

Busato, Francesco; Chiarini, Bruno; Cisco, Gianluigi; Ferrara, Maria; Marzano, Elisabetta

## Article

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# Lockdown policies: A macrodynamic perspective for COVID-19<sup>☆</sup>

Francesco Busato<sup>a</sup>, Bruno Chiarini<sup>a</sup>, Gianluigi Cisco<sup>a,\*</sup>, Maria Ferrara<sup>a</sup>,  
Elisabetta Marzano<sup>b</sup>

<sup>a</sup> University of Naples Parthenope, Italy

<sup>b</sup> University of Naples Parthenope and CESifo GmbH, Italy



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## ABSTRACT

The COVID-19 pandemic has produced a global health and economic crisis. The entire world has faced a 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, variable labor utilization, and four lockdown policies with different degrees of size and duration. There are three main results in this study. First, the model matches rather well with the main European economies' preliminary stylized facts during the COVID-19 pandemic. In particular, a temporary lockdown policy reduces the epidemic's size but exacerbates the recession's severity. The negative peak in aggregate production ranges from 10% with a soft containment measure to 25% with a strong containment measure; second, recovery from recession emerges when the lockdown policy is relaxed. On that basis, the output return to its pre-lockdown level after about 50 weeks. Third, sectors characterized by flexible and capital-intensive technology suffer a more severe slowdown.

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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 worldwide in the next weeks. The epidemic propagation is bringing considerable human losses and suffering. On the other hand, the actions to prevent infection propagation have produced economic disruption. There are several direct channels through which the virus affects 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). Besides, the decline in hours worked reduces the income entailing an additional damper on households' demand (OECD, 2020). The COVID-19 pandemic can be considered an unprecedented shock to labor

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<sup>\*</sup> Corresponding author.

E-mail addresses: [francesco.busato@uniparthenope.it](mailto:francesco.busato@uniparthenope.it) (F. Busato), [bruno.chiarini@uniparthenope.it](mailto:bruno.chiarini@uniparthenope.it) (B. Chiarini), [gianluigi.cisco@uniparthenope.it](mailto:gianluigi.cisco@uniparthenope.it) (G. Cisco), [maria.ferrara1@uniparthenope.it](mailto:maria.ferrara1@uniparthenope.it) (M. Ferrara), [elisabetta.marzano@uniparthenope.it](mailto:elisabetta.marzano@uniparthenope.it) (E. Marzano).

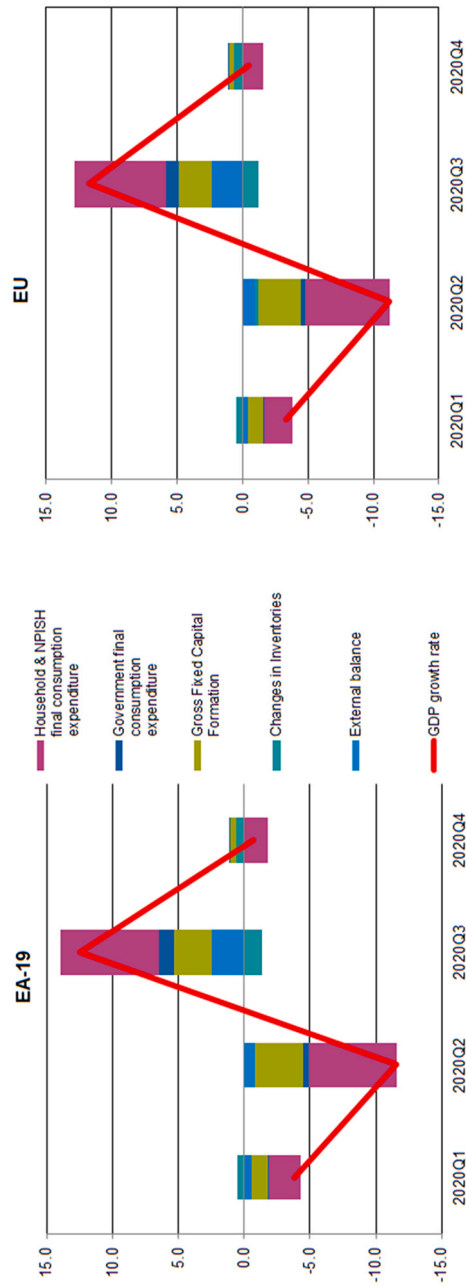


Fig. 1. Decomposition of GDP growth by expenditure aggregates, contributions to growth (over the previous quarter) in percentage points - 2020Q1–2020Q4. Source Eurostat.

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 (Wren-Lewis, 2020).

In particular, as the virus has spread, the euro area growth slowed down between February and April 2020 (see Fig. 1). The impact of the COVID-19 pandemic in the European Union (EU) determined sharp drops of growth rates in main aggregates such as employment, and these were by far the sharpest declines observed since the time series started in 1995. The crisis was caused by the containment measures widely applied by all member states during the second quarter of 2020 with the progressive easing of containment measures towards the end of the reference period. Notably, the gross domestic product (GDP) decreased by 11.8% in the euro area (EA-19) and 11.4% in the EU-27 during the second quarter of 2020 compared with the previous quarter, according to Eurostat's estimate. Moreover, the decisive contribution to GDP growth in both the euro area and the EU-27 is associated with the household final consumption expenditure: drop by 12.4% in the euro area and 12.0% in the EU-27 (after - 4.5% in the euro area and - 4.2% in the EU in the previous quarter). In addition, the social containment measures negatively contributed to the gross fixed capital formation (-17.1% in the euro area and 15.4% in the EU-27).

Furthermore, the lockdown policy significantly affected the labor market through the forced quarantine of a substantial part of the workforce. Eurostat estimated a decrease in the number of hours worked of 17.3% in the euro area and 14.3% in the EU-27 in the second quarter of 2020. However, the number of individuals employed decreased by 2.9% in the euro area and by 2.7% in the EU-27 in the second quarter of 2020 compared with the previous quarter. Note that, concerning the COVID-19 pandemic, there was a sharp decline in productivity based on persons in the first and second quarter of 2020 as GDP dropped clearly while the influence on employment in persons was still relatively moderate (Eurostat, 2020). In that context, one of the measures taken to stem the negative effects in the economy of the recent pandemic is the job retention (JR) scheme. This latter has played a significant role in explaining labor market developments in the first months after the onset of the COVID-19 pandemic. During the early stage of the pandemic, while a considerable fraction of employees was in short-time work (e.g., 15% in Germany, 34% in France, 30% in Italy, and 21% in Spain), job retention schemes reached unprecedented levels. However, they remained elevated even after the easing of containment measures (Anderton et al., 2020).

During the third quarter, associated with the slow in infections, several European countries designed multiple-phase reopening plans, which have been implemented since early May. Consequently, the EA-19 and EU-27 real GDP rebounded strongly and rose by about 12.5% in the third quarter, although remaining well below pre-pandemic levels. The growth rate in the EA-19 and EU-27 was driven mainly by household expenditures (about 50%). Also, the government expenditure and the external balance have influenced the economic recovery strongly. The second wave of the pandemic and the associated intensification of containment measures observed since mid-October resulted in a renewed significant decline in activity in the fourth quarter of 2020.

The response of the EU's primary economic aggregates shows how the lockdown is essential to save lives, but it also has tremendous adverse macroeconomic effects. Therefore, policymakers face a severe trade-off between preventing deaths from COVID-19 and GDP slowdown. This preliminary but strong evidence suggests the importance of understanding the economic mechanisms during a pandemic event and in the presence of a lockdown policy. Against this background, a critical macroeconomic question is how much the COVID-19 pandemic affects macroeconomic dynamics and which economic mechanisms are triggered during a lockdown policy. To this purpose, this paper proposes a model in which economic activity and disease progression are jointly determined and contribute to the growing literature examining this trade-off. In the mathematical modeling of infectious diseases, there exist many compartmental models that can be used to describe the spread of a disease within a population (Shen, 2021). The SIR models represent one of the methodologies used to investigate the spread of a disease within a population and impact on the economy. However, recently have arisen new research fields to examine this topic. Indeed, in the economic literature, there exist mainly two research lines. The first line of research encompasses studies investigating how employment and consumption decisions could affect the equilibrium dynamics of a viral infection in a Macroeconomic SIR (Susceptible-Infectious-Recovered) model (Eichenbaum et al., 2020). The second line of research moves away from the SIR modeling to examine economic dynamics after a pandemic shock. Our work aligns with this part of the literature focused on evaluating the initial macroeconomic impact of an exogenous pandemic shock, such as (Fornaro and Wolf, 2020) and (Junior et al., 2021). This methodological choice allows us to evaluate how economic agents respond to an unexpected pandemic shock and how this once again interacts with the lockdown policy.

In particular, we ask the following questions: *what are the macroeconomic mechanisms of the epidemic containment measures? Under what conditions could it be possible to think about the recovery phase?*

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 four lockdown policies with different degrees of size and duration of the containment measures. The pandemic is modeled as an exogenous virus propagation shock in our model. 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, declining labor productivity.

The propagation shock 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. We focus deliberately on data referring to the first wave of COVID-19 disease when lockdown measures were more restrictive and persistent worldwide than other measures applied afterward to contrast infection propagation (e.g., lockdown policies for regions and local areas).

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](#)). 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 et al., 2020](#)).

Finally, we deliberately do not consider in the model the vaccination campaign. First, because in this analysis, we are purely interested in stressing the trade-off between preventing health and GDP slowdown. Second, the vaccination campaign is still ongoing, and its effects are not well known, mainly in the aftermath of the recent virus’ variants that arise while we are writing.

This paper presents two novelties. First, to the best of our knowledge, no other in the DSGE framework calibrate the stochastic process for the COVID-19 disease propagation through specific econometric analysis. Second, in our work, economic and epidemiological issues affect the size and the intensity of the lockdown policy, allowing us to explore in a general equilibrium context the interaction between the demand and the supply side of the economy and the virus propagation.

Our results are summarized as follows. First, we show that a temporary lockdown policy reduces the epidemic’s size 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 10% with a soft containment measure and 25% 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 one year since the pandemic shock. The recovery phase is more lasting for investments. In this regard, it is worth noting that our parsimonious model matches the UE economic stylized facts during the COVID-19 pandemic, representing, by this end, an attractive benchmark to carry out economic and policy (scenario) analysis in the case of a pandemic event.

The rest of the paper is organized as follows. [Section 2](#) presents a brief review of the literature on the pandemic and its effect on the economy. [Section 3](#) describes the model. [Section 4](#) discusses the calibration of the model. [Section 5](#) displays the dynamic properties of the model with one wave of contagions. [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 worldwide. This attracted the attention of many scholars starting to 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 ([Atkeson, 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 economy’s pandemic effects. 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 exacerbates the recession’s size. [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 and Louis \(2020\)](#) 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 borrowers’ income, 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 further 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 literature strand 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. \(2020\)](#), ([Facundo and Shi, 2020](#)), ([McKibbin and Fernando, 2020](#)) and [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.<sup>1</sup> In this context, it would be incredibly interesting to analyze the implications of the adoption of new technologies and strong reallocation pressures (composition effects) on labor productivity. Nevertheless, a more articulated formulation of the DSGE model would be necessary to assess the impacts mentioned above. Hence, to make the intuition for our results as transparent as possible, we use a relatively simple model to focus exclusively on the trade-off between the severity of the recession and the health consequences of the epidemic.<sup>2</sup> The economy is populated by a representative household, a representative final-good-producing firm, and a government that decides the containment measures. Technically, the government contrasts virus contamination by 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. Time is discrete, weekly, and infinite.<sup>3</sup>

#### 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:

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

where  $\beta \in (0, 1)$  denotes the discount factor,  $\theta$  is the disutility from labor,  $\psi$  is the inverse of Frish elasticity,  $q$  denotes risk aversion parameter and  $c_t$  and  $n_t$  denote consumption and hours 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  $\chi$  is the sensitivity parameter for the investment adjustment costs.

The first-order condition for consumption, supply of labor, investment and capital are the following<sup>4</sup>:

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

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

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

$$q_t = \beta [q_{t+1}(1 - \delta) + \lambda_{t+1} r_{t+1}] \tag{7}$$

where  $\lambda_t$  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.

<sup>1</sup> Certainly, the aspects relating to the frictions of the economy and policy are the subject of future research.

<sup>2</sup> To this end, we do not consider measures such as loan guarantees, job retention schemes, direct transfers affecting optimal choices of firms and households. We plan to address these important issues in future work.

<sup>3</sup> 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.

<sup>4</sup> See the appendix for a detailed derivation.

### 3.2. Firms

The representative firm produces homogeneous commodity using effective hours worked and capital through a constant elasticity of substitution (CES) technology:

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

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

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

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

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

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

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

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. Two main motivations have influenced the sample period selection for the pandemic shock calibration. The first motivation is related to this paper's goal. This paper aims to evaluate the macroeconomic response of a pandemic shock and relative lockdown policies implications. In this regard, this sample period is crucial to define a characteristic dynamic for the pandemic shock, i.e., beginning of infection and peak in the newly infected curve. Nevertheless, pandemic shock only partially affects pandemic dynamics in the model. Indeed, we suppose that government determines the intensity and duration of social distancing measures considering the total infected curve (see Eq. 16), influencing, in turn, the dynamics of newly infected people (see Eq. 13). The second motivation is related to the delay in the onset of COVID-19 symptoms. During the early stages of the recent pandemic, the World Health Organization set the average symptom onset to 14 days (Lauer et al., 2020). Consequently, the beneficial effects of the lockdown policy have been partially limited in this sample period. Moreover, to focus exclusively on the early phases of a pandemic, in this paper, we do not consider other mitigation mechanisms such as a temporary or regional lockdown policy. 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 Kwiatkowski–Phillips–Schmidt–Shin (KPSS) (Kwiatkowski et al., 1992) tests 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 the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). 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,  $\rho$  is the parameter of the autoregressive part of the model,  $\phi$  is the parameters of the moving average part and  $\varepsilon_t \sim iid. \mathcal{N}(0, \sigma_\varepsilon^2)$  is the pandemic shock. Hence, the innovations  $\varepsilon_t$  represent unexpected changes in infected people. The appendix B shows a detailed analysis.

#### 3.3.2. COVID-19 in the DSGE framework

In this section, we introduce the COVID-19 pandemic in the DSGE model. Disease transmission occurs in the workplace, in consumption activities, at home, and in non-economic activities. In detail, starting from the case in which the fraction of the infected population is low (about 0.001%), the pandemic shock affects the contagion propagation and the epidemic's dimension.

Besides, the disease’s propagation is also related to economic activity: labor and consumption increase contagion. The newly infected people for COVID-19 is given by <sup>5</sup>:

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

where,  $v_t$  is the part of quarantined workers and  $\kappa_t$  is the fraction of workers employed in production. In detail, lockdown policies affect several sectors in different ways: some sectors are considered essential and are permitted to remain open; non-essential sectors are closed down, mainly if their nature makes social distancing hard. We use  $v_t$  is a proxy for the labor force in the non-essential production sector whereas  $\kappa_t$  represents the fraction of workers employed in sectors defined as necessary (such as agriculture and energy). Furthermore, we assume that the probability of the virus spreading depends on people’s economic decisions. In detail, activities such as purchase consumption goods or working increase the contact between people. The parameters  $\pi_c$  and  $\pi_n$ , define the probability of virus spreading as a result of consumption and labor interactions, respectively. In particular, only the fraction  $\kappa_t$  of workers amplify the infection’s growth through work activity. Moreover<sup>6</sup>, the virus can increase its spread due to actions not related to economic activities, such as meeting kin or neighbor. Furthermore, since the virus has persistence times on surfaces, any activity can increase infection propagation. The parameter  $\pi_p$  defines the random infection propagation.

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:

$$TI_{t+1} = (1 - \delta_V) TI_t + NI_t \tag{14}$$

where  $\delta_V$  define the proportion of weekly deaths and recoveries, respectively. Since our model is weekly we set the total removal rate equal to 7/18.

### 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:

$$v_t n_t + \kappa_t n_t = n_t \tag{15}$$

Before the pandemic, worker is not in quarantine:  $v_0$  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  $v_t \in [0, 1]$ . Hence, only a part  $\kappa_t < 1$  of total employment are available in production, whereas the other part  $v_t$  is in quarantine and temporarily unemployed. In consequence, smoothing the epidemic curve inevitably steepens the macro-economic 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 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:

$$v_t = \left\{ \left[ \left( \frac{TI_t}{TI_0} \right)^{\gamma_\kappa} \left( \frac{y_t}{y_0} \right)^{1-\gamma_\kappa} \right] - 1 \right\}, v_t \in [0, 1] \tag{16}$$

The policy behavior of the government is captured by  $\gamma_\kappa$  and  $(1 - \gamma_\kappa)$  which are the elasticities of the policy target with respect to COVID19 size and output gap, respectively. The policy-maker defines size of the non-essential sectors that will be closed. This choice determines the reduction of the fraction of labor available in the production function. 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 ( $\varepsilon_t$ ) 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  $TI_t > TI_0$ , a fraction of workers are in quarantine and 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.

<sup>5</sup> The infection of COVID-19 refers to the deviation from the initial state.

<sup>6</sup> To this end, we do not consider measures such as loan guarantees, job retention schemes, direct transfers affecting optimal choices of firms and households. We plan to address these important issues in future work.



**Table 1**  
Model Calibration.

Parameter	Description	Value
$\beta$	Discount Factor	$0.96^{1/52}$
$\delta$	Depreciation Rate Capital	0.025/12
$q$	Risk Aversion	1.5
$\psi$	Inverse of Frish Elasticity	1
$\alpha$	Share of capital	0.36
$\sigma$	Elasticity of substitution between capital and labor services	0.7
$\kappa$	Investment adjustment cost parameter	6
$\pi_c$	Consumption weight in epidemic propagation	0.005
$\pi_n$	Labor weight in epidemic propagation	7.398
$\pi_p$	Non-economic activity weight in epidemic propagation	0.206
$\delta_v$	Infection removal rate	0.38
$\rho$	Persistence of the pandemic shock	0.98
$\phi$	Parameters of the moving average	0.66
$\sigma_v$	Standard deviation of the pandemic shock	0.9

### 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  $I_0$ , initial labor utilization  $\kappa_0$ , the decentralized dynamic competitive equilibrium is a list of sequences  $\{c_t, n_t, k_{t+1}, \kappa_t\}$  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:

$$y_t = c_t + i_t \quad (17)$$

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. We adopt a transformation of these parameters from quarterly to weekly. Table 1 lists the parameters used in the model. Regarding the pandemic parameters we follow Eichenbaum et al. (2020). The weights of consumption, labor, and non-economic activity in epidemic propagation are  $\pi_c = 0.0046$ ,  $\pi_n = 7.3983$  and  $\pi_p = 0.2055$ . The parameters in the lockdown policy are subject to a sensitivity analysis. The standard deviation of the pandemic shock is set at 0.9 and the dimension of the epidemic  $I_0$  is equal to 0.001 (see Appendix A and B for further details).

## 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 degrees. To examine the dynamic properties of the model, we carry out a numerical analysis. Notably, we use a first-order Taylor approximation of the model around its steady state. We use the computer package Dynare to find the solution to 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 the first week of March 2020. We consider four different government attitude: (i)  $\gamma_\kappa = 0$  (no lockdown policy), (ii)  $\gamma_\kappa = 0.25$  (pro-economy), (iii)  $\gamma_\kappa = 0.50$  (indifferent between economy and people health), (iv)  $\gamma_\kappa = 0.75$  (pro-people health).

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 assess 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. Fig. 2 reports the effects of lockdown policies on pandemic dynamics and macroeconomic variables. As a result of the unexpected positive pandemic shock on the virus propagation, the total infected people rise (see Eq. 13). The government reacts by imposing a lockdown policy and the quarantine for a fraction  $\nu_t$  of workers following the rule in Eq. 16. Note that the size and

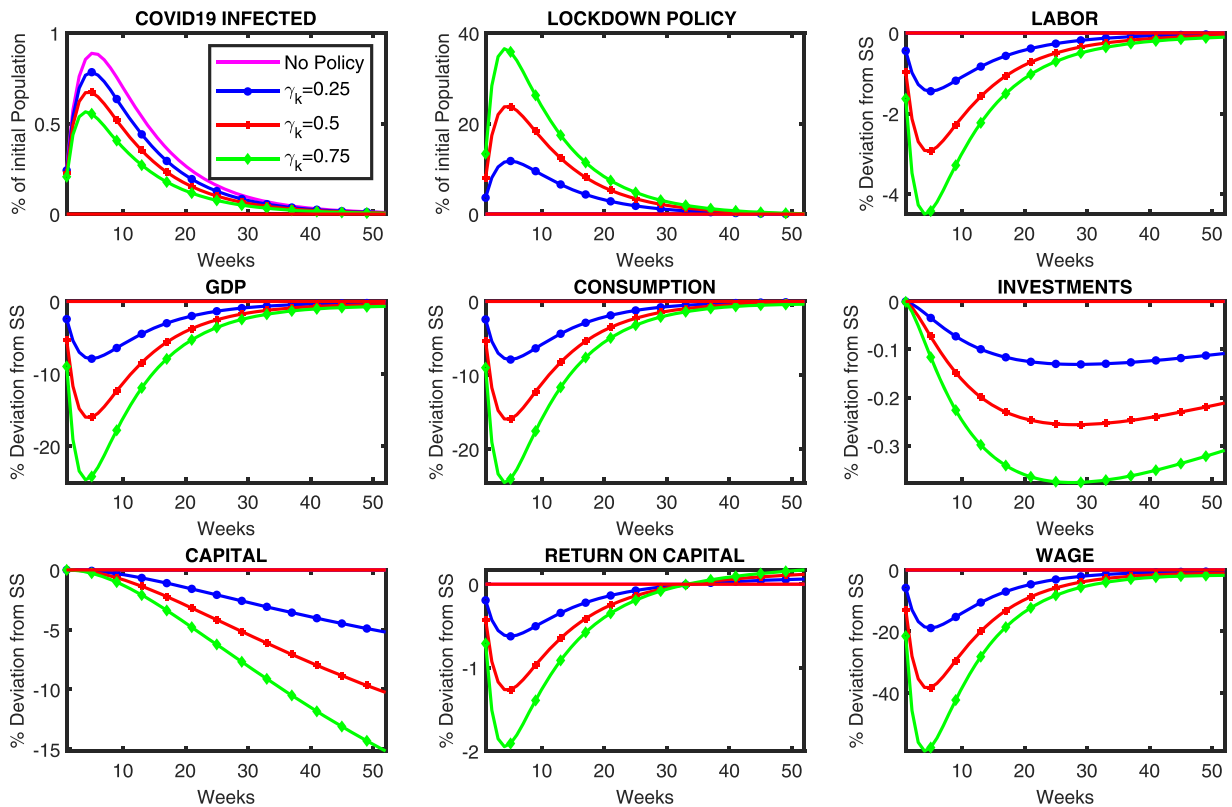


Fig. 2. Response to a pandemic shock.

persistence of the lockdown policy depend on government aptitude. The government policy drops the labor force availability in the economy, so consumption and output fall upon impact via Eq. 5 and Eq. 8. Simultaneously, the decrease in productivity reduces the return on the two factors of production, labor and capital. The representative household responds to price disincentives reducing the supply of capital. In turn, the fall in capital input feeds back in output through the production function and further adds to the pandemic shock's negative effect. In the labor market, wages fall, and the household decreases hours worked, further reducing further production.

Furthermore, following the pandemic shock, the rise in lockdown policy is parallels the dynamics of the COVID-19 disease. 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 epidemic's dimension: strict containment policy reduces the peak level of infections.

Fig. 2 also indicates how the macroeconomic variables evolve under different lockdown policies. Let us start with the case in which the government is a pro-economy attitude. A lockdown policy driven by preserving macroeconomic conditions results in a 10% peak of quarantined workers. On impact, the drop in GDP is about 3%, and the overall decline is much larger because the lockdown is lifted gradually. The overall reduction in GDP thus reaches almost 10% after seven weeks. The temporary unemployment affects consumption: on the impact, the reduction is 2%. The containment policy's persistence aggravates the conditions of households, and after two months, the consumption reaches a negative peak of 9%. Besides, the lockdown's economic conditions determine a reduction in the labor demand of about 1% during the first six weeks since the pandemic shock.

However, stricter lockdown policies intensify the slowdown. On impact, GDP falls about 10% and 15% in the event of an indifferent government and pro-health government. 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 25% (17% in the case of  $\gamma_k = 0.5$ ). The pandemic shock, in turn, pushes down investment via an income effect. Due to the government-imposed quarantine, the households' disposable income falls, and consequently, they prefer to disinvest. Since adjust capital is costly, the adverse impact on investments is gradual: the negative peak is reached after about thirty weeks.

Finally, if the government does not apply social distancing measures, the impact on the economy is null. By contrast, the virus spreads faster, reaching a higher contagion peak than the other cases. 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

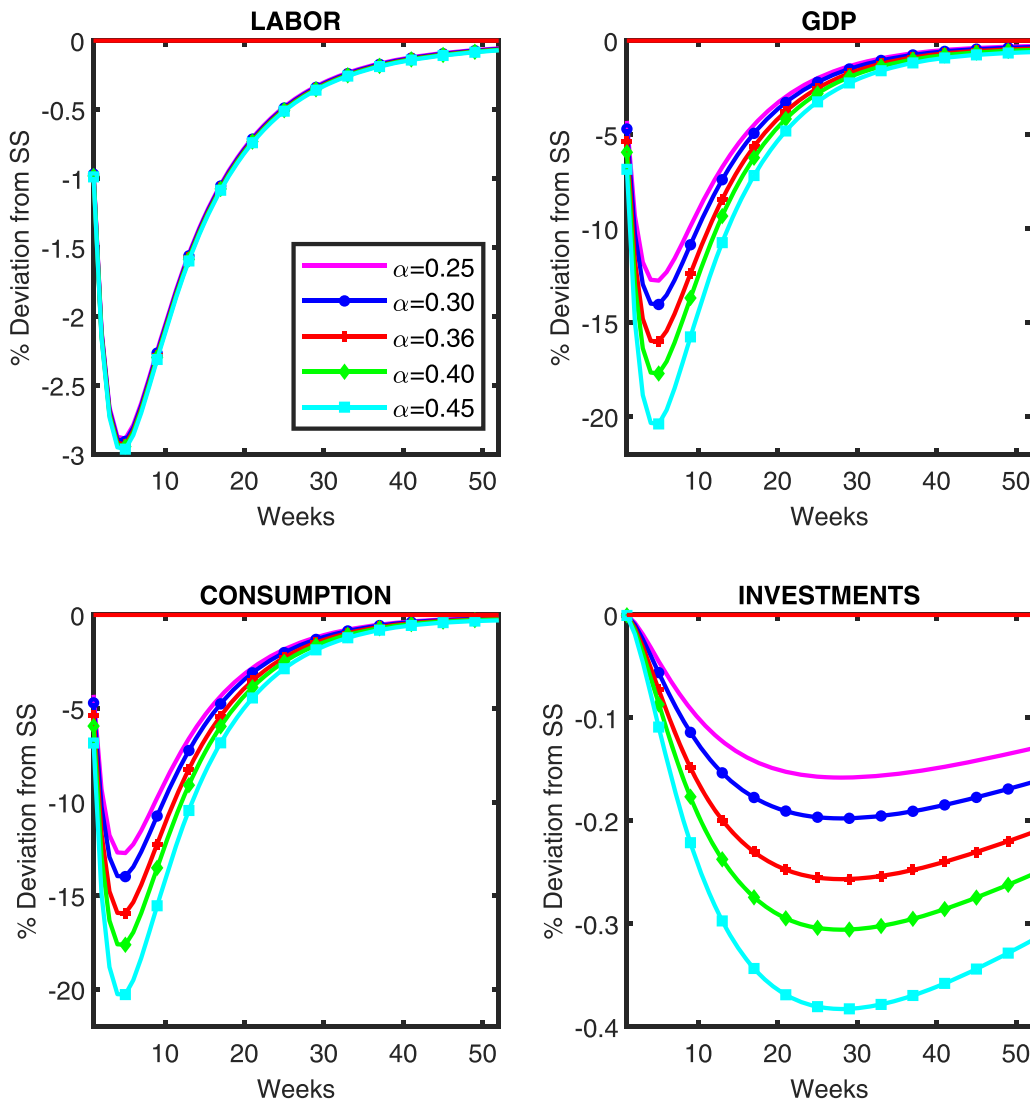


Fig. 3. Pandemic Shock: sensitivity analysis on capital share parameter.

much persistent. After one year since the epidemic outbreak, the investments are still in the early stages of recovery for all degree of lockdown.

Note that the analysis presented in this section shows that this parsimonious model matches the EU stylized economic facts quite well during the first and second quarter of 2020.

### 5.2. Sensitivity analysis: Pandemic shock and technology

The previous sections examine the impact of the pandemic shock on the economy, applying the calibration listed in Table 1. On the contrary, this section provides a sensitivity analysis by varying some crucial parameters associated with the production technology. In fact, exists remarkable differences in performance across and within sectors (de Vet et al., 2021)). Sectors dependent on human contact and interaction have experienced substantial hits by the crisis. These sectors are likely to experience a U-shaped recovery from the crisis, with different recovery rates. This study aims to explore how the specific characteristics of the productive structure affect the dynamics of the economic variables during the pandemic.

First, our analysis investigates the impact of the capital share, focusing on one sector economy, as it is standard in this range of modeling. The section aims to understand how specific economic structures interact with a medium lockdown policy dynamics ( $\gamma_k = 0.5$ ) First, our analysis investigates the impact of the capital share, focusing on one sector economy, as it is standard in this range of modeling. The section aims to understand how specific economic structures interact with a medium lockdown policy dynamics. We deliberately do not focus on the implications across sectors, as the current characteristics of the model do not allow us to grasp the specific structural features of each production sector. However, evaluating the pandemic economic

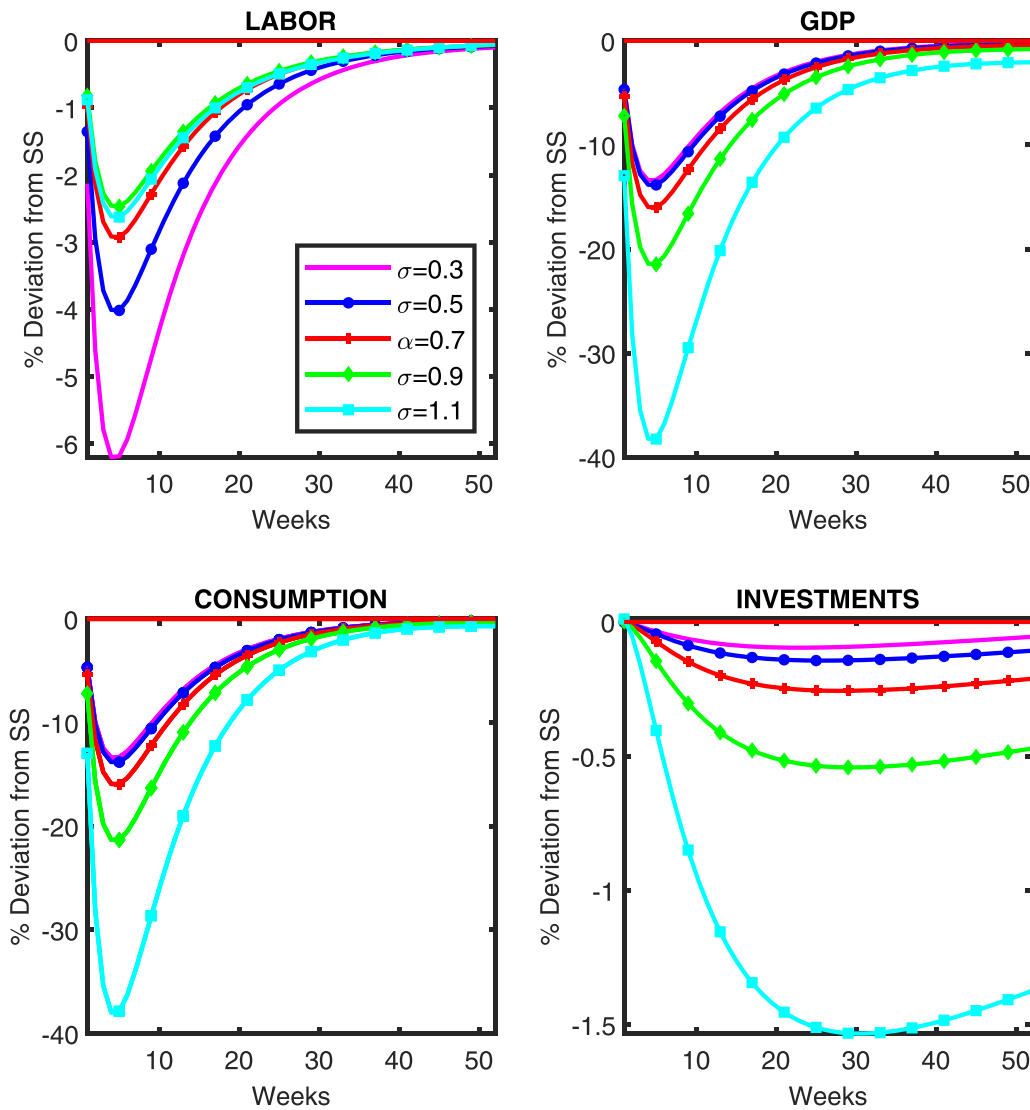


Fig. 4. Pandemic Shock: sensitivity analysis on input substitutability parameter.

implications across sectors requires employing a multisector model. On the other hand, differences in the share of capital in the production function cannot explain alone differences across sectors. Fig. 3 shows that the share of capital in the production technology does not affect labor force dynamics since it is directly associated with the lockdown policy. However, the composition of the production structure affects output, consumption, and investments. Notably, in the high-labor intensity sector, the negative impact of the government's social distancing policy on the economy is less severe. Since the labor force is independent of capital share on total output, wages do not change with  $\alpha$ . The different recessive effects are mainly related to the reduction in the return on capital, which is stronger in sectors with a smaller share of workforce (see Eq. 10). The fall in capital input affects output through the production function inducing a more significant slowdown. Consequently, the negative impact on investments is much severe if production technology requires large amounts of capital.

Second, we examine how the elasticity of substitution between capital and labor services affects the macroeconomic variables' response during a lockdown policy. To this end, we conduct a sensitivity analysis by varying  $\sigma$  from 0.3 to 1.1. Fig. 4 shows how the inputs elasticity in the production process affects the economy dynamics during a lockdown policy with "indifferent government". Differently to the previous case, low substitutability among factors negatively affects the labor force dynamic. In detail, when the substitutability between capital and labor decreases, wages fall, and the household reduces hours worked. The activities with a high probability of virus propagation linked to the labor environment are reduced, and the lockdown policy will be less stringent. This response implies a less severe economic slowdown. Moreover, the impact of  $\sigma$  on the economy is not linear: the policy's harmful effects increase more than the increase (reduction for labor) recorded by  $\sigma$ . Finally, a

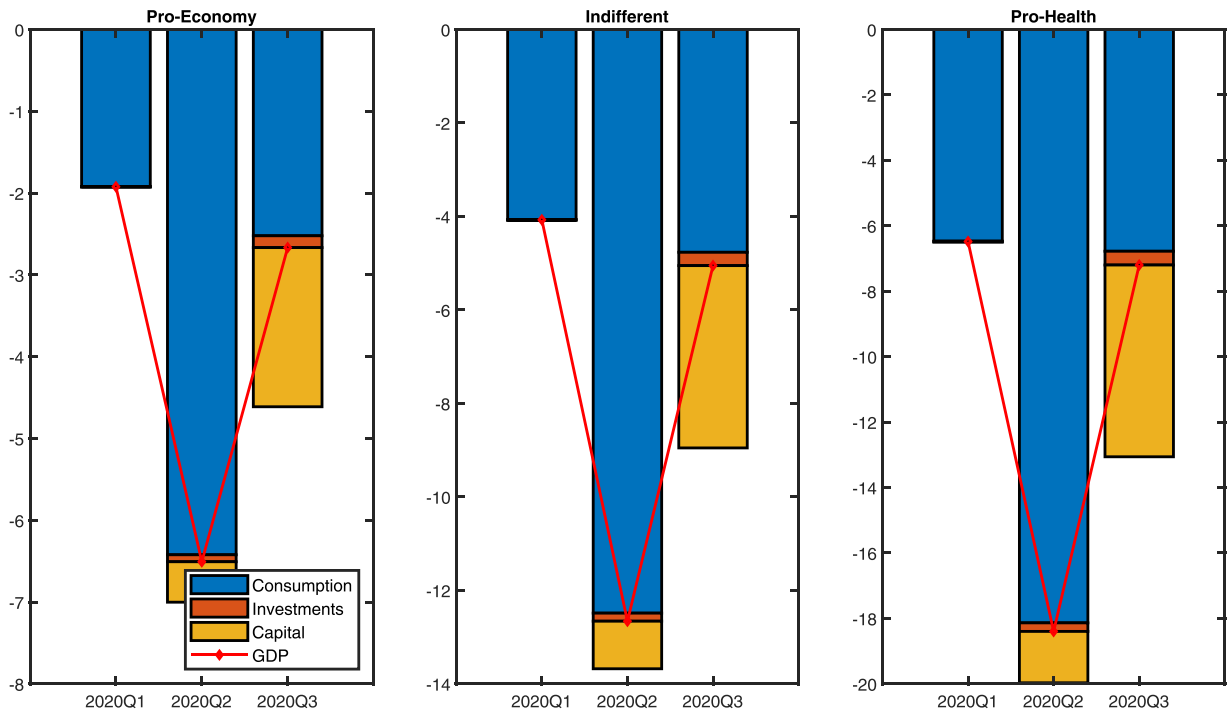


Fig. 5. Model decomposition of GDP growth by expenditure aggregates, contributions to growth in percentage points- 2020Q1–2020Q3.

more flexible technological structure allows avoiding extreme suffering to the labor market, but it triggers a more severe recession.

## 6. Conclusions

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. To investigate this model's capability to replicate economic dynamics during a pandemic, we made a comparison between real data (as in Fig. 1) and our model results. However, this comparison cannot be extended beyond the first three quarters. Indeed, starting by autumn 2020, government actions to fight the pandemic have changed (e.g., partial lockdown according to the number of new infected per area). As a result, the comparison between real and model data becomes less significant as we move forward through the quarters. To this end, Fig. 5 shows the model decomposition of GDP growth by expenditure aggregates (consumption, investment, and capital) in percentage points 2020Q1–2020Q3, under the three alternative lockdowns policies: pro-economy, indifferent, and pro-health. As shown in real data (Fig. 1), GDP growth shows a V-shaped dynamic in all three policy scenarios. In particular, our model shows a recession worsening during the second quarter of 2020 and the consequent recovery in the third quarter of 2020. The negative peak ranges from 6.5% in the pro-economy scenario to about 18% in the pro-health scenario. In line with real data, consumption is the aggregate that suffers a greater contraction in the first stage of the pandemic event. However, consumption positively responds quickly when lockdown policies are relaxed.

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.

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. Another solution to a pandemic event is to vaccinate a massive population to achieve herd immunity. A successful vaccination program could reduce the need for stringent lockdown policies and enforced quarantines. However, the potential benefits of a vaccine are known in the short term but not in the medium- long term when new virus variants could arise.

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. We do not consider policies to mitigate the economic hardships suffered by households and firms, to focus exclusively on the initial macroeconomic impact of a lockdown policy in a context where this policy is the only strategy to fight the pandemic event. However, government responses to the crisis have been unprecedented since the onset of the pandemic. Fiscal packages have often consisted of many measures, including loan guarantees, job retention schemes, direct transfers, expanded access to benefits, and tax measures. As part of these large fiscal packages, tax measures have played a significant role in providing crisis relief to firms and households (Clemens and Stan, 2020). The unprecedented nature of the crisis is prompting a reflection on whether some new tax measures could be contemplated and more traditional ones reconsidered. In a post-crisis environment, authorities will likely address the tax challenges of the digitalization of the economy (OECD,2020). We are already working to address these issues, employing this model to discuss different policy recipes and active fiscal policies.

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**Code availability**

The code that support the findings of this study are available on request from the corresponding author.

**Data Availability**

The data that support the findings of this study are available on request from the corresponding author.

**Declaration of Competing Interest**

The authors declare no conflict of interest.

**Appendix 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:

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

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

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

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

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

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

*A.2. Firms’ Optimization Problem*

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

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

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

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

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

### 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):

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

It implies from equation (11):

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

from equation (10):

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

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 no. determinations (Fig. 6). The standard deviation of the log differentiates series of the weekly new infected is equal to 0.94.

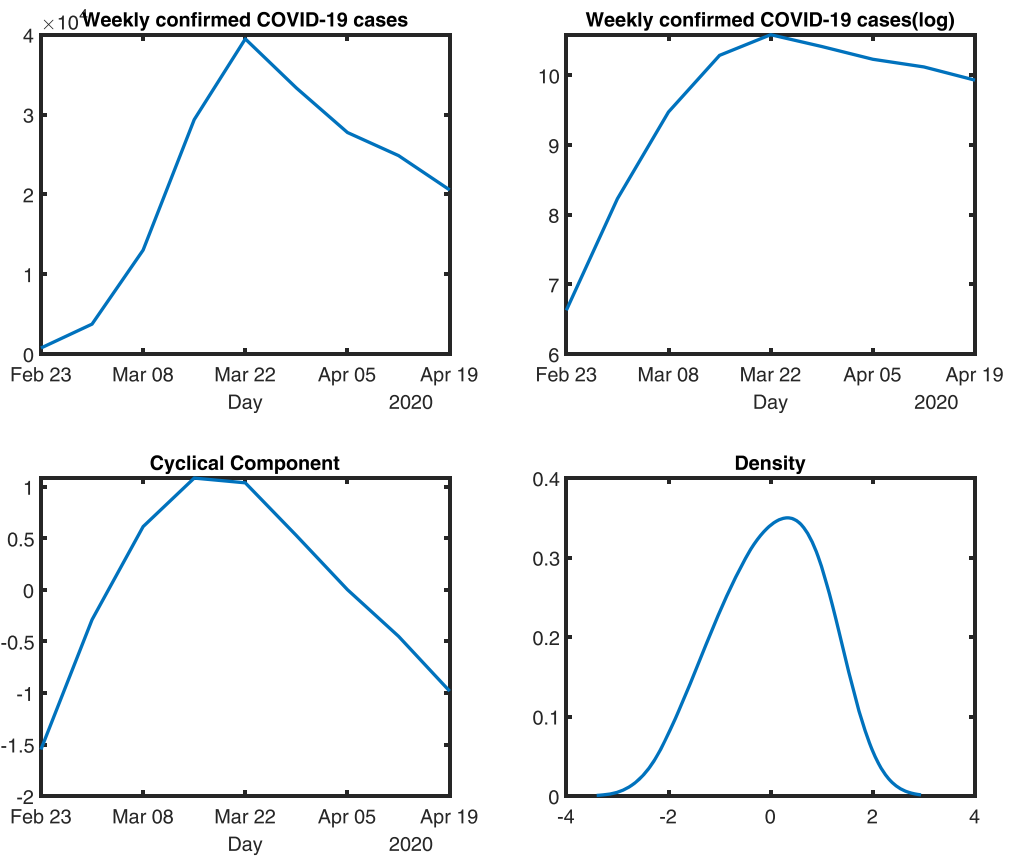


Fig. 6. COVID-19 Weekly Incidence in Italy from February 23 to April 25, 2020.

Table 2  
KPSS Test.

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

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.

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: Table 3 Table 4.

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

Table 3  
AIC and BIC values.

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



**Table 4**  
COVID19-ARIMA(1,0,1) Model.

	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

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