Banco de Portugal
Banco de Portugal Economic Studies, Vol. VIII, No. 3

Pandemic shocks

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July 2022

Abstract
We introduce three pandemic shocks—impacting domestic households' demand, external agents' demand, and worldwide supply—in a standard general equilibrium model and devise a strategy to estimate those for Portugal. We setup a piecewise linear Kalman filter where lockdown disturbances have zero variance until 2019:4 and are estimated thereafter. Pandemic shocks are endowed with contemporaneous impacts on output 6–16 times greater than non-pandemic equivalents, and explain around 90 percent of the Gross Domestic Product forecast error variance up to 1 year. The first confinement wave is essentially marked by supply side perturbations (which in our model have also a demand-side flavor by affecting households' expected income), *i.e.* an inability of firms to produce goods. The ensuing confinement waves rely more heavily on demand-side disturbances—domestic on a first stage and external on a second stage—*i.e.* an inability to consume goods. The productive sector seems to have become more resilient to COVID-19 effects throughout 2021 in line with a gradual recovery in supply disturbances on the aftermath of the collapse triggered by the first confinement period. In contrast, inflation is mostly determined by non-pandemic disturbances, particularly by cost-push shocks. (JEL: C11, C13, E20, E32)

Keywords: DSGE models, Portugal, euro area, small-open economy, Bayesian estimation, pandemic crisis, Lockdown.

1. Introduction

The 2020-21 period was marked by the pandemic crisis, encountering no parallel in recent history. Lockdowns and social distancing inflicted important damages to firms and households alike, suspending productive capabilities (inability to produce the same amount of goods and services) on the supply side and triggering forced savings (inability to consume the same amount of goods and services) on the demand side. Portugal was no exception. The lockdown period impacting the first half of 2020 triggered an unprecedented decline in Gross Domestic Product (GDP) totaling nearly 20 percent (Figure 1). Impacts were partially reverted in the third quarter, but the

Acknowledgements: We are grateful to Nuno Alves, João Amador and Pedro Duarte Neves for helpful comments and sugestions. The analyses, opinions and conclusions expressed herein are the sole responsibility of the authors and do not necessarily reflect the opinions of Banco de Portugal or the Eurosystem. Any errors and mistakes are ours. This paper is financed by National Funds of the FCT—Portuguese Foundation for Science and Technology—within the project UIDB/04007/2020.

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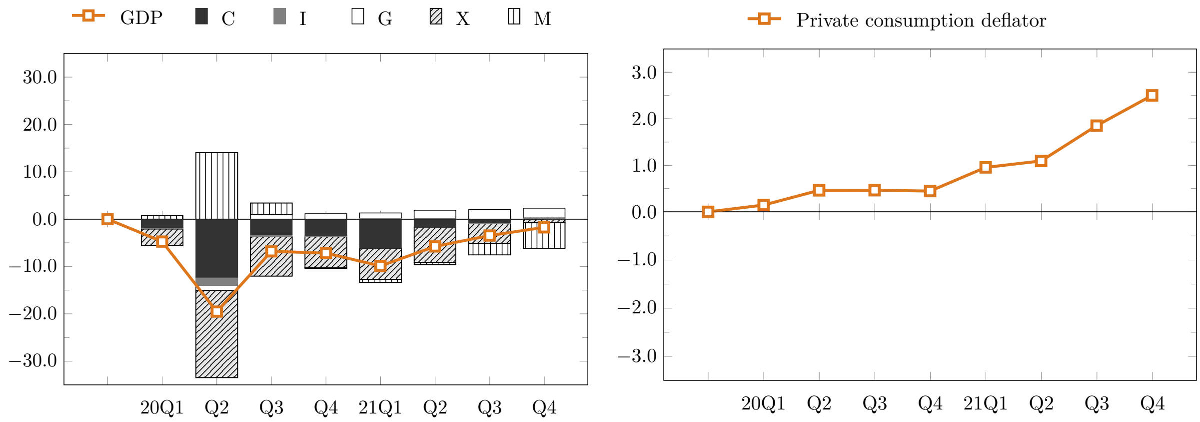


(A) GDP and demand components.

(B) Consumer prices.

FIGURE 1: Output and consumer prices during the pandemic crisis.

Sources: Statistics Portugal and authors' calculations.

Notes: GDP, demand components and consumer prices (National Accounts) are measured as an index (2019Q4 = 0). Private consumption is identified by C, private investment by I, government consumption and investment by G, exports by X and imports by M.

new lockdown phase that came into force by the end of 2020 and beginning of 2021 triggered a new downfall in output, placing GDP around 10 percent below the pre-pandemic level. The ensuing quarters were characterized by a gradual recovery of lost output, even though GDP was still around 1.5 percent below the pre-pandemic level by the end of 2021. Private consumption and international trade were particularly affected in 2020Q2. Imports recovered rapidly, but exports were still below the pre-pandemic level by the end of 2021. Impacts on the nominal side were contained, with consumer prices depicting an upward path, particularly during 2021.

In this article we devise a strategy to identify the economic driving forces and properties that lay behind the Portuguese pandemic crisis, under the lens of an estimated Dynamic Stochastic General Equilibrium (DSGE) model. The model is estimated using Bayesian methods and quarterly observations for twenty five observable time series, including real, nominal and financial variables.[1] We disentangle a domestic demand-side effect (*aka* forced savings due to the households' inability to consume goods), an external demand-side effect (*aka* collapse in the export penetration of goods and services, including tourism, due to the foreign agents' inability to consume domestically produced goods), and a global supply-side effect (*aka* forced closures and shutdowns). This choice was based on extensive experimentation, and these disturbances (henceforth also named pandemic shocks) are able to absorb the bulk of economic volatility during

1. Estimated DSGE models, which have assumed an important role amongst a number of policy-making institutions (see Júlio and Maria (2021) for a list of references), provide a structural interpretation of business cycle fluctuations. Estimation byproducts constitute powerful storytelling devices and instruments of policy analysis. For example, Júlio and Maria (2017) present an estimated version of the PESSOA model to address the post-2008 period. This version has also been used to identify the main determinants behind GDP projections of Banco de Portugal over 2020–2022 (Banco de Portugal 2020).

the pandemic period.[2] The implementation of the domestic forced-savings shock offers little disagreement, and follows the approaches in Faria-e-Castro (2021) or Cardani *et al.* (2021). The external demand shock came out as playing a key role in our experimentation exercises, reflecting fluctuations in exports during this period that could not be mimicked by any other source. Both shock processes are assumed non-persistent in line with Cardani *et al.* (2021), due to their highly temporary nature. Nonetheless, they may depict persistent effects *via* the endogenous dynamics of the model. The supply shock is more controversial. We settled on a moving average process of order 2 in the worldwide technology growth rate, such that a period of negative growth is followed by an expected recovery and *vice-versa*.[3] Although different in spirit, this shock has some resemblance with that developed in Guerrieri *et al.* (2020).[4]

The model cannot be plainly estimated from the 2000s' until the pandemic crisis, since the concomitant structural break generates severe parameter instability. Standard deviations estimated for the pre-pandemic period convey a poor description of recent years, endowed with greater volatility levels in several dimensions. We overcome these issues by first estimating the model for the 1999:1–2019:4 period, along the lines in Júlio and Maria (2022). The model is exactly identified apart from measurement errors, embodying 25 shock processes for 25 observed variables. The three lockdown shocks have a calibrated zero variance at this stage. We then lift the zero-variance assumption and estimate the lockdown shocks for the 2020:1–2021:4 period (specifically the three parameters related with the standard deviation of new shock processes and the two parameters related with the moving average components of the pandemic growth shock), taking as calibrated all remaining parameters and standard deviations.

We thereafter apply a piecewise linear Kalman filter to infer structural shocks during the pandemic period, in a heteroskedastic environment where lockdown shocks have zero variance until 2019:4 and a positive estimated value thereafter. During the pandemic period the filter uses lockdown perturbations, endowed with much greater estimated standard deviations as compared with their non-pandemic counterparts, to allocate the bulk of economic volatility. Lockdown perturbations result in impacts on output 6–16 times greater than non-pandemic equivalents, explain around 90 percent of the GDP forecast error variance up to one year, and around 80 percent up to 3 years.

The year of 2020 is highly marked by supply-side perturbations (which in our case also affect demand through income effects). The correlated downfall in all demand components alongside Euro Area output favors a shock that impacts domestic and

2. We use the terms "pandemic shocks" and "lockdown shocks" interchangeably.

3. Our shock selection also follows from the small-open economy framework. For instance, Eichenbaum *et al.* (2021, 2020) argue in favor of perturbations in aggregate demand and aggregate supply, driven by risk-management decisions affecting consumption and labor supply from households. However, they have in mind the United States economy. As compared to theirs, our small-open economy model attributes a greater role to a supply shock that affects both the domestic and the foreign economy, and feeds an external demand perturbation that mimics the collapse in exports and subsequent recovery.

4. The authors develop a supply shock in a multi-sector new Keynesian model that is able to generate demand-side effects that may be larger than the shock itself, due to their repercussions in households' income. They argue that shutdowns, layoffs, and firm exits during the pandemic may depict this feature.

foreign production alike rather than specific sectors, *i.e.* an inability of firms to produce goods during the first lockdown period. Under the lens of the DSGE model, this interpretation is more likely than the alternative which consists in allocating the economic downfall to several individual (theoretically uncorrelated) shocks impacting demands in each sector of the domestic economy—*viz.* private consumption, public consumption and investment, private investment and exports—jointly with a shock impacting foreign demand. Output volatility throughout 2021 relies more heavily on demand-side disturbances. The larger decline in private consumption *vis-à-vis* other demand components in the first quarter and the large recovery in exports during the second half of the year favored sector-specific demand impacts, rather than supporting an inability of firms to produce goods. To put differently, ensuing confinement waves impacted to a greater extent the inability of domestic households and foreign agents to consume goods, as the productive sector adapted to become more resilient to COVID-19 effects, in line with the gradual recovery in supply disturbances on the aftermath of the huge 2020 collapse.

The literature on the relationship between the pandemic disease and economic activity is still scarce, though expanding rapidly. An important research stream fetches ideas from mathematical biology (*e.g.* Kermack and McKendrick 1927; Atkeson *et al.* 2020; Berger *et al.* 2020) and inserts them into modern general equilibrium frameworks (*e.g.* Eichenbaum *et al.* 2020, 2021; Glover *et al.* 2020; Alvarez *et al.* 2021).[5] These models endogenize the dynamics of epidemics jointly with the economy, thus being able to address issues like optimal health policy responses, a topic outside the scope of our article. Another literature stream takes the epidemic as exogenous and studies its effects on some economic dimension, such as fiscal policy (*e.g* Faria-e-Castro 2021; Bayer *et al.* 2020). More related to ours is the article of Cardani *et al.* (2021), who analyze the short-term economic effects of the pandemic crisis through the lens of a DSGE model. The authors introduce one-off pandemic shocks into the model, *viz.* forced savings (households being unable to consume) and labor hoarding (gap between hours paid and worked). They estimate the model for the Euro Area economy until 2019:4 through Bayesian methods and use a piecewise linear Kalman filter to infer structural shocks during the pandemic period, assuming a calibrated standard deviation for the forced savings shock substantially higher than the estimated value during the pandemic period. Their conclusions favor the domestic savings shock as key driver of GDP growth during the recent period.[6] Our approach differs from theirs along two key dimensions. First, our selection of pandemic shocks is based on experimentation, and identifies different lockdown disturbances. This cannot be dissociated from our small-open economy framework, which attributes a greater role to external shocks, contrasting with their DSGE setup designed for the Euro Area. Second, our piecewise linear Kalman filter is based on estimated standard deviations of lockdown shocks, providing a more

5. Other references within this literature include, for instance, Krueger *et al.* (2021) and Farboodi *et al.* (2021).

6. This deterministic heteroskedasticity assumption is in line with the approach followed by Lenza and Primiceri (2020) in the context of a VAR model.

accurate description of pandemic impacts. Corrado *et al.* (2021) also devise a strategy to identify structural shocks in disaster times, concluding that the COVID-19 pandemic is attributable to a combination of both demand and supply-side factors.[7]

The remainder of the article is organized as follows. The next section provides a short description of the model. We continue by presenting our methodology, the database, and the stochastic content. This is followed by a section highlighting the key drivers and features of the pandemic crisis under the lens of our estimated DSGE model. The last section concludes.

2. A DSGE model for a small euro area economy

The model is identical to the full-fledged infinitely-lived agents model described in Júlio and Maria (2022). It is a New-Keynesian DSGE model for a monetarily-integrated small economy, featuring a multi-sectoral production structure, imperfect market competition, nominal and real rigidities, and financial frictions. Trade and financial flows are restricted to euro area countries, and the euro area is immune to domestic shocks, a consequence of the small-open economy framework. The law of one price implies that domestic prices are tied down by the euro-area price level in the long run.

The domestic economy is composed of eight types of agents: households, intermediate goods producers (manufacturers), final goods producers (distributors), importers, government, capital goods producers, entrepreneurs, and banks. The model is closed with the foreign economy—the remaining euro area composed of foreign agents and the central bank—with whom domestic agents interact in the goods and financial markets. The rest of the euro area is pinned down by a system of three equations—an IS curve, an AS curve and a Taylor rule (henceforth IS-AS-TR framework).[8] We assume that the demand for domestic exports depends on foreign demand, which in turn depends on euro area output via an Autoregressive Distributed Lag (ADL) equation.

Two household types coexist in the model: asset holders, who are able to smooth consumption over lifetime by trading assets; and hand-to-mouth households, who have no access to asset markets and therefore consume all their income in each and every period. A representative household derives utility from consumption and disutility from working. Flow utility is additive and separable in all arguments. Asset holders are composed of workers and entrepreneurs, and there is perfect consumption insurance within the family. They supply labor services to manufacturers, and receive an after-tax wage rate from employers, transfers from the government, and dividends originating from manufacturers, distributors, capital goods producers, importers and

7. Other articles related to the identification of shocks during the pandemic include Charalampidis and Guillochon (2021), Céspedes *et al.* (2020) and Can *et al.* (2021).

8. In comparison with Júlio e Maria (2021), the current model no longer features labor unions. These agents were essential in the overlapping generation model to create a wage markup (a wedge between the wage paid by firms and the wage received by households). Unions' profits were afterwards distributed to households in the form of dividends.

entrepreneurs. Asset holders can invest in foreign bond holdings, domestic government bonds, and domestic corporate bonds. The no-arbitrage condition matches expected returns of bond holdings in equilibrium, and there exists a nationwide endogenous risk premium placing a wedge between domestic and foreign interest rates. On the expenditure side, asset holders buy consumption goods, and the gap between expenditures and income is reflected in changes in their net asset position. Hand-to-mouth households also supply labor services to manufacturers and receive government transfers.

All households supply labor-specific varieties. Asset holders are wage setters and hand-to-mouth households wage takers. From the interaction in the labor market results an equilibrium wage equation embodying a markup charged by asset holders to manufacturers, which reflects a wedge between the marginal disutility from work and the wage rate.

Manufacturers combine capital, rented from entrepreneurs, with labor services, to produce an intermediate good, which is thereafter sold to distributors. Manufacturers are perfectly competitive in the input market and monopolistically competitive in the output market, and face quadratic adjustment costs on price changes. They pay social security taxes on their payroll and capital income taxes on profits.

The financial accelerator mechanism—whereby financial frictions affect the after-tax return on capital and therefore capital demand—comprises capital goods producers, entrepreneurs, and banks, along the lines of Bernanke *et al.* (1999) and Christiano *et al.* (2014). Capital goods producers are the exclusive producers of capital. Before each production cycle, they buy the undepreciated capital from entrepreneurs and combine it with investment goods bought from distributors to produce new installed capital, which is thereafter sold to entrepreneurs. Capital goods producers face quadratic adjustment costs when changing investment levels and are assumed to operate in a perfectly competitive environment in both input and output markets.

Entrepreneurs' actions have a direct effect on the capital accumulation of the economy. They do not have sufficient funds to finance desired capital purchases, but can cover the funding gap by borrowing from banks.[9] With net worth taken as given, they decide capital holdings—bought from capital goods producers—and concomitantly balance sheet composition and leverage. Entrepreneurs face a risky environment in which idiosyncratic shocks change the value of the capital stock (after the balance sheet composition has been decided). They rent the capital stock to manufacturers for usage in the production process, receiving a rental rate in return, and pay a capital income tax on their profits.

Banks operate in a perfectly competitive environment, and their sole role is to borrow funds from asset holders and lend them to entrepreneurs. If an entrepreneur goes bankrupt, due to an adverse idiosyncratic shock, the bank must pay a repossession cost. Since capital acquisitions are risky, so are the loans of banks, who therefore charge a

9. Dividend distribution prevents net worth accumulation beyond which external finance is no longer required.

spread over the nationwide interest rate to cover for bankruptcy losses. Even though individual loans are risky, aggregate banks' portfolio is risk free since each bank holds a fully diversified portfolio of loans. The contract celebrated between the entrepreneur and the bank features a menu of state contingent interest rates that ensures zero profits for banks in each period and in all possible states of the world. All households loans are therefore secure at all times.

Distributors combine domestic intermediate goods with imported goods to produce final goods. Consumption goods are acquired by households, investment goods by capital goods producers, public consumption goods by the government, and export goods by foreign distributors. They are perfectly competitive in the input market and monopolistically competitive in the output market, face quadratic adjustment costs on price changes, and pay capital income taxes on profits.

Government spending comprises not only the above-mentioned acquisition of public consumption goods from distributors but also lumpsum transfers to households and interest outlays. These activities are financed through tax levies on wage income, capital income, and households' consumption. The government may issue one-period bonds to finance expenditure, paying an interest rate on public debt. Wage income taxes include the contributions paid by employees (henceforth referred to as labor taxes) and the payroll tax paid by manufacturers. Labor taxes ensure that debt follows a nonexplosive path, although automatic stabilization policies allow the fiscal balance to temporarily deviate from the pre-determined target level.

The rest of the world corresponds to the rest of the monetary union, and thus the nominal effective exchange rate is irrevocably set to unity. The domestic economy interacts with the foreign one via the goods and financial markets. In the goods market, importers buy imported goods from abroad to be used in the production of final goods, paying quadratic adjustment costs on price changes. In the international financial market, asset holders trade assets to smooth out consumption.

3. Shocks and data

The huge disturbances that characterize the 2020:1–2021:4 sample period severely impact estimated persistence and standard deviations of shock processes if the model is estimated until 2021:4. Some parameters become highly unstable once the sample is expanded to include the pandemic crisis.[10] We circumvent these issues by carrying out a simple three step procedure, as clarified in Figure 2. First, we estimate the model using quarterly observations for the 1999:1–2019:4 period (prior to the pandemic crisis), as in Júlio and Maria (2022). The stochastic behavior of the model is driven by twenty one structural shocks affecting directly the domestic economy and following first-order

10. The large disturbances impacting the economy during this time period give rise to non-negligible computational issues (*e.g.* the Metropolis-Hastings algorithm cannot be properly initialized and posteriors distributions are badly behaved). Estimating the model from 1999:1 until 2021:4 while acknowledging the specificity of the pandemic crisis requires sophisticated estimation methods that are yet being developed in the literature, a topic outside the scope of this article.

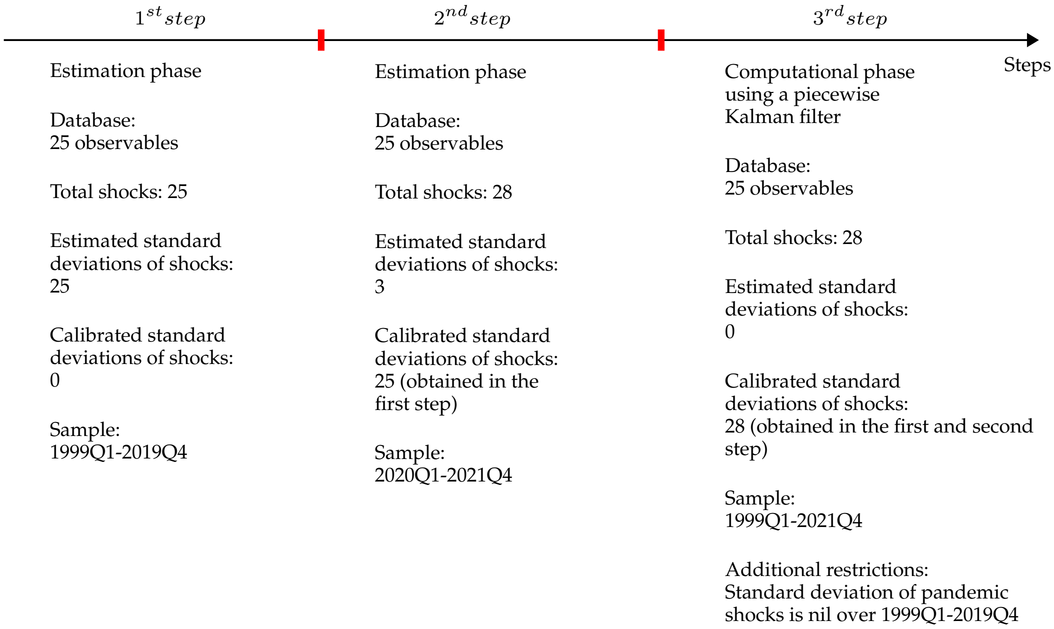


FIGURE 2: Estimation and computational phases.

Source: The authors.

Notes: The stochastic content of the model is presented in Figure 1, and the database in Figure 2.

autoregressive processes. To these we add the shocks brought about by the IS-AS-TR system of equations, and by the ADL equation for foreign demand (Table 1). The data includes twenty five observable time series (described below), and hence the model is exactly identified, apart from measurement errors.

Next, we implement three pandemic-specific (lockdown) shocks in the model. These represent the bulk of impacts during this period, and their selection followed extensive experimentation. The first is a domestic demand shock, implemented as a household preference *iid* shock impacting the Euler equation of both asset holders and hand-to-mouth households. The second is an exports penetration *iid* shock, mimicking an exogenous foreign demand perturbation. The third is a Harrod-neutral supply-side shock, impacting the unit root labor-augmenting technology. This disturbance performed better in explaining the pandemic crisis when compared with a disturbance on the stationary element because it captures co-movements in both domestic and external variables alike.[11] More precisely, technology T_t is driven by a unit root process $\log(T_t/T_{t-1}) = g_t^{\mathrm{NP}} + g_t^{\mathrm{P}}$ where the non-pandemic component g_t^{NP} follows a standard autoregressive process of order 1, and

11. We do not distinguish between intensive and extensive margins, and provide hours worked and wages per hour (instead of heads) as observable time series in estimation. There exists a large co-movement between these data and GDP during the pandemic crisis, and therefore the effects of labor hoarding are not embedded in the model nor captured by any stochastic process.

Component	Agent	Processes	Aggregation
Households			
Preference shock	Households	AR(1)	O-Domestic
Growth			
Unit root labor-augmenting technology	Manufacturer	AR(1)	O-Domestic
Technology			
Stationary labor-augmenting technology	Manufacturer	AR(1)	O-Domestic
Private investment efficiency	Capital goods producer	AR(1)	O-Domestic
Markup			
Wages	Households	AR(1)	O-Domestic
Consumption goods prices	$\mathcal{C}$ - Distributor	AR(1)	O-Domestic
Investment goods prices	$\mathcal{I}$ - Distributor	AR(1)	O-Domestic
Government goods prices	$\mathcal{G}$ - Distributor	AR(1)	O-Domestic
Export goods prices	$\mathcal{X}$ - Distributor	AR(1)	O-Domestic
Government/fiscal shocks			
Public consumption and investment	Government	AR(1)	O-Domestic
Lumpsum transfers	Government	AR(1)	O-Domestic
Tax rates, labour	Government	AR(1)	O-Domestic
Tax rates, consumption	Government	AR(1)	O-Domestic
Tax rates, capital	Government	AR(1)	O-Domestic
Fiscal rule	Government	AR(1)	O-Domestic
Financial shocks			
Nationwide risk premium	*Several*	AR(1)	O-Domestic
Borrowers' riskiness	Entrepreneur	AR(1)	O-Domestic
Entrepreneurial net worth	Entrepreneur	AR(1)	O-Domestic
External/foreign shocks			
IS-AS-TR structure			
Inflation	$\mathcal{X}$ - Distributor	IS-AS-TR	O-External
Output	$\mathcal{X}$ - Distributor	IS-AS-TR	O-External
Interest rate	*Several*	IS-AS-TR	O-External
Other			
Import penetration	*All Distributors*	AR(1)	O-Domestic
Imports prices markup	*All distributors*	AR(1)	O-Domestic
Export penetration	$\mathcal{X}$ - Distributor	AR(1)	O-External
Foreign demand	$\mathcal{X}$ - Distributor	AR(1)	O-External

TABLE 1. Stochastic content of the model.

Source: The authors.

Notes: The unit-root labor-augmenting technology shock is implemented by assuming that the first difference of the shock follows a stationary AR(1) process. The Portuguese interest rate is defined as the sum of the Euro area interest rate (included in the IS-AT-TR structure) and the exogenous nationwide risk premium. Column "Agent" identifies the agent that is directly affected by the shock, whenever applicable. Agent $\mathcal{H}$-Distribuitor, $\mathcal{H} \in \{\mathcal{C}, \mathcal{I}, \mathcal{G}, \mathcal{X}\}$, stands for the distributor of consumption goods, investment goods, government goods, and export goods, respectively. Column "Aggregation" identifies two groups of non-pandemic shocks, namelly "O-Domestic" and O-External", which are "other" disturbances not directly related with lockdown shocks.

$$\log\left(g_t^{\mathrm{P}}/g\right) = \tilde{\varepsilon}_t^{g,\mathrm{P}} - \omega_1 \tilde{\varepsilon}_{t-1}^{g,\mathrm{P}} - \omega_2 \tilde{\varepsilon}_{t-2}^{g,\mathrm{P}}$$

is the pandemic growth rate following a zero-mean second-order moving average process with *iid*-normal disturbances $\varepsilon_t^{g,\mathrm{P}}$. The prior mean postulates a full reversion of impacts (*i.e.* $\omega_1 + \omega_2 = 1$), though the posterior mean implies only a partial reversion (*i.e.* $\omega_1 + \omega_2 < 1$). Hence, a negative perturbation to the growth rate, driving technology downwards, is followed by two periods where growth settles above steady-state levels and technology recovers but remains below the initial level. The behavior of other smoothed shock processes during the pandemic period did not differ substantially from that depicted during the pre-pandemic period, and therefore we ruled out additional lockdown disturbances. Note that the technology level T_t pertaining the manufacturer's production function impacts the production of an intermediate good which is used as input by all sectors, thus identically affecting all demand components.[12]

The model becomes over-identified, embodying twenty eight stochastic processes for twenty five observable time series. Next, we estimate the model—specifically the standard deviations of the three newly introduced disturbances and the moving average components of the growth shock—for the 2020:1–2021:4 period, taking as calibrated all previously estimated parameters (including persistence and standard deviation of the original twenty five shock processes). All endogenous variables and their transformations, prior to estimation, follow standard practice in the literature (*e.g.* Ratto *et al.* 2009; Christiano *et al.* 2011) and are reported in Table 2. It should be noted that observed data transformations isolate the estimation from exogenous influences not directly accounted by the model's structure. Implicit payroll taxes and the social benefits-to-GDP ratio are two examples of observed data endowed with in-sample trends that are to a great extent related with a protracted increase in social protection and with aging. The model is not designed to capture these features, which assume a structural nature. To properly take into account their high frequency movement we computed the first (log) difference. We also demean most time series—thus suppressing exogenous trend growth differences or level differences—to favor the business cycle content of observed data and to avoid trending exogenous processes that affect the great ratios. Means are computed for the 1999:1–2019:4 period and remain unaffected by the pandemic crisis. All quarterly observations are seasonally adjusted. Whenever adjusted official series were not available, the transformation was performed using X12 ARIMA. The exception is fiscal data, which are converted from annual to quarterly frequency through a four-period moving average to eliminate erratic movements related with cash

12. The non-persistence of the two demand shocks is key to overcome some identification issues in the estimation process which are triggered by persistence parameters. When evaluating supply shocks, we experimented a domestic stationary labor-augmenting technology perturbation and placed it against a Harrod-neutral worldwide partial mean reverting technology perturbation of the same type. The latter performed substantially better in explaining the observed time series, both in terms of likelihood and explained variance. It is able to better take into account co-movements between domestic and foreign observable variables, particularly GDP. Furthermore, the shock also generates a slight demand-side flavor by impacting households' expected income (the effects on inflation are theoretically indeterminate). We experimented alternative processes (including ARMA models), but the chosen specification performed better overall in terms of identification and Bayes ratio.

Observed variables	Transformation
Real side	
GDP, per capita	First log difference, demeaned
Private consumption, per capita	First log difference, demeaned
Public consumption and investment, per capita	First log difference, demeaned
Private investment, per capita	First log difference, demeaned
Exports, per capita	First log difference, demeaned
Imports, per capita	First log difference, demeaned
Real wages, per capita	First log difference, demeaned
Hours worked, per capita	First log difference, demeaned
Nominal side	
Private consumption deflator	First log difference, demeaned
Public consumption and investment deflator	First log difference, demeaned
Private investment deflator	First log difference, demeaned
Exports deflator	First log difference, demeaned
Imports deflator	First log difference, demeaned
Fiscal policy	
Implicit indirect taxes	Level, demeaned
Implicit household income taxes	Level, demeaned
Implicit corporate taxes	Level, demeaned
Implicit payroll taxes	First log difference, demeaned
Expenditure-to-GDP ratio: social benefits	First log difference, demeaned
Financial side	
Real loans to Non-financial corporations, per capita	First log difference, demeaned
Corporate interest rate spread	Level, demeaned
Nationwide risk premium	Level, demeaned
Euro area data	
Real GDP, per capita	First log difference, demeaned
HICP	First log difference, demeaned
3-month EURIBOR	Level, demeaned
Other variables	
External demand, per capita	First log difference, demeaned

TABLE 2. Observed variables.

Source: Statistics Portugal, EUROSTAT, Banco de Portugal and authors' calculations.

Notes: *Per capita* aggregates are computed with the overall population. Real wages are deflated by the private consumption deflator. Real loans are deflated by the GDP deflator. The corporate interest rate spread, measured in percentage points (pp), is computed as the difference between the interest rate paid by non-financial corporations on new loans and the 3-month EURIBOR. The nationwide risk premium is measured by the differencial between Portuguese and German short-term Treasury bills (except over 1999–2002, a period where we assumed a nil risk premium, and over 2011–2012, a period where we used the differential between Portuguese and German corporate interest rates). HICP stands for Harmonized Index of Consumer Prices.

flows that undermine estimation. The variance of measurement errors is calibrated at 5 percent of the variance of each data series.[13]

We follow common practice in the literature and calibrate several non-identifiable or weakly identified parameters in the first estimation step according to related empirical

13. Measurement errors allow for the inclusion of data for all GDP components in addition to GDP itself, while avoiding stochastic singularity in the resource constraint, and greatly facilitate estimation.

	prior			posterior		
	dist.	mean	s.d.	mean	5%	95%
Pandemic shocks (second estimation step)						
Moving average of growth						
Order 1	Γ	0.75	0.10	0.50	0.38	0.60
Order 2	Γ	0.25	0.10	0.44	0.28	0.59
Standard deviations						
Domestic HH demand	Inv-Γ	0.1	$+\infty$	0.326	0.179	0.469
Foreign demand	Inv-Γ	0.1	$+\infty$	0.364	0.202	0.524
Growth	Inv-Γ	0.01	$+\infty$	0.0600	0.0308	0.0945
Pre-Pandemic shocks (first estimation step)						
Autoregressive parameters						
Domestic HH demand	β	0.50	0.15	0.26	0.12	0.41
Foreign demand	β	0.50	0.15	0.18	0.07	0.29
Growth	β	0.75	0.10	0.62	0.51	0.73
Standard deviations						
Domestic HH demand	Inv-Γ	0.01	$+\infty$	0.055	0.030	0.080
Foreign demand	Inv-Γ	0.01	$+\infty$	0.057	0.040	0.073
Growth	Inv-Γ	0.001	$+\infty$	0.0024	0.0019	0.0030

TABLE 3. Estimated parameters.

Sources: The authors.

Notes: For both estimation stages, prior information is combined with the likelihood to obtain the posterior kernel, which is maximized through a numerical optimization routine to obtain an estimate for the posterior mode and the corresponding variance-covariance matrix. This information is used as an input to initialize the Random-Walk Metropolis-Hastings algorithm, yielding a sample from the posterior density of model parameters. For each estimation step, we compute 3 parallel chains of 1 million draws each and discard the first 500 thousand as the burn-in phase. Convergence of the simulation is assessed through the diagnostics suggested by Brooks and Gelman (1998). Γ stands for the gamma distribution, Inv-Γ for the inverse gamma distribution, and β for the beta distribution. Standard deviation is abbreviated by "s.d."

studies or micro evidence, or by matching "great ratios" or any other quantifiable steady-state measure. The remaining parameters are estimated through Bayesian methods. Prior to estimation and for better tractability, we stationarize the model with the technology level shared by Portugal and the euro area. The final stage uses the piecewise linear Kalman filter to bring together the results from both estimation stages, setting up a heteroskedastic environment where lockdown shocks have zero variance until 2019:4 and a positive value thereafter. We then use the results from filtered data to evaluate several byproducts of the model—in particular historical decompositions and impulse response functions, all of them evaluated at the posterior mean.

4. Drivers of the pandemic crisis

In this section we identify and describe several key aspects of the pandemic crisis that follow from our two-stage estimated model. The large degree of volatility observed during the pandemic period does not fit into the estimated standard deviations from the first step, and lockdown perturbations identified in the second step are endowed with substantially larger values (Table 3). This increment in volatility is transposed to smoothed shock processes (Figure 3), with pandemic components overpowering

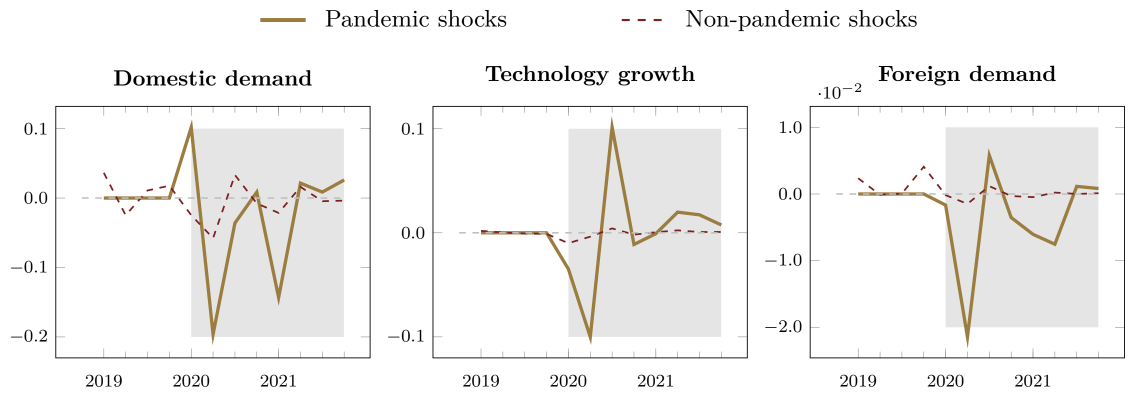


FIGURE 3: Selected smoothed shock processes during the pandemic crisis.

Sources: The authors.

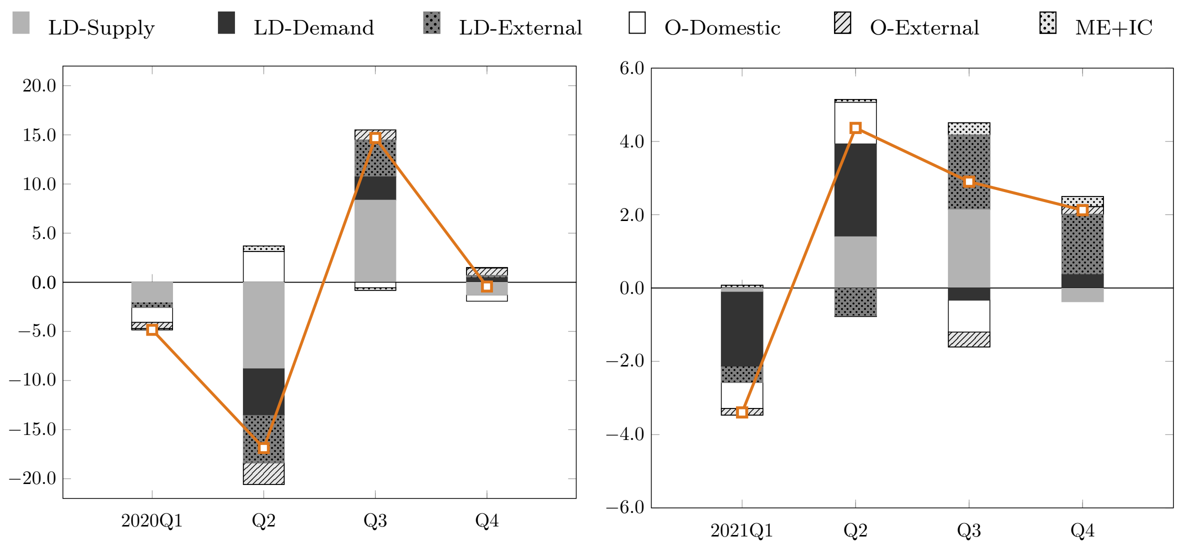
Notes: Non-pandemic shocks were identified by the piecewise linear Kalman filter using parameters estimated for the pre-pandemic period. They can be interpreted as the part of the shock that has some resemblance with the past.

their non-pandemic counterparts during the recent period.[14] Nonetheless, a direct comparison of estimated standard deviations should be interpreted with caution, since the stochastic processes for our three lockdown shocks are different due to the absence of autoregressive components (impulse response functions below provide a more detailed comparison of impacts). The moving average component of the growth shock suggests a permanent impact in technology of just 6 percent of the initial perturbation after two quarters, which is quite different from the pre-pandemic specification which postulates an accumulation over the initial impact due to the autoregressive component.

4.1. Historical decomposition

Historical decompositions in Figures 4 and 6 pinpoint key structural drivers of Portuguese GDP growth and private consumption price inflation under the lens of our two-stage estimated DSGE model. For exposition purposes we focus on lockdown disturbances and catalog all twenty five shocks that are not related with the pandemic period into two categories, "O-external" and "O-domestic", as clarified in Table 1. We must also account for measurement errors and initial conditions, aggregated into a single category. Amongst lockdown disturbances, supply restrictions account for the bulk of the GDP fluctuation in 2020:2 and 2020:3, explaining around 50 percent of the downfall and subsequent recovery (Figure 4). Domestic and external demand factors explain around 15–25 percent each, whereas non-pandemic perturbations play a marginal role. A direct interpretation of these results is that roughly half of the GDP downfall in 2020:2 was driven by inability of firms to produce goods, as many were forced to close, shut

14. All results are available from the authors upon request. The shocks whose parameters were estimated for the pre-pandemic period but pinned down during the pandemic crisis are henceforth named non-pandemic shocks.



(A) Year 2020.

(B) Year 2021.

FIGURE 4: Historical decomposition of GDP growth.

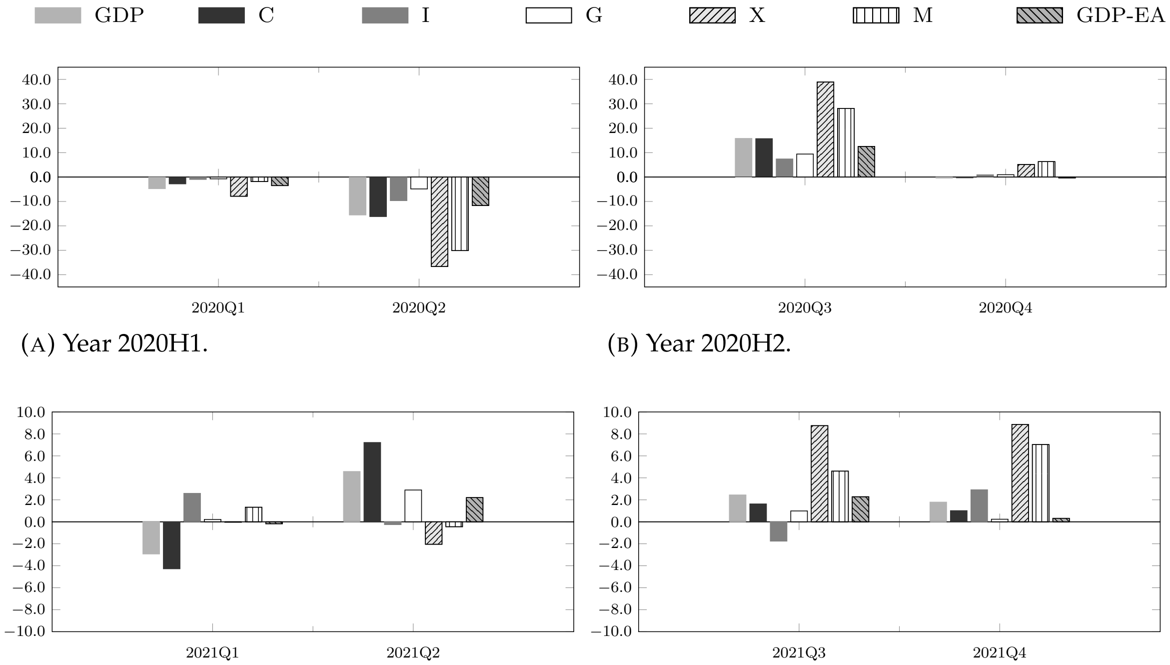
Sources: The authors.

Notes: The quarter-on-quarter GDP growth, measured in percentage, is identified by the orange line plot, and contributions, measured in percentage points, by bar plots. LD stands for lockdown disturbances and O for other disturbances (not directly related with the lockdown). ME denotes measurement errors and IC Initial Conditions.

down, or halt production in the follow-up of the lockdown. The remaining half relies on the demand contraction of domestic households and foreign agents—an inability to consume goods—with evenly distributed impacts.

The decomposition for 2020 identified by the model strongly hinges on the co-movement depicted by all demand components and by domestic and foreign output (see Figure 5). The model reads that all sectors—namely the four domestic and the foreign final goods distributors—are being disrupted in a correlated fashion, and allocates the explanation to a common disturbance that impacts all of them—technological growth. Alternative perturbations, for instance individually impacting each of the final goods producers, are theoretically possibly but deemed unlikely by the model, which settles on the assumption of *iid* and hence uncorrelated shocks. As a result, only fluctuations in demand components that cannot be explained by the common technological growth disturbance are allocated to idiosyncratic perturbation sources. The most pivotal impact the demand of domestic households and foreign agents, directly affecting private consumption and exports. The decline in these GDP components in 2020:2 and the subsequent recovery in 2020:3 are larger than the impacts triggered by technology alone, with idiosyncratic perturbations explaining the remaining effects.

After 2020:4 and during 2021, co-movements between demand components are less pronounced and as a result lockdown-related supply restrictions become comparatively less important in explaining GDP growth fluctuations (except for 2021:3). During the first half of 2021, the lockdown-related disturbance in domestic households' demand stands out as the key output driver, accounting for roughly 60 percent of the GDP



(A) Year 2020H1.

(B) Year 2020H2.

(C) Year 2021H1.

(D) Year 2021H2.

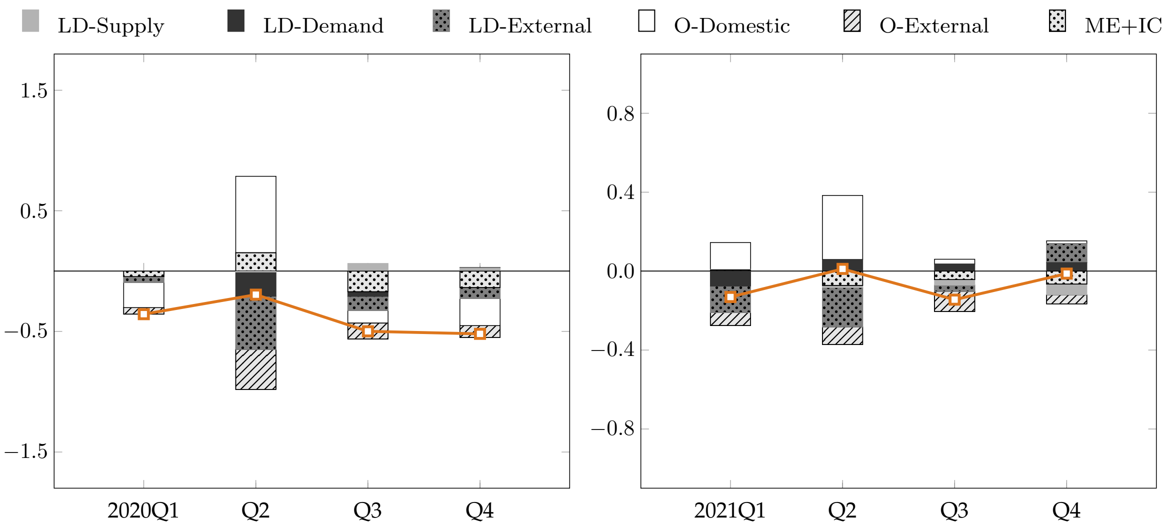
FIGURE 5: GDP, selected demand components, and Euro Area GDP growth.

Sources: Statistics Portugal and authors' calculations.

Notes: All data refers to quarter-on-quarter rates of change, measured in percentage. GDP and GDP-EA corresponds to Portuguese and Euro Area GDP. Private consumption is identified by C, private investment by I, government consumption and investment by G, exports by X and imports by M. The first and second halves of the year are identified by H1 and H2, respectively.

fluctuation during this period (Figure 4). Lockdown-related supply restrictions are roughly nil in the first and account for 30 percent in the second quarters. This interpretation is in line with the large co-movement depicted by the growth rates of private consumption and GDP, which is not matched by other demand components nor by foreign output (Figure 5). In particular, the GDP downfall in 2021:1 and subsequent recovery in 2021:2 is primarily linked to developments in private consumption, while private investment, exports and imports either remain unchanged or co-move negatively with GDP growth during this period. The 2021:2 decline in exports is interpreted by the model as an exogenous perturbation in the lockdown-related foreign agents' demand. Furthermore, when production expands, the model expects an increase in imported goods, used as inputs in production. The slight decline in imports observed in 2021:2 contrasts with a positive GDP growth, and is interpreted by the model as a shift towards domestically produced intermediate goods (whose effects are considered in the category 'O-Domestic'), providing a boost to domestic economic activity.

During the second half of 2021, the lockdown-related recovery in foreign agents' demand stands out as the key output driver (Figure 4), contributing around 70 percent to GDP growth in the third and fourth quarters. This interpretation follows from the robust recovery in exports during this period, well above that of Portuguese and Euro Area GDP (Figure 5). Lockdown-related supply restrictions contribute around 70 percent to



(A) Year 2020. (B) Year 2021.

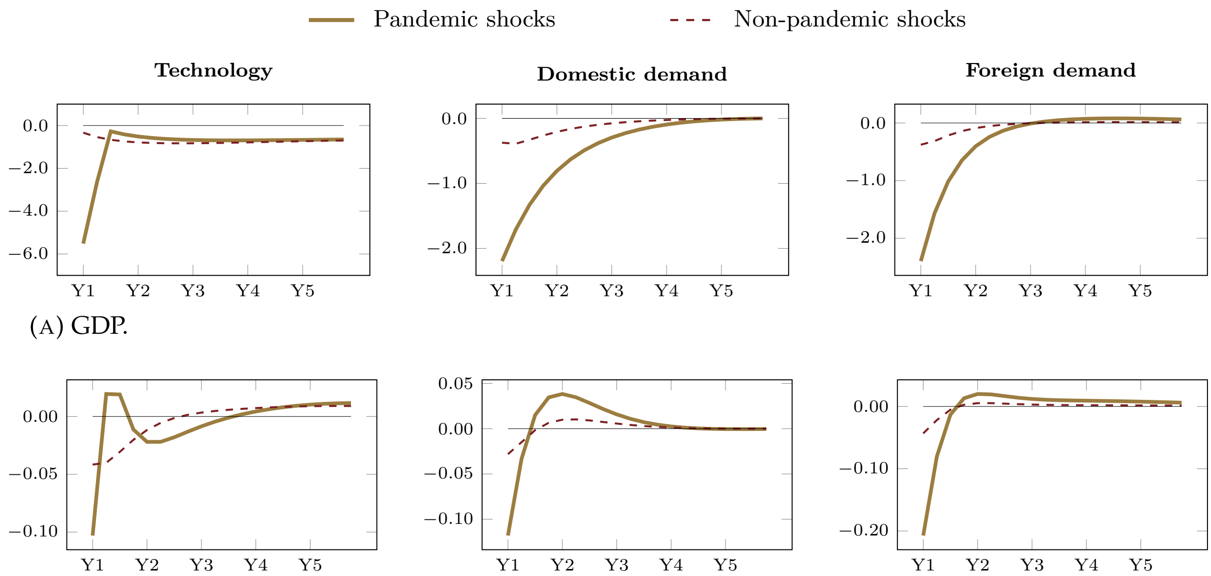
FIGURE 6: Historical decomposition of inflation .

Sources: The authors.

Notes: The quarter-on-quarter inflation rate, centred and measured in percentage, is identified by the orange line plot, and contributions, measured in percentage points, by bar plots. LD stands for lockdown disturbances and O for other disturbances (not directly related with the lockdown). ME denotes measurement errors and IC Initial Conditions. The latter plays an important role in the historical decomposition, since the model has a built-in steady-state level of inflation of 0.5 percent per quarter, which is reflected here.

GDP growth in 2021:3, though their effects are partly offset by other domestic factors, which mimic a shift from domestically produced intermediate to imported goods (a reversion of events from the previous quarter). In 2021:4 lockdown-related supply restrictions depict a slight negative contribution to GDP growth.

Inflation is mostly determined by disturbances that we do not classify as pandemic related. The decline in the lockdown-related demand components (domestic and foreign) contributes negatively to inflation in 2020:2 (Figure 6). The disinflationary impacts add up to those generated by the demand contraction triggered by lower foreign income—an effect included in the category 'O-External'—as less expenditure in domestically produced goods pressure the price downwards. These negative contributions are mostly absorbed by cost-push shocks—included in the category 'O-Domestic'—which may be associated with extra-costs faced by firms to deal with the pandemic crisis and includes fluctuations in monopolistic competition markups. The lockdown-related supply disturbance does not contribute in an important manner to inflation developments. Recall that the growth shock has also a demand impact in our model channeled to the economy through lower households' income, which breaks the classical negative association between inflation and output for supply-side disturbances. Low inflation rates during the second half of 2020 are sustained by a lower inflation environment abroad (included in the category 'O-External') and lower consumer and import price markups (included in the category 'O-Domestic').



(A) GDP.

(B) Inflation.

FIGURE 7: Impulse response functions for GDP and inflation.

Sources: The authors.

Notes: Inflation is measured by quarter-on-quarter changes in the private consumption deflator. All impacts are in deviations from steady state. Y1 identifies the first quarter of the first year, Y2 the first quarter the second year, etc.

Inflation in 2021 is mostly marked by the volatility of cost-push shocks, against increasing import prices. Cost-push shocks contribute positively to inflation in the first quarter, preventing a slowdown in prices despite the activity downfall. The economic recovery in the second quarter is accompanied by an increase in inflation, triggered by an even larger contribution of cost-push shocks. In the second half of 2021, inflation settles close to steady-state levels, driven by higher euro area inflation and foreign demand, against a background of a nil contribution of cost-push shocks. The latter contrasts positive (and increasing) contributions from import goods markups shocks, with negative contributions from consumer goods and wage markup disturbances.

4.2. *Impulse response functions and variance decomposition*

Impulse response functions (depicted in Figure 7) provide an alternate perspective on the size and type of shocks hitting the Portuguese economy during the pandemic period. Lockdown-specific disturbances are endowed with much greater real impacts as compared with their non-pandemic counterparts. The contemporaneous amplification brought about by lockdown shocks are comprised between sixfold for domestic households' and foreign agents' demand, and sixteenfold for technology perturbations. Despite the *iid* assumption, impacts of pandemic shocks can last for several years due to endogenous persistence. Households spread the impacts through time to avoid large fluctuations in consumption, an implication of the permanent income hypotheses.

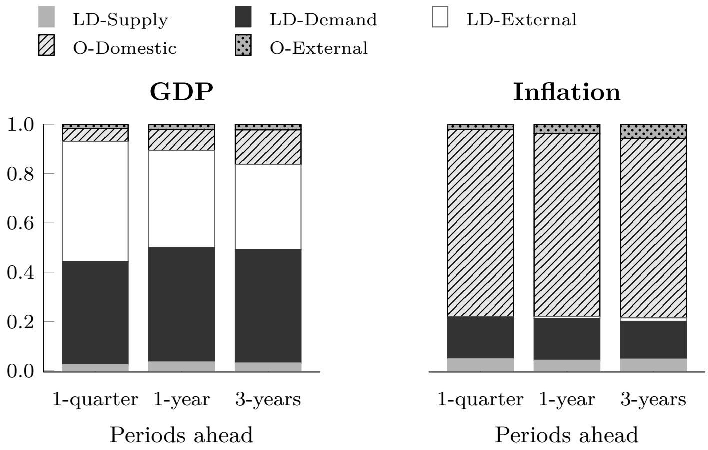


FIGURE 8: Forecast error variance decomposition for GDP and inflation.

Sources: The authors.
Notes: GDP is stationarized by the level of technology.

Demand shocks are associated with a contemporaneous negative impact on inflation, substantially larger in the case of pandemic shocks. A period of above steady-state inflation must necessarily follow so that any difference in relative prices vanishes in the long run, an imposition of the absolute law of one price required to close the model.

The forecast error variance decomposition, computed with parameters estimated for the 2020-21 period (Figure 8), pinpoints the main contributors to business cycle volatility around the technology component *vis-à-vis* the forecast trajectory of the model. Therefore, supply disturbances that impact the stochastic trend component of the model have little expression in this decomposition. Amongst lockdown disturbances, demand explains around 80 percent of the forecast error variance of stationary GDP over three years and around 90 percent over 1 year. The impacts are distributed evenly across domestic and external sources. Inflation volatility is mostly dictated by cost-push shocks (which constitute the bulk of the category 'O-Domestic'), while lockdown disturbances have little expression.

5. Concluding remarks

This article identifies the structural determinants of the pandemic crisis in light of an estimated Dynamic Stochastic General Equilibrium model for the Portuguese economy. Three shocks—impacting domestic households' demand, foreign agents' demand, and worldwide supply—excel in shaping the economic activity during this period. Demand shocks can be associated with the inability to consume goods, whereas supply shocks mimic the failure of firms to produce those goods.

The role of perturbations changed throughout the pandemic period. Supply factors played a greater role in shaping GDP growth during 2020, as the productive structure adapted to deal with the crisis. This result is induced by the coordinated co-movement depicted by domestic and foreign output, and by the various demand components.

The first half of 2021 is marked by swings in domestic households' demand, a result explained by the large contribution of private consumption to GDP growth. The recovery in exports during the second half of 2021 dictated a major contribution of foreign demand to GDP growth in this period. Pandemic shocks had a limited expression in inflation due to the role played by cost-push shocks.

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