor effective utilization and it is a proxy for the measures of social restrictions. We assume that social containment measures, as the quarantine, prevent labor force utilization. A pre COVID-19 economy implies $\kappa_t = \kappa_{ss} = 1$.

Furthermore, investment decisions are subject to convex capital adjustment costs and physical capital accumulates according to the following laws of motion:

$$k_{t+1} = (1-\delta)k_t + i_t \left[1 - \frac{\chi}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right] \tag{3}$$

where $\delta \in (0,1)$ is the capital depreciation rate and χ is the sensitivity parameter for the investment adjustment costs.

The first-order condition for consumption, supply of labor, investment and capital are the following[3]:

$$\lambda_t = c_t^{-q} \tag{4}$$

$$\theta n_t = \lambda_t w_t \kappa_t \tag{5}$$

$$\lambda_t = q_t \left[1 - \frac{\chi}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2 - \chi\left(\frac{i_t}{i_{t-1}} - 1\right)\frac{1}{i_{t-1}}\right] + \beta Q_{t+1}\chi\left(\frac{i_{t+1}}{i_t} - 1\right)\left(\frac{i_{t+1}}{i_t}\right)^2 \tag{6}$$

$$Q_t = \beta\left[Q_{t+1}(1-\delta) + \lambda_{t+1} r_{t+1}\right] \tag{7}$$

where λ_t denotes the Lagrangian multiplier associated to the budget constraint. Q_t is the Lagrangian multiplier associated with the capital stock and represents the shadow price of capital.

3.2 Firms

The representative firms produce homogeneous commodity using effective hours worked and capital through a CES technology:

$$y_t = \left[\mu k_t^{\frac{\sigma-1}{\sigma}} + (1-\mu)\left(\kappa_t n_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{8}$$

where $\mu \in (0,1)$ is a distribution parameter reflecting capital intensity in production, and σ is the elasticity of substitution between capital and labor services. Final good price is normalize to unity.

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[3] See the appendix for a detailed derivation.

Firms maximize instantaneous profit, renting labor services and productive capital on a period by period basis.

$$\max_{n_t, k_t} \pi_t = y_t - w_t n_t - r_t k_t \tag{9}$$

The first order conditions for capital and labor inputs are given respectively as:

$$r_t = \left[\mu k_t^{\frac{\sigma-1}{\sigma}} + (1-\mu)\left(\kappa_t n_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}-1} \mu k_t^{\frac{\sigma-1}{\sigma}-1} \tag{10}$$

$$w_t = \left[\mu k_t^{\frac{\sigma-1}{\sigma}} + (1-\mu)\left(\kappa_t n_t\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}-1} \kappa_t \left(1-\mu\right)\left(\kappa_t n_t\right)^{\frac{\sigma-1}{\sigma}-1} \tag{11}$$

In the pre-COVID19 economy, all available labor is used in the production process. However, after the pandemic shock and social distancing measures, the intensity with which available labor is used varies over time and depends on virus dynamics and the policymakers' commitment to enforcing lockdown.

3.3 COVID-19 Pandemic

This paper's primary purpose is to study the dynamic response of the economy during the partial lockdown. In order to replicate the infection dynamics, we consider a positive shock that affects the size of infected people. To this end, we analyze the time series of the confirmed COVID-19 cases in Italy and define the best ARIMA model. The second part provides modeling of the COVID-19 dynamics and the containment policy in the DSGE framework.

3.3.1 COVID-19 Stochastic Process

The pandemic shock has specific characteristics and needs for a precise analysis. To this end, we analyze the new weekly COVID-19 cases data from February 23 to April 25, 2020, in Italy, and proposes a simple econometric model to define the stochastic process of COVID-19 disease. The data used in this paper are sourced from the official website of the *European Center for Disease Prevention and Control.* Here, the new cases were counted in Italy for nine weeks. We employ the KPSS test to examine the time series stationarity. Besides, we apply the logarithmic transformation and differences to stabilize the time series. The fitted ARIMA model is chosen using AIC and BIC values. The virus propagation (V_t) is formalized as a stochastic process that follows an ARIMA (1,0,1):

$$(1-\rho L)\log(V_t) = (1+\phi L)\,\varepsilon_t \tag{12}$$

where L is the lag operator, ρ is the parameter of the autoregressive part of the model, ϕ is the parameters of the moving average part and $\varepsilon_t \sim iid\ \mathcal{N}(0, \sigma^2)$ is the pandemic shock. Hence, the innovations ε_t represent unexpected changes in infected people. The appendix B shows a detailed analysis.

3.3.2 COVID-19 in the DSGE framework

Next, this section introduces the COVID-19 pandemic in the DSGE model. Disease transmission occurs in the workplace, in consumption activities, at home, and in hospitals (non-economic activities). We consider the stochastic process to replicate the standard dynamics of pandemics. In detail, starting from the case in which the fraction of the total infected population is low (about 0.001 percent), the pandemic shock affects the contagion propagation and the epidemic's dimension. Besides, the propagation of the disease is also related to economic activity: labor and consumption increase contagion. The newly infected people for COVID-19 is given by [4]:

$$NI_t = (V_t, c_t, n_t) = (V_t NI_0) c_t \pi_c + (V_t NI_0) n_t \pi_n + (V_t NI_0) \pi_p \tag{13}$$

where π_c, π_l, and π_p define the weights on virus propagation for consumption, labor, and non-economic activity, respectively. Here, the standard dynamics of the epidemics is given from the stochastic process. This latter already includes the reduction in susceptible people (trough deaths and recovered). As in Atkeson (2020), we consider that infected people it takes on average 18 days to either recover or die from the infection. Hence, the size of COVID-19 infected in each time is given by:

$$TI_{t+1} = (1 - \delta_t^d - \delta_t^r) TI_t + NI_t \tag{14}$$

where δ_t^d and δ_t^r define the proportion of weekly deaths and recoveries,respectively. Since our model is weekly we set the total removal rate equal to 7/18. As in Eichenbaum et al. (2020), we assume that the efficacy of the healthcare system deteriorates if a substantial fraction of the population becomes infected. This scenario implies that the mortality rate increase with the rise in pandemic size:

$$\delta_t^d = \delta_0^d + \varphi TI_t \tag{15}$$

We suppose that the case fatality rate is a linear function of the fraction of the population that becomes infected. The initial populations normalized to one .

3.4 Government and lockdown policy

This paper considers a central government implementing a lockdown policy to avoid the spread of the virus. The containment measures consist of quarantine and social distancing, which influence the effective labor utilization. We assume that the total labor force has the following composition:

$$n_t = \upsilon_t n_t + \kappa_t n_t \tag{16}$$

where υ_t is the part of workers in quarantine and κ_t is the fraction employed in the production. Before the pandemic, worker is not in quarantine: υ_0 is equal to zero and all available labor is used in the production process ($\kappa_{ss} = 1$). After the pandemic shock, the policy-makers applies the containment measures, and decides to lockdown a fraction of workers $\upsilon_t \in [0, 1]$. Hence, only a part $\kappa_t < 1$ of total employment are available in production, whereas the other part υ_t is in quarantine and temporarily unemployed. In consequence, smoothing the epidemic curve inevitably steepens the macroeconomic recession curve through a fall in labor utilization and labor income. It is like saying that a government would not be able to minimize both deaths from COVID-19 disease and the economic impact of viral spread. Keeping mortality as low

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[4] The infection of COVID-19 refers to the deviation from the initial state.

as possible is the highest priority, but governments must put in place measures to enhance the inevitable economic downturn. What has happened in China, in Italy and other west countries shows that quarantine, social distancing, and isolation of infected populations can curb the epidemic, albeit with high costs in terms of added value and employment.

In order to replicates the trade-off between preventing deaths and GDP slowdown, we assume that the government implements the lockdown policy according to the following simple rule:

$$\upsilon_t = \min\left\{1, \left[\left(\frac{TI_t}{TI_0}\right)^{\gamma_\kappa}\left(\frac{y_t}{y_0}\right)^{1-\gamma\kappa}\right] - 1\right\} \tag{17}$$

where the parameter ρ_κ captures the degree of lockdown smoothing. The policy behavior of the government is captured by γ_κ and $(1-\gamma_\kappa)$ which are the elasticities of the policy target with respect to COVID19 size and output gap, respectively. In this framework, the whole dimension of infected people is used as a proxy for the pressure on the healthcare system. The mechanism of the policy is the following. When the pandemic shock (ε_t) is equal to zero, the outbreak dimension is under control and the government does not apply containment measures $(\kappa_t = \kappa_0 = 1)$. After the pandemic shock, the size of the virus grows up, and the government active the lockdown policy. The aim is to reduce contact-intensive activities to avoid contagion propagation. Since $TI_t > TI_0$, the effective labor utilization is lower than one. The size and intensity of the lockdown policy depend on the weight given by the policy-maker to epidemic propagation and slow-down of the economy.

3.5 Equilibrium and Aggregation

In this section, we analyze the decentralized dynamic competitive equilibrium. For a given process of the pandemic shock $\{V_t\}_{t=0}^{\infty}$, initial level of capital stock k_0, the initial size of COVID-19 infections TI_0 , initial labor utilization κ_0 , the decentralized dynamic competitive equilibrium is a list of sequences $\{c_t, n_t, k_{t+1}\}$ given the input prices $\{w_t, r_t\}$ such that (i) the household maximizes its utility function subject to its budget constraint; (ii) the representative firm maximizes profit; (iii) capital and the pandemic follow their dynamics of accumulation. The set of equilibrium conditions includes a resource constraint:

$$y_t = c_t + i_t \tag{18}$$

A full list of equilibrium conditions is in Appendix A.

4 Calibration

This section presents model calibration between parameters drawn for typical macroeconomic literature and epidemic parameters extracted from selected studies. Moreover, parameters for the pandemic shock were defined through our analysis of the Italy epidemic data. Since the topic is a novelty in the economics literature and the pandemic's real size is unknown, there is considerable uncertainty about the valid values of these parameters. For this reason, in ongoing work, we are exploring alternative calibrations.

The parameters characterizing the economy are calibrated as in most dynamic stochastic general equilibrium studies (see, e.g., King and Rebelo 1999). We adopt a transformation of these parameters from quarterly to weekly.Table1 lists the parameters used in the model.

Parameter	Description	Value
β	Discount Factor	$0.96^{1/52}$
δ	Depreciation Rate Capital	0.025/12
q	Risk Aversion	1.5
ψ	Inverse of Frish Elasticity	1
α	Share of capital	0.36
σ	Elasticity of substitution between capital and labor services	0.7
π_c	Consumption weight in epidemic propagation	0.005
π_n	Labor weight in epidemic propagation	7.398
π_p	Non-economic activity weight in epidemic propagation	0.206
δ_0^d	Death rate	0.0039
φ	Mortality rate convex function parameter	12.5
ρ	Persistence of the pandemic shock	0.98
ϕ	Parameters of the moving average	0.66

Table 1- Model Calibration

Regarding the pandemic parameters we follow Eichenbaum et al. (2020). The initial dimension of the epidemic T_0 is equal to 0.001. The weights of consumption, labor, and non-economic activity in epidemic propagation are $\pi_c = 0.0046, \pi_n = 7.3983$ and $\pi_p = 0.2055$. Mortality rate convex function parameter is equal to 12.5, as in Eichenbaum. et al. (2020). The parameters in the lockdown policy are subject to a sensitivity analysis.

5 Impulse Response Analysis

This section explores the dynamic response of the economy during a pandemic shock. It is first interesting to discuss how the economy responds to a pandemic under different lockdown degree. Moreover, it exists a possibility of a subsequent wave of infection, as was the case with the Spanish Flu (see among others, Barro et al. 2020). To this end, we simulate the economy dynamics evaluating the possibility of a return infection in the autumn 2020. To examine the dynamic properties of the model, we carry out a numerical analysis. Notably, we use a second-order Taylor approximation of the model around its steady state. We use the computer package Dynare to find the solution of the model.

5.1 Pandemic Shock Experiment

This section analyzes the impulse response functions to the pandemic shock of selected variables. We suppose the model to be in the steady-state in February 2020, and consider a pandemic shock starting in March 2020. We consider four alternative degrees of epidemic containment measures; the case of absence of lockdown ($\gamma_\kappa = 0$); a soft lockdown ($\gamma_\kappa = 0.25$), which involves quarantine of 20 percent of the labor force; a medium lockdown with 40 percent of workers in quarantine ($\gamma_\kappa = 0.50$); an intensive lockdown ($\gamma_\kappa = 0.70$) that reduces the available labor force to 40 percent. Caution should be exercised when reading simulations which, of course, do not consider the effects of the enormous uncertainty shock created by the COVID-19, which several studies assesses similar in magnitude to the rise in uncertainty during the Great Depression of 1929-1933 (see Baker et al. 2020), and capable of sinking the estimates of falling GDP in the coming months.

Figure 1 reports the effects of lockdown policies on pandemic and economy dynamics. Following the shock, the rise in lockdown policy is parallels the dynamics of the COVID-19 disease.

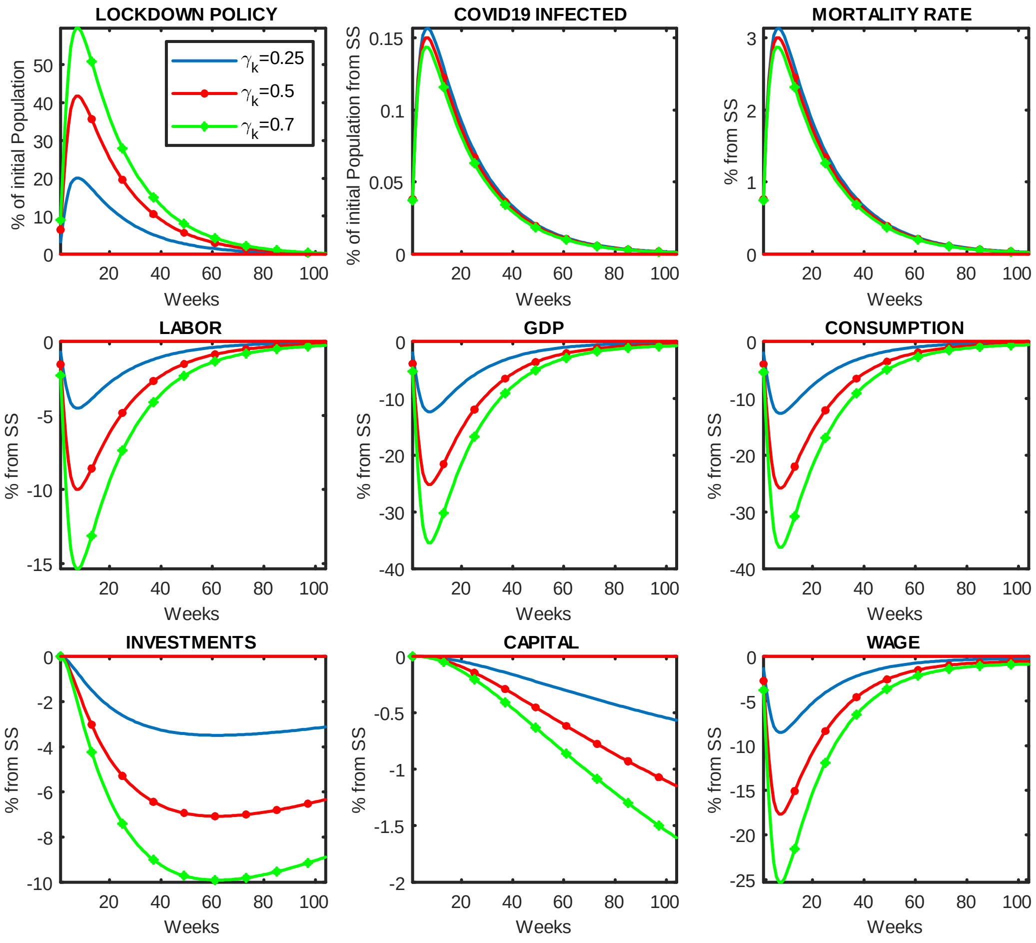

Figure 1: Pandemic Shock

The basic intuition is as follows: when the size of infection rises, the containment measures become more intensive. The government's decision to cut back the highly contagious activities diminishes the dimension of the epidemic and the percentage of deaths. The strict containment policy reduces the peak level of infections from 0.16 to 0.14 percent (of the initial population), reducing the weekly mortality rate from 3.2 to 2.8 percent. This advantageous outcome is associated with a much more critical recession.

Let us start with the effects of the soft lockdown. On impact, the drop in GDP is 2% percent, and the overall decline is much larger because the lockdown is lifted gradually. The overall reduction in GDP, thus reaches almost 14 percent after seven weeks. The effect on the labor market is not immediate. The fall in employment is 0.7 percent on impact and reaches a peak of 5.5 percent at the start of May 2020. The temporary unemployment affects consumption: on the impact, the reduction is 2 percent. The persistence of the containment policy aggravates the conditions of households, and after two months, the consumption reaches a negative peak of 15 percent. The pandemic shock does not influence investments on impact. The adverse effect on investments is gradual: the negative peak is reached after about one year.

Furthermore, stricter lockdown policies intensify the slowdown. On impact, GDP falls to 3.2 and 4.6 in the event of a medium and intensive lockdown. The persistence of the shock produces a deep recession. In particular, after two months since the outbreak of the epidemic, the extreme containment measures make a dramatic fall in GDP that reaches a negative peak of 35 percent (23 percent in the case of ($\gamma_\kappa = 0.5$). The recession is related to the drop in employment. This latter reaches a negative peak of 9 and 15 percent when γ_κ is equal to 0.50 and 0.70,respectively. The drastic reduction in wages and hours worked affects the consumer's choices. Households suffer a dramatic reduction in their consumption due to the pandemic, whit a maximum negative peak of 35%.

Once interventions are relaxed, the economy starts the recovery phase. Nevertheless, the phase of recovery is persistent. In all scenarios, after two years, the production is still below the initial levels. Although this paper considers a shock on the labor market, the effects in the investments sector are much persistent. For all degree of lockdown, after two years since the epidemic outbreak, the investments are still in the early stages of recovery.

5.2 Return Infection Scenario

In this section, we analyze the response of the economy after a return infection. A recent simulation by epidemiologists at Britain's Imperial College (Report 9, 2020) suggests a dynamic for the COVID-19 pandemic similar to the Spanish Flu. Their simulation shows that once interventions are relaxed, infections begin to rise, resulting in a predicted peak epidemic later in the year. In detail, the more successful is a strategy, the more significant is the last outbreak is expected (in the absence of vaccination) due to lesser build-up of herd immunity (Ferguson et al., 2020). To this end, we simulate a second wave of infection in November 2020. Figure 2 shows the impulse response function of selected variables to the pandemic shock in the last week of February 2020 and in the first week of November 2020. The return infection triggers more stringent containment measures than the first wave. The temporary lockdown policies remain active for seven weeks after the outbreak of the new wave of infections. The containment measures are put in place to mitigate the more severe return of the disease. The new peak of infections is reached after six weeks at 0.19 for the more intense policy, 0.18 for the medium intensity policy, at 0.17 with less stringent containment measures.

Besides, weekly mortality rates reach higher peaks than the first wave. The policies put in place require that a more substantial fraction of the labor force to temporary unemployment. The second pandemic shock affects the economy during the recovery phase, triggering a much severe recession. In the case of an intensive lockdown policy, production reaches a negative

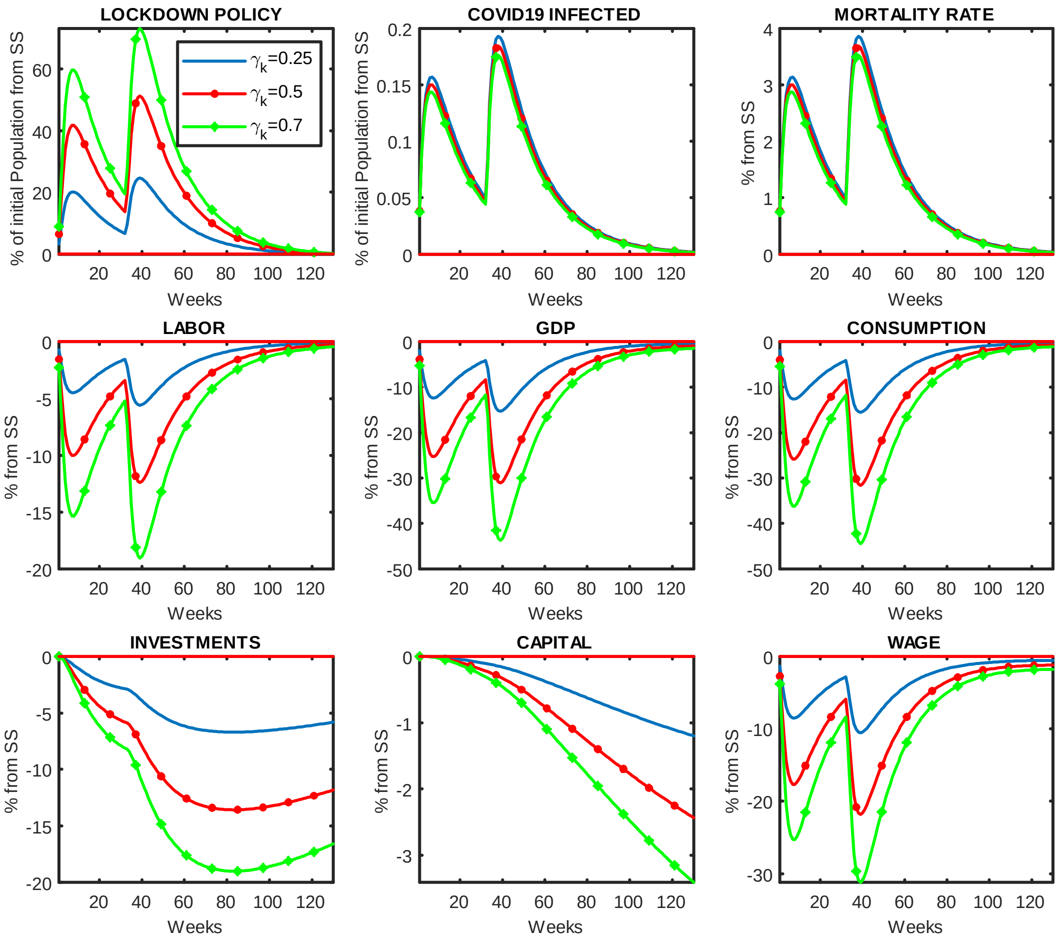

Figure 2: Pandemic Shock: Return Infection

peak of 40 percent. The new infection wave has the same negative impact on consumption. Still, investments suffer a persistent drop. First, a second wave of the virus propagation doubles their fall. In addition, after two years since the first pandemic shock, investments are still below their steady-state value. Nevertheless, a less stringent lockdown allows mitigating the recession and fall in consumption and investments. However, this latter can only be achieved with an increase in human losses.

6 Conclusion

This paper studies a DSGE model augmented with the COVID-19 virus dynamics to study the interaction between economic decisions and epidemics. The pandemic is a shock on infection size while generating supply and demand effects on the labor force. We consider the outbreak as a shock that reduces labor utilization and determines an adverse impact on economic activity. These effects generate a large and persistent recession.

The analysis shows a trade-off between the severity of the economic slowdown and epidemic consequences on health. A temporary lockdown policy reduces the outbreak dimension but intensifies the severity of the recession. Besides, once interventions are slackened, the economy starts the recovery phase, but the pre-COVID 19 conditions are reached only after two years. The recovery phase for the investments could be more lasting. Finally, the returns infection triggers more stringent containment measures than the first wave.

Of course, we can also think that governments make use of the experience linked to the first wave, and equip themselves with contrasting tools to be also used with temporary lockdown (such as the ability to carry out tests on a large part of the population and limit hospital constraints as the pandemic evolves). Being able to identify positive individuals and impose personalized quarantines rather than indiscriminate ones should ease the recession.

If this does not happen, the second pandemic shock affects the economy during the recovery phase, which could trigger a much severe recession. Policymakers address this trade-off, and the choice of the useful tool to stabilize the economy is a critical challenge. Our model may denote a parsimonious analytical tool to provide policy recipes that might be taken into account in the case of pandemic shock.

In order to keep the analysis as simple as possible in this first work, we do not insert nor the specification of a budget constraint and the dynamics of public debt (essential to consider the effects of the intervention of the economic policy aimed at limiting the damage of the pandemic and redefine the recovery of the economy) or frictions of various types on prices, wages and on supply and demand for labor. The aim is to build a macroeconomic framework to analyze the economic impact of the epidemic shock and its relative dynamics.

A Appendix

A.1 Households' Optimization Problem

The representative household chooses the sequences $\{c_t, n_t, k_{t+1}, i_t\}$ so as to maximize (1), subject to (2) and (3). The Lagrangian function associated to the optimization problem of the representative household is:

$$\mathcal{L}_t = E_t \sum_{t=0}^{\infty} \beta^t \left\{ \begin{array}{c} \left(\frac{c_t^{1-q}}{1-q} - \frac{\theta}{1+\psi} n_t^{1+\psi} \right) + \lambda_t \left[w_t \kappa_t n_t + r_t k_t - c_t - i_t \right] \\ +Q_t \left\{ -k_{t+1} + (1-\delta) k_t - i_t \left[1 - \frac{\chi}{2} \left(\frac{i_t}{i_{t-1}} - 1 \right)^2 \right] \right\} \end{array} \right\}$$

The first-order conditions follow from the solution to the intertemporal optimization problem:

$$\frac{d\mathcal{L}_t}{dc_t} = \lambda_t - c_t^{-q} = 0$$

$$\frac{d\mathcal{L}_t}{dn_t} = \theta n_t^{\psi} - \lambda_t w_t \kappa_t = 0$$

$$\frac{d\mathcal{L}_t}{di_t} = \lambda_t - q_t \left[1 - \frac{\chi}{2} \left(\frac{i_t}{i_{t-1}} - 1 \right)^2 - \chi \left(\frac{i_t}{i_{t-1}} - 1 \right) \frac{1}{i_{t-1}} \right] + \beta Q_{t+1} \chi \left(\frac{i_{t+1}}{i_t} - 1 \right) \left(\frac{i_{t+1}}{i_t} \right)^2 = 0$$

$$\frac{d\mathcal{L}_t}{dk_{t+1}} = Q_t - \beta \left[Q_{t+1} (1-\delta) + \lambda_{t+1} r_{t+1} \right] = 0$$

A.2 Firms' Optimization Problem

Firm maximize instantaneous profit, renting labor services and productive capital on a period by period basis.

$$\max_{n_t, k_t} \pi_t = y_t - w_t n_t - r_t k_t$$

The first order conditions for capital and labor are given respectively as:

$$\frac{d\pi_t}{dk_t} = \left[\mu k_t^{\frac{\sigma-1}{\sigma}} + (1-\mu) \left(\kappa_t n_t \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1} - 1} \mu k_t^{\frac{\sigma-1}{\sigma} - 1} - r_t = 0$$

$$\frac{d\pi_t}{dn_t} = \left[\mu k_t^{\frac{\sigma-1}{\sigma}} + (1-\mu) \left(\kappa_t n_t \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1} - 1} \kappa_t (1-\mu) \left(\kappa_t n_t \right)^{\frac{\sigma-1}{\sigma} - 1} w_t = 0$$

B Steady-State

In this section, we derive the steady states of the model. First, we impose that labor in steady-state is equal to 0.33 and the steady-state of the exogenous shocks to be equal to one.

From equation (7) we obtain the steady-state sectoral real return on capital:

$$r_{ss} = \beta^{-1} - (1-\delta)$$

It also implies from equation (10):

$$\frac{y_{ss}}{k_{ss}} = \left(\frac{r_{ss}}{\alpha}\right)^{\frac{1}{1-B}}$$

where $B = (\sigma - 1)/\sigma$.

The steady state consumption-capital ratio is also obtained accordingly from equation (18):

$$\frac{c_{ss}}{k_{ss}} = \frac{y_{ss}}{k_{ss}} - \delta$$

From equation (8):

$$\frac{l_{ss}}{k_{ss}} = \left(\frac{y_{ss}}{k_{ss}}^{B} - \alpha\right)\left[\frac{1}{(1-\alpha)}\right]^{\frac{1}{B}}$$

It implies from equation (11):

$$w_{ss} = (1-\alpha)\left(\frac{y_{ss}}{k_{ss}}\frac{k_{ss}}{l_{ss}}\right)^{1-B}$$

from equation (10):

$$k = l_{ss}\left(\frac{y_{ss}}{k_{ss}}^{B} - \alpha\right)\left[\frac{1}{(1-\alpha)}\right]^{\frac{-1}{B}}$$

In recursively way we obtain the following steady-states:

$$y_{ss} = \frac{y_{ss}}{k_{ss}}k_{ss}$$

$$c_{ss} = \frac{c_{ss}}{k_{ss}}k_{ss}$$

$$i = \delta k$$

$$\lambda_{ss} = c_{ss}^{-q}$$

$$Q_{ss} = \lambda_{ss}$$

And :

$$\theta = \frac{\lambda_{ss} w_{ss}}{l_{ss}^{\psi}}$$

C Time Series Analysis

We use the daily incidence data of COVID-2019 from February 23 to April 25, 2020, collected from the official website of the European Center for Disease Prevention and Control. We apply the ARIMA model to a dataset consisting of 9 number determinations. To test the time-series stationarity we apply the KPSS test developed by Kwiatkowski et al. (1992). It is a hypothesis test that is used when you want to compare the stationary null hypothesis of a self-progressive historical series with the alternative hypothesis that the series has one (or more) unit-roots.

Lags	p-value
0	0.0100
1	0.0451
2	0.0618
3	0.0441
4	0.0196

Table 2-KPSS Test

Table 2 show that the model is stationary at lag one.

The comparison and parameterization of the ARIMA model have been made using the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). We choose the model with the lowest BIC and AIC value:

Model	AIC	BIC
ARIMA(1,0,0)	17.3486	17.5458
ARIMA(1,0,1)*	15.5256 *	15.9200*
ARIMA(1,0,2)	16.2367	16.8283
ARIMA(1,0,3)	17.2886	18.0775
ARIMA(1,0,4)	19.2805	20.2666

Table3- AIC and BIC values

For the logarithmic series of newly diagnosed patients, the ARIMA (1,0,1) model is selected with the following parameters:

	Value	SE	TStatistic	P-value
Constant	0	0	NaN	NaN
AR(1)	0.98	0.48871	2.0462	0.040738
MA(1)	0.6686	0.55485	1.205	0.2282
Variance	0.21071	0.12381	1.7019	0.088781

Table4-COVID19-ARIMA(1,0,1) Model

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