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Content

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Editor's note[1]

Pedro Duarte Neves

July 2022

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1. This issue of *Banco de Portugal Economic Studies* includes four studies. The first study analyses the behaviour of corporate insolvencies and restructuring in Portugal from March 2020 to June 2021. The second provides estimates of the effects that the necessary increase in energy taxation to achieve the carbon neutrality of the Paris Agreement may have on the economy. The third study – motivated, like the first, by the COVID-19 pandemic – identifies the nature of the shocks that affected the behaviour of the Portuguese economy in 2020 and 2021. The final study, presented as a synopsis, is a review of the literature on the solvency conditions of a central bank.

2. The 2021 Nobel Prize in Economics was awarded to economists David Card, Joshua Angrist and Guido Imbens for their pioneering work[2] in identifying *cause and effect* relationships from *natural experiments* that, in the words of the Committee for the Prize in Economic Sciences, revolutionised empirical research. Natural experiments correspond to situations in which individuals may be allocated by a random draw to sets that have been handled differently, in a perfect analogy to clinical trials in medicine. These laureates have been able to show how conclusions about *cause and effect* can be drawn from these experiments, answering key questions such as how minimum wages can affect employment or how an extra year of education can contribute to wages.[3]

One way of establishing causality is to use random samples and distribute observations among two groups: the treatment group (e.g. the one receiving the vaccine) and the control group (the one not receiving the vaccine). This is how clinical trials are conducted in medicine. Unfortunately, this approach cannot be applied to social

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1. The analyses, opinions and conclusions expressed in this editorial are entirely those of the editor and do not necessarily coincide with those of Banco de Portugal or the Eurosystem.

2. One half of the prize was awarded to David Card for his empirical contributions to labour economics and the other half jointly to Joshua D. Angrist and Guido W. Imbens for their methodological contributions to the analysis of causal relationships.

3. David Card concluded in the early 1990s that increasing the minimum wage does not necessarily lead to a reduction in the number of employees. This possibility – which was against all the prevailing ideas on the functioning of the labour market – is often ignored in the analyses of the effects of a minimum wage increase on the functioning of the labour market. Joshua Angrist and Guido Imbens have left their mark through their methodological contributions to the estimation of causal relationships from natural experiments, which, inter alia, can help estimate wage premiums for education.

and economic phenomena unless these natural experiments exist, arising from chance events or changes in policy or institutional rules. David Card, Joshua Angrist and Guido Imbens have illustrated how natural experiments can be used to answer key economic issues, while also helping to identify causal relationships.

3. The first study in this issue of *Banco de Portugal Economic Studies*, by Nogueira, analyses the behaviour of corporate insolvencies and restructuring in Portugal over the course of the COVID-19 pandemic. Worthy of note is the use of a natural experiment to analyse the effect of the credit moratorium on insolvency and restructuring applications.

The credit moratorium introduced in March 2020 excluded firms with loans more than 90 days past due. The moratorium thus treats differently firms that are in default in January 2020 for two consecutive months (and will therefore not benefit from the moratorium if they remain in default, since it took effect only in mid-March) from firms that are in default for two months in a row in February 2020, because the latter are able to access the moratorium and thus avoid three months' default.

The study begins by describing the mechanisms for corporate insolvency and restructuring in Portugal, as well as the measures in place to support firms during the pandemic. The empirical part analyses – for the period from the beginning of the pandemic until the end of the first half of 2021 – developments in the number of corporate insolvency and restructuring applications. As mentioned above, it also seeks to identify the effects of the introduction of credit moratoria.

One of the most distinctive features of this study is the combination of several databases in the empirical analysis: Citius portal, Central Credit Register, Simplified Corporate Information, and data from the Sociedade Interbancária de Serviços and Google Mobility Reports for Portugal. The basic statistical information therefore captures several dimensions of firms' heterogeneity.

The main findings of this study are as follows:

(i) despite the unprecedented decline in economic activity in 2020, the number of insolvency and restructuring applications remained close to the levels seen in the previous year; there was even a reduction – of 27% – in 2021, highlighting the importance and effects of the various measures adopted to support the economy;
(ii) behaviours differed greatly among the sectors most affected and least affected by the pandemic, as shown by the insolvency and restructuring applications;
(iii) the results of the natural experiment indicate that the credit moratorium contributed to a significant decline in the number of insolvencies; the moratorium decreased the likelihood of insolvency from 6.4% to 3.9%.

4. The study by Hasna, Lourenço and Santos analyses for Portugal the aggregate and distributional effects of an increase in carbon taxation that might achieve the reductions agreed in the Paris Agreement (considering emission reductions of 35%

and 70% respectively). The model used offers the possibility to capture two important dimensions of heterogeneity: the distribution of labour force skills and the sectoral composition of the economy.

The authors consider four alternative scenarios. This editor's note highlights those where increased tax revenue – resulting from the increase in taxation – is offset by an equivalent amount of additional expenditure: investment in 'green' energy, subsidies to low-carbon industries, or subsidies for education expenditure. The main results of this exercise are as follows:

(i) climate transition, as it takes place, has negative impacts on the level of economic activity and private consumption;[4]
(ii) carbon taxation has a pronounced effect on labour use in carbon-intensive energy sectors (polluters) – oil, coal and natural gas – with reductions ranging from 20% to 40%;
(iii) carbon taxation has very asymmetric effects on wellbeing for different types of workers: there is a very pronounced impact on the wellbeing of workers in the most carbon-intensive energy sectors, especially those that continue to work in these industries (workers who are able to switch to other sectors of the economy are less affected, although they suffer considerably more than workers in other sectors of the economy).

5. Dynamic Stochastic General Equilibrium (DSGE) models are regularly used by international organisations and central banks to analyse the behaviour of the economy. The third study of this issue of Banco de Portugal Economic Studies, by Júlio and Maria, offers a narrative, based on a DGSE model, for the nature and relative importance of the economic shocks that influenced the behaviour of the Portuguese economy in 2020 and 2021.[5]

This exercise is particularly important, as the truly unique nature of the pandemic shock is the result of simultaneous supply and demand shocks that have interacted with each other in a way that has changed as economic agents – and their expectations – adjust. A negative supply shock reduces the productive capacity of the economy, making it impossible for firms to maintain the levels of production hitherto seen. Because they

4. Naturally, the hypothetical scenario where climate transition measures are not adopted would – in 2050 and much more significantly in 2100 – have substantially more negative effects on economic activity. In this respect, see for example the scenarios 'disorderly transition' and, above all, 'hot house world' presented in various studies by the Network for Greening the Financial System (NGFS).

5. The authors published the study "Lessons from a finitely-lived agents structural model" in the January 2021 issue of *Banco de Portugal Economic Studies*, which applied the PESSOA general equilibrium model, regularly used by the Banco de Portugal. The Editor's Note of that issue reads as follows: "Hence, this creates the expectation that, at a time when economic activity has fully recovered from the effects of the COVID-19 pandemic crisis, the PESSOA model will be able to produce a stabilised narrative of the behaviour of the Portuguese economy in this unprecedented period". This expectation was thus met by this study by Júlio and Maria.

limit the ability of workers to carry out their usual activities, lockdowns are a negative supply shock; the disruption of production chains is a possible further amplification. A negative demand shock corresponds to a situation in which economic agents are unable – or unwilling – to maintain their usual levels of consumption (of goods and, above all, services); income declines, increases in unemployment or unfavourable changes in expectations may amplify these effects.

Identifying the nature of shocks – and in particular their relative intensity – is important when choosing the most appropriate macroeconomic policies: demand shocks typically justify a countercyclical response from monetary and fiscal policies; in the case of supply-side (negative and temporary) shocks, insurance mechanisms for economic agents (such as credit moratoria or support for gradual recovery/simplified layoffs) are more appropriate.

The results of the study are very informative as to how the pandemic has affected the real economy. In the initial phase of the pandemic, the relative magnitude of supply and demand shocks (of resident and non-resident agents) was almost balanced. As the consequences of the pandemic became more known and especially less dramatic – following the development of vaccines – the relative importance attributable to supply declined markedly, with the adoption of production solutions more resilient to social distancing restrictions, such as the more widespread use of remote work. In this context, the second period of general lockdown particularly affected demand considering the renewed practical impossibility of consuming a number of services.

These results do not differ significantly from those obtained for other economies: for the initial phase of the pandemic, studies by the World Bank[6] and the De Nederlandsche Bank (DNB)[7] estimate, for the United States and the Netherlands, that demand and supply shocks have a very close quantitative importance in the effects on economic activity; the World Bank study also highlights a larger relative role of demand shocks in the subsequent phases of the pandemic. Finally, a publication by the Federal Reserve Bank of St. Louis[8] concluded that, in the early phase of the pandemic, approximately two-thirds of the drop in hours worked are attributable to supply shocks. These three studies also document a very important feature of the pandemic shock: a substantial heterogeneity across sectors in the relative importance of demand and supply shocks.

6. Ruch, F. U. and Taskin, T., "Demand and Supply Shocks: Evidence from Corporate Earning Calls", *Policy Research Working Paper 9922, World Bank Group*, February 2022.

7. "Supply and demand shocks due to the coronavirus pandemic contribute equally to contraction in production", DNB, *General news*, 5 November 2020.

8. Brinca, P., Duarte, J. B. and Faria e Castro, M., "Measuring Sectoral Supply and Demand Shocks during COVID-19", *Federal Reserve Bank of St. Louis Working Paper*, 2020-011.

6. In a recent publication,[9] William English and Donald Kohn – two well-known economists with high-level experience at the Federal Reserve[10] – examine the possibility and consequences of a central bank's accounts incurring losses. This is particularly timely in a context such as the current one, marked by a strong expansion of balance sheets over the past decade and ongoing increases in central bank intervention rates.[11]

Two of this publication's transcripts are particularly interesting. As regards the possibility of the Federal Reserve incurring losses, in the current context of rising interest rates, it reads as follows: "... with the Fed now raising rates "expeditiously", the Fed's net interest income on its securities holdings will fall as the rate earned on the securities it holds remains relatively fixed while the interest rate it pays on its liabilities rises. The Fed has noted that if interest rates rise sufficiently high, it could end up paying more out in interest than it takes in, resulting in a loss for the Fed".[12]

The authors continue with the following question: "But couldn't Fed losses lead it to default in some way, causing a financial crisis or high inflation?" To which they replied: "The Fed can´t default because it can always create reserves to pay its bills. Moreover, the banking sector must hold the reserves created by the Fed, so the Fed cannot suffer from a run on its funding. That said, if the Fed had large enough losses for a long enough time, it would have to create such a large amount of interest-bearing liabilities to cover its expenses that it wouldn't be able to implement monetary policy appropriately. (In term of the Fed's accounting, its losses could outstrip all its future profits). In that extreme case, the Fed would need to get fiscal support from the Treasury".

Losses incurred by central banks are rare, but have happened.[13] For example, the Swiss National Bank registered a loss in 2010 corresponding to about 3.5% of GDP; the Czech National Bank registered losses in 2006, 2007 and 2010; finally, the Central Bank of Chile has declared losses on several occasions since the early 1980s. In these three cases, the losses were mainly the result of an appreciation of the domestic currency resulting in losses on foreign asset holdings. In the case of Switzerland, the central

9. English, W. B. and Kohn, D., "What if the Federal Reserve books losses because of its quantitative easing?", *Economic Studies Blog Posts*, Brookings, 1 June 2022.

10. William B. English was Director of the Division of Monetary Affairs and Secretary to the Federal Open Market Committee at the Board of Governors of the Federal Reserve System in the period 2010-15; Donald Kohn had a long career at the Federal Reserve and was a member and then Vice Chair of the Board of Governors between 2002 and 2010.

11. On this see also the recent *Annual Economic Report* (AER) of the BIS: "Moreover, where central banks have engaged in large-scale asset purchases, higher interest rates will also reduce central bank remittances to the government (see last year's AER). These central banks have de facto replaced long-term debt with debt indexed to the overnight interest rate – the rate on bank reserves. As a result, in the largest advanced economies, as much as 30-50% of marketable government debt is effectively overnight. In the process, losses could heighten political economy risks for central banks".

12. The quotation marks and underlining of this transcript appear in the original text, referenced in footnote 9.

13. Chaboud, A. and Leahy, M., "Foreign Central Bank Remittance Practices", Division of International Finance, 8 March 2013, authorised for public release by the FOMC Secretariat on 1 November 2019.

bank's equity position remained positive despite the abovementioned loss; however, for both the Czech Republic and Chile, the respective central banks had a negative equity position (approximately 4% and 2.25% of GDP in 2011 respectively). In none of these cases were there any limitations to the ability of monetary policy to control inflation.

7. The final study of this issue of *Banco de Portugal Economic Studies*, by Costa, is a review of the literature on the relevance of a central bank's solvency for the credibility of monetary policy. This synopsis covers the following main aspects: analytical presentation of the interactions between monetary policy and fiscal policy; definition of the conditions for a central bank's intertemporal solvency; key conditions for the credibility of monetary policy in pursuit of the price stability mandate; finally, the synopsis analyses the case of central banks operating in a monetary union.

This study is particularly important in the abovementioned context of a strong expansion of central bank balance sheets observed over the past decade and the upward path in intervention rates. While there are limits to the ability of central banks to act, economic literature suggests that these limits are still very distant, at least for advanced economies. Rather than providing a summary of the main findings presented, we take this opportunity to invite the readers of this issue of *Banco de Portugal Economic Studies* to read the study "On the solvency and credibility of a central bank".

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Non-technical summary

July 2022

Corporate insolvency and restructuring during COVID-19

Gil Nogueira

Corporate insolvency and restructuring are two key mechanisms for the reallocation of productive resources in the economy typically used by firms that face financial difficulties. As there was an unexpected and large pandemic shock to economic activity, it is important to study the evolution of those two mechanisms during the pandemic. This study does the analysis for Portugal following similar papers for France, Sweden, and the United States.

Using data from the *Citius* website, this analysis compares the number of filings in the weeks of 2020 affected by the pandemic and in 2021 to the number of filings between 2017 and the beginning of 2020, a period when economic growth was on average higher in Portugal than in the euro area. Despite the economic activity slump in the beginning of the pandemic, the number of filings stayed close to their historical average in 2020 and dropped below the average in 2021 (Figure 1). This pattern affected both insolvencies and restructurings.

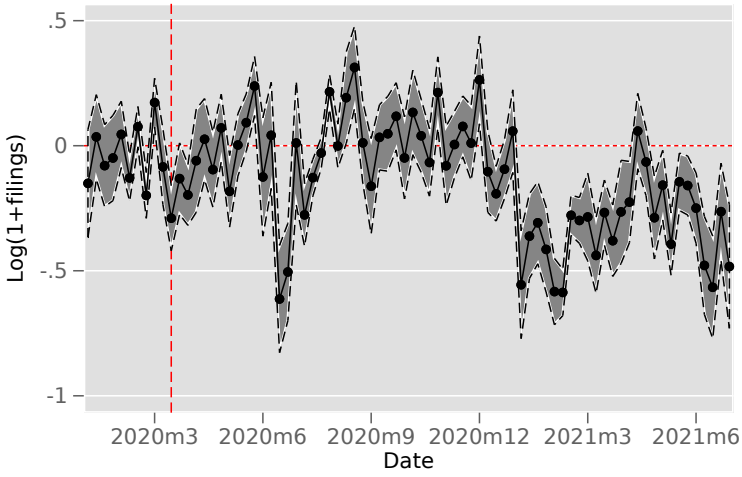

FIGURE 1: Weekly corporate insolvency and restructuring filings
Fonte: Citius and author's own calculations.

In the sectors that were the most affected by the pandemic, the number of filings was above the historical average in the 2020 weeks affected by the pandemic and stayed

close to the historical average in 2021. In the remaining sectors, the number of filings was below the historical average both in 2020 and in 2021.

The study analyzes the effect of the credit moratorium on the number of insolvency and restructuring filings using a natural experiment. The natural experiment is possible because the moratorium does not cover credit that is more than 90 days overdue on March 18 2020. With this exclusion, firms with overdue credit for two months in February 2020 are more likely to have access the moratorium than firms with overdue credit for two months in January 2020. The moratorium reduces the probability of insolvency by 2.5 pp, from 6.4% to 3.9%.

The natural experiment estimates the partial equilibrium effect of the moratorium on the probability of insolvency. Partial equilibrium analysis studies part of the economy (in this case, firms with overdue credit), abstracting from interactions between the moratorium and other economic agents. General equilibrium interactions should amplify partial equilibrium results, increasing the probability of insolvency in a counterfactual economy without the moratorium. In this economy, firms that were healthy before the pandemic might file for insolvency because of pandemic-related factors.

The suspension of the insolvency filing deadline does not seem to be the primary factor explaining the fall in the total number of filings. The number of filings requested by debtors dropped by 19.1% in 2021 when compared to the historical average, less than the 27.1% drop for other cases. Finally, the study analyzes the evolution of the number of insolvency and restructuring filings during state of emergency periods. The number of filings dropped by 10.1% in the first state of emergency period (between March and May 2020) and practically did not change in the second period (between November 2020 and April 2021). The fall in the number of filings during the first period was smaller than the 54.3% drop in the in-person access to courts, measured by the utilization of payment methods at legal services.

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Corporate insolvency and restructuring during COVID-19

Gil Nogueira
Banco de Portugal

July 2022

Abstract
How did corporate insolvency and restructuring mechanisms evolve during the COVID-19 pandemic? Even though economic activity contracted, the number of insolvency and restructuring filings remained stable in 2020 and dropped consistently below the historical average in 2021. There were opposing factors conditioning this trend. Lower economic activity led to fewer insolvency and restructuring filings. In the economic activity sectors that were the most exposed to the pandemic, the number of filings was above the historical average in 2020 and stayed close to the average in 2021. In the remaining sectors, the number of filings stayed below the average in 2020 and 2021. Empirical results based on a natural experiment show that the credit moratorium, a policy that supported firm continuation, reduced the probability of insolvency. State of emergency restrictions had a negative but small effect on the number of filings. (JEL: G28, G33, G38)

1. Introduction

Portugal suffered drastic changes to the organization of its economy during the pandemic. Many firms were forced to close or operate remotely. Consumers also suffered movement constraints, which limited their ability to buy goods and services. On the other hand, Portugal introduced unprecedented economic support measures such as credit moratoriums or furlough subsidies, which permitted firm survival.

Insolvency and restructuring are key resource reallocation procedures. As there was an unforeseen and large shock to economic activity, it is important to track these mechanisms during the pandemic. This analysis was done for other countries such as France (Cros *et al.* (2021)), Sweden (Cella (2020)) or the United States (Wang *et al.* (2021)). This study does the analysis for Portugal.

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Taking this context into account, the study tracks corporate insolvency and restructuring filings in Portugal during the pandemic, splitting the analysis into three parts. First, it does a brief description of the existing insolvency and restructuring mechanisms and of the special corporate support measures adopted during the pandemic. Firms might use two types of court procedure when they face financial difficulties: insolvency and the Processo Especial de Revitalização (PER). In Portugal, insolvency is a procedure used to repay creditors that typically leads to asset liquidation and creditor reimbursement. PER is a negotiation procedure between the firm and creditors that gives firms a three-month window to agree on a restructuring plan with creditors. Creditors cannot force the liquidation of the firm during this period. In 2020, Portugal introduced restructuring incentives and a new restructuring mechanism, the Processo Extraordinário de Viabilização de Empresas (PEVE), which allows fast restructuring without court costs. At the same time, Portugal adopted corporate support measures that avoided restructuring and liquidation. These measures, similar to the ones taken in other countries (Kozeniauskas *et al.* (2021)), included a moratorium and credit lines, subsidies to corporate activity, tax deferrals and a state-sponsored furlough scheme.

The second part of this study tracks the evolution of the number of insolvencies and restructurings in Portugal during the pandemic using microdata from *Citius*, the official repository of court documents for insolvency and corporate restructuring cases in Portugal. With this data, it is possible to track the number of new filings with weekly frequency. Even though there was a large economic contraction, the number of insolvencies and restructurings did not increase significantly during the pandemic. The number of filings remained stable in 2020 and dropped 27% below the historical average in 2021. This pattern affected both insolvencies and restructurings.

The third part of the study analyzes the mechanisms that affected insolvency and restructuring during the pandemic. Firm exposure to the effects of the pandemic led to an increase in the number of filings. In the most exposed sectors, the number of filings was above the historical average in 2020 and stayed at the historical average in 2021. In the remaining sectors, the number of filings remained stable in 2020 and dropped below the historical average in 2021. The difference in the filings growth rate between the most and the least affected sectors was significant: 39.6 pp in 2020 and 37.1 pp in 2021.

During the pandemic, Portugal suspended the deadline given to debtors to file for insolvency. To analyze the contribution of this suspension to the reduction in the number of filings, the study compares the evolution of debtor filings (affected by the deadline suspension) against other insolvency and restructuring filings. The drop in the number of filings was larger for filings that were not affected by the deadline suspension, therefore the suspension does not seem to be determinant to justify the drop in the number of filings.

During the pandemic, Portugal approved many corporate support measures, which makes it impossible to establish a causal relationship between all measures and changes in the number of insolvency and restructuring filings. Alternatively, the study measures the causal effect of the credit moratorium on the probability of filing for insolvency or restructuring using a natural experiment introduced in March 2020. A natural

experiment is an empirical analysis that is possible because of external factors in which the exposure of firms to the experiment is approximately random. In this study, the natural experiment is possible because the credit moratorium does not cover credit that is more than 90 days overdue. This external event allows the comparison between firms with two months of overdue credit in January 2020 (control group) and firms with two months of overdue credit in February 2020 (treatment group). Some firms in the treatment group have less than 90 days of overdue credit when the moratorium starts (March 18th 2020), therefore they have higher probability of accessing the moratorium than firms in the control group. These firms have a lower probability of becoming insolvent because having overdue credit is one the the factors that determines corporate insolvency. Belonging to the treatment group reduces the probability of insolvency by 2.5 pp, which represents a 39.1% drop in the probability of insolvency from 6.4% to 3.9%. Even though estimates are economically relevant, they have a high level of statistical noise. The effect of the moratorium is smaller and statistically not significant for restructurings. This effect is estimated in partial equilibrium, i.e. it ignores the effect of the moratorium on firms that are not in the sample and the interactions between firms. As the moratorium avoids overdue credit by firms that were healthy before the pandemic, general equilibrium interactions should reinforce partial equilibrium effects.

State of emergency declarations introduced changes in court operations, including building access restrictions and the usage of digital tools in court procedures. Restrictions led to a drop in usage of court buildings, especially in the first stage of emergency period (between March and May 2020). In this period, the usage of national payment cards at legal services dropped 54.3%. The number of filings dropped 10% in the first state of emergency period and changed negligibly in the second period (between November 2020 and April 2021).

The study only does a positive analysis of the evolution of the number of insolvency and restructuring filings during the pandemic. There are factors that make corporate insolvency and restructuring more or less desirable. On the one hand, fewer insolvency and restructuring filings reduce transfers of the means of production to more productive economic activities, leading to lower firm production (Acemoglu *et al.* (2018)). On the other hand, insolvency and restructuring filings may cause asset fire sales (Pulvino (1998))) or layoffs, with persistent and negative effects on wages (Graham *et al.* (2019)).

This study contributes to the literature that studies the adaptation of court-supervised insolvency and restructuring mechanisms to the pandemic. Historically, there is a negative relationship between firms' economic activity and the probability of insolvency or restructuring (Altman (1968)). In this context and in the absence of corporate support measures, the pandemic could lead o a significant increase in the number of insolvency and restructuring filings. The literature proposed various mechanisms to reduce the effect of the pandemic, such as moratoriums (Greenwood *et al.* (2020)), debt purchases (Crouzet and Tourre (2021)), subsidies (Saez and Zucman (2020)), or more judges (Iverson *et al.* (2020)). However, these measures may reduce the number of corporate insolvencies and restructurings for reasons that are unrelated to the pandemic. The results of this study are consistent with the predictions from this literature. By comparing firms from the sectors that were the most exposed to

the pandemic against firms from other sectors, the study concludes that the pandemic led to an increase in the number of insolvency and restructuring filings. The credit moratorium, a support measure given to firms during the pandemic, had a negative effect on the number of filings, including for firms already facing economic difficulties before March 2020.

This study is related to the literature that tracks the evolution of insolvency and restructuring filings during the pandemic in other countries. Wang *et al.* (2021) use a methodology similar to the one used in this study to track the evolution in the number of insolvency and restructuring filings in the United States. In 2020, filings dropped by 17% year on year. Credit moratoriums contributed to the drop in the number of filings, while physical barriers to court access had an unimportant effect. The evolution in the number of insolvency and restructuring filigns is similar in other countries. In France, the number of filings dropped by 45% between March 2020 and October 2021 when compared to the equivalent pre-pandemic period (Maadini and Hadjibeyli (2022)). In Sweden, the number of filings increased between March and May 2020 but reverted to the historical average in June 2020 (Cella (2020)).

The study also contributes to a better understanding of the Portuguese corporate insolvency and restructuring system. In this respect, Pereira and Wemans (2022) characterize the length of insolvency filings in Portugal. Bonfim and Nogueira (2021) show that corporate reorganization benefits workers in Portugal.

Finally, this study contributes to the literature that characterizes corporate insolvency and restructuring systems (e.g., Strömberg (2000) in Sweden and Bris *et al.* (2006) in the United States), discussing the corporate insolvency and restructuring mechanisms in Portugal, with an emphasis on the changes introduced during the period of the analysis and on the interactions between these mechanisms and corporate support measures.

2. Corporate insolvency and restructuring in Portugal

This section describes the insolvency and restructuring mechanisms in Portugal, focusing on judicial mechanisms (involving courts). There are also extrajudicial corporate restructuring mechanisms in Portugal. The legal literature studies legal developments in the Portuguese territory since the Roman period (e.g., Kalil (2017), Vasconcelos (2017)), Simões (2019))).

2.1. Pre-Covid framework

Firms facing financial difficulties may negotiate with creditors using extrajudicial negotiation mechanisms or court-supervised procedures. Courts are necessary to change firms' capital structure or management without creditor consent. The Portuguese corporate insolvency and restructuring system is regulated by the *Código da Insolvência e Recuperação de Empresas* (CIRE), introduced by Decree-law 53/2004. In its initial form, the law was based on the insolvency concept applied in Germany at the time (Insolvenzordnung). The law covers other entities such as individuals or associations.

In 2012, Portugal introduced the Processo Especial de Revitalização (PER). PER is a restructuring system inspired by *Chapter 11*, the corporate restructuring legal framework for American firms. PER allows debtors facing economic difficulties or imminent insolvency to submit a restructuring plan and negotiate with creditors without risking the immediate dismissal of the management or a sudden stop to economic activity. Plans are approved by a majority of creditors, and affect even those who vote against the plan or do not participate in the negotiation process. After approval, plan acceptance requires ratification by a judge. Bonfim and Nogueira (2021) explain PER with more detail.

Insolvency might be requested by the debtor or by creditors, while PER can only be requested by the debtor. Debtors must file for insolvency when they are in a situation of present insolvency (insolvência atual). Debtors are in present insolvency if they cannot comply with their overdue debt obligations, or when liabilities are substantially greater than assets. Present insolvency is unexculpable when in the debtor cannot largely comply with certain payment obligations for more than three months, such as tax or labor liabilities. The debtor might also file for insolvency if insolvency is just imminent (and not present). Firms that file for PER must face imminent insolvency or a difficult economic situation.

The insolvency process might end with the liquidation of firm assets and distribution of the insolvent estate between creditors or an insolvency plan. Liquidation is the dominant final outcome of the insolvency process. From the group of firms that file for insolvency, estimates show that only 1% of all firms restructure and survive (Ministério da Economia e do Emprego (2012)). This percentage might not reflect changes to the corporate insolvency and restructuring code introduced after 2012. A successful PER ends up with the approval of a restructuring plan by a majority of creditors and the ratification by the judge. This plan has the objective of keeping the firm operational.

2.2. COVID-19 period

In 2020 and 2021, Portugal adopted temporary measures that affected firm liquidation and restructuring. Some measures were direct, i.e. they implied changes to corporate insolvency and restructuring law. Other changes were indirect but potentially discouraged insolvency and restructuring.

Direct measures. Law 4-A/2020 suspended the deadline to file for insolvency from March 2020 onwards. Law 75/2020 introduced changes to corporate insolvency and restructuring law. The law promotes the restructuring of firms affected by COVID-19, especially through the Processo Extraordinário de Viabilização de Empresas (PEVE). This procedure differs from PER for being accessible to firms that are presently insolvent, having shorter deadlines and no court costs. Only firms demonstrably affected by the pandemic may use PEVE. The Law also promotes restructuring through PER by allowing that new funds disbursed by partners and shareholders have seniority over pre-existing credit. Before COVID-19, only creditors benefited from this prior ranking.

Indirect measures. At the same time, Portugal introduced measures that avoided corporate liquidation and restructuring indirectly (Kozeniauskas *et al.* (2021) also discuss these measures). Essentially, the measures are split into four groups: 1) a credit

moratorium; 2) state-guaranteed loans; 3) subsidies to firm continuation; 4) tax and social contribution deferrals and tax collection suspensions.

The credit moratorium allowed firms to postpone loan and/or interest payments to financial institutions. This measure was kept in force until September 2021 for most firms. The economic activity sectors that were the most exposed to the pandemic benefited from an additional 12-month loan maturity extension. Loans guaranteed by the state allowed firms to get credit with personal guarantees from the state. Firm subsidies promoted the continuation of economic activity. The *layoff simplificado*, a furlough scheme sponsored by the state, stands out as one of these measures. Additionally, the state gave subsidies through the *Apoiar* program to firms that suffered sales declines. Tax deferrals extended the deadline to pay taxes and social contributions, and allowed payments in installments.

3. Data

Corporate insolvency and restructuring data comes from the *Citius* website, a public repository that contains documents for these cases. The data collection procedure is similar to the one used by Bonfim and Nogueira (2021) and Pereira and Wemans (2022). This repository contains cases for firms and for other entities such as associations and individuals. The analysis filters *Citius* data to select non-financial corporations only. First, it restricts the dataset to restructuring cases (PER and PEVE) and insolvencies from legal persons. Within restructuring cases, the analysis focuses mostly on PER. PEVE is a recent procedure that did not have immediate adoption. The sample used in this study has 7 cases regulated by PEVE, with the first case being filed in March 2021. Second, the analysis keeps entities with the institutional code for non-financial corporations,[1] excluding legal persons such as associations. This procedure generates a series of insolvency and restructuring filings with daily frequency between 2017 and 2021. There is a gap between the court filing date and the submission of court documents to the platform that is heterogeneous between filings. This gap might cause the relative underreporting of cases at the most recent dates. The analysis addresses this problem by including only filings in which the difference between the date of the filing and the date of the first document is equal or smaller than 180 days and by restricting the dataset to events between January 2017 and June 2021. Table A.1 (online appendix) shows descriptive statistics for filings that were excluded by the 180 days criteria. Excluded filings represent approximately 4.8% of all filings. From the excluded filings, 93.8% are insolvency filings started by creditors. The weight of these filings is natural, given that the debtor might contest the insolvency before the case is opened. Using this procedure, the percent change in the number of new insolvency filings retrieved from the database is similar to the change obtained with official aggregate data (see Figure B.1 in the online appendix).

1. The institutional sector code comes from the Sistema de Partilha de Informação de Referência (SPAI), a database managed by Banco de Portugal. In this dataset, non-financial corporations have code S.11 in the European System of Accounts (ESA 2010)

Overdue credit data originates from the Central de Responsabilidades de Crédito (CRC). This database contains credit exposures above €50 from banks operating in Portugal. Overdue credit is obtained using values reported monthly for non-financial corporations[2] between January 2017 and December 2021.

The Classificação das Atividades Económicas (CAE) allows for the characterization of firms' economic activity sector. This data originates from Informação Empresarial Simplificada (IES), which contains the balance sheet and the income statement of the universe of resident non-financial corporations with annual frequency.

The study uses two datasets to measure the movement of people during state of emergency periods. First, it uses the payments database from the Sociedade Interbancária de Serviços (SIBS). This database contains monthly data on the number of payments done with payment cards issued in Portugal in the SIBS network using ATM and POS systems between 2018 and 2021. SIBS represented 85% of all operations with payment systems in Portugal in 2019, hence the data represents a substantial fraction of all payments made in Portugal.[3] The data is grouped by sector of activity. Second, the analysis uses Google Mobility Reports data for Portugal, which compares the intensity of movement by individuals to certain places (e.g., workplace) against the median measured between January 3 and Feburary 6 2020.[4] The data has daily frequency between Feburary 15 2020 and December 31 2021.

4. Descriptive statistics

Table 1 depicts descriptive statistics for the insolvency and restructuring cases included in the sample. There are important differences between the two types of filing. Firms with restructuring filings are considerably larger than firms with insolvency filings: restructurings represent 14% of the filings and 42% of the assets. The financial situation for firms with restructuring filings is also less degraded than for firms with insolvency filings, as expected from the different conditions to access the two procedures. When compared to the Portuguese average, firms with insolvency or restructuring filings have similar assets, more workers and worse operational and capital ratios. Insolvency and restructuring filings represent 2.7% of all firms in Portugal in 2016 and 4.9% of the workers of these firms.

5. Methodology and results

This section is divided into two parts. The first part tracks the number of corporate insolvency and restructuring filings during the pandemic. The second part analyzes the mechanisms that affect the number of filings.

2. Entities with code S.11 in ESA 2010.

3. See Cabral *et al.* (2021) to know more details about the SIBS payments database.

4. See details about Google Mobility Reports in `https://support.google.com/covid19-mobility/answer/9824897?hl=en&ref_topic=9822927`.

	Insolvency+ restructuring (1)	Insolvency (2)	Restructuring (3)	Difference (4)	All firms (5)
Assets (€M)	1.342	0.901	4.061	3.16***	1.554
	(7.336)	(6.154)	(11.983)		(50.216)
Workers	11.911	9.679	25.671	15.992***	6.569
	(51.700)	(47.225)	(72.008)		(84.824)
Asset/ workers (€ 000)	97.836	85.559	166.585	81.026***	88.179
	(143.700)	(133.074)	(177.675)		(124.315)
Equity ratio (%)	-119.112	-133.862	-30.382	103.48***	-3.907
	(292.339)	(306.680)	(156.925)		(116.889)
EBITDA/ assets (%)	-22.440	-24.911	-7.557	17.354***	0.021
	(49.626)	(52.035)	(27.022)		(32.124)
Observations	11,179	9,619	1,560		411,041

TABLE 1. Descriptive statistics for insolvency and restructuring filings

Notes: this table depicts descriptive statistics (averages and standard errors) for the insolvency and restructuring cases included in the sample. Column 1 contains descriptive statistics for all firms. Column 2 contains statistics for insolvency filings. Column 3 includes descriptive statistics for restructuring filings. Column 4 depicts the difference between insolvency and restructuring filings. Column 5 contains descriptive statistics for firms that report data in IES in 2016. Statistics for the assets/worker ratio, equity ratio, EBITDA/assets do not include firms whose ratio has denominator equal to 0. Extreme observations are winsorized at the 95% level. Standard errors are reported in parentheses. Data from preceding years is used when there is no data for the year before the filing. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant differences at the 10%, 5% and 1% levels.
Source: IES, Citius e the author's own calculations.

5.1. Insolvency and restructuring filings

Figure 1 shows the number of insolvency and restructuring filings in Portugal during the sovereign debt crisis (Panel A) and during the pandemic (Panel B). The dashed lines shows the economic sentiment indicator for Portugal.[5] As Altman (1968) and the extensive literature that follows it show, there is a historical negative relationship between the number of new filings and the intensity of economic activity. In Portugal, the number of filings grew steadily following the degradation of economic activity in the sovereign debt crisis. The economic sentiment indicator remained stable between the third quarter of 2009 and the second quarter of 2021, when the Memorandum of Economic and Financial Policies (memorandum of understanding) was signed. After the signing of the memorandum of understanding, the index dropped by 8%

5. The methodology for the confidence indicator is available at `https://ec.europa.eu/info/business-economy-euro/indicators-statistics/economic-databases/business-and-consumer-surveys_en`

and 6% in the third and fourth quarters of 2011, respectively. The increase in the number of insolvencies happened gradually in the four quarters after the signing of the memorandum of understanding. In the third quarter of 2011 (quarter after the drop in the economic confidence indicator), the number of filings remained stable, but grew 17% in the fourth quarter. In the first quarter of 2021, there were 1,667 legal person insolvencies, the highest value in the sovereign debt crisis.

If the correlation between the economic confidence index and the number of insolvency and restructuring filings were similar during the pandemic, one would expect a gradual increase in the number of filings in 2020 and 2021. In March 2020 there was a sudden drop in the economic confidence indicator that persisted until the first quarter of 2021. However, the number of filings remained stable in 2020 and dropped in 2021. These values are consistent with findings from other countries. In the United States, the number of insolvency and restructuring filings dropped by 17% in 2020 (Wang *et al.* (2021)). In France, the number of filings dropped by 45% between March 2020 and October 2021 in comparison to the equivalent pre-pandemic period (Maadini and Hadjibeyli (2022)).

(A) Sovereign debt crisis (B) Pandemic

FIGURE 1: Insolvency and restructuring filings

Notes: in Panel A, the continuous line depicts the number of insolvencies for legal persons, according to DGPJ statistics. In Panel B, the continuous line depicts the number of insolvency and restructuring filings reported by Citius. The dashed lines depicts the monthly economic sentiment indicator for Portugal in both panels. I n Panel B, the dashed vertical line denotes the date of the first state of emergency declaration associated to the pandemic. Panel A does not present restructuring filings because these filings were only introduced by PER in May 2012.
Source: Banco de Portugal, DGPJ and the author's own calculations.

This study uses a methodology similar to the one used by Wang *et al.* (2021) to characterize the evolution of the number of filings with more detail. First, the data is grouped by weekly periods between January 2017 and June 2021. The base specification includes indicators for each week starting from the beginning of 2020, which allows the creation of confidence intervals and the comparison of the number of filings during the pandemic to the historical average before the pandemic. Seasonal and within-month variation is removed with fixed effects for the week of the month and the month of the

year. The specification also includes indicators for weeks with fewer than five business days because of holidays.

$$y_t = \alpha + \sum_{\tau=2020w1}^{2021w26} \beta_\tau \mathbb{1}_{t=\tau} + \gamma_{week} + \gamma_{month} + \gamma_{days} + \epsilon_t \quad (1)$$

y_t is the logarithm of one plus the number of filings,[6] $\mathbb{1}_{t=\tau}$ is an indicator equal to 1 in week $t = \tau$, γ_{week}, γ_{month} and γ_{days} are fixed effects for the week of the month, the month of the year and the number of work days in the week.

Alternatively, the study considers a specification that compares the number of filings after the pandemic, in 2020 and 2021. The inclusion of year indicators allows for the comparison of the number of filings in these periods against the historical average before the pandemic. The specification is given by:

$$y_t = \alpha + \beta_1 \mathbb{1}_{post,t} \times \mathbb{1}_{year=2020,t} + \beta_2 \mathbb{1}_{post,t} \times \mathbb{1}_{year=2021,t} + \gamma_{week} + \gamma_{month} + \gamma_{days} + \epsilon_t \quad (2)$$

$\mathbb{1}_{post}$ is equal to one from March 19 2020 onwards (state emergency declaration in Portugal)[7], $\mathbb{1}_{year=2020,t}$ is equal to one for weeks in 2020, $\mathbb{1}_{year=2021,t}$ is equal to one for weeks in 2021.

Figure 2 estimates the weekly evolution of the number of new filings using equation (1). There was no significant increase in the number of filings after the beginning of the pandemic in March 2020. From January 2021 onwards the number of filings dropped consistently below the historical average. The historical average contains insolvency and restructuring filings between 2017 and 2020, a period when gross domestic product growth was higher in Portugal than in the Euro Area [8] and the number of filings was stable (see Figure 2).

The lag between the beginning of economic difficulties faced by firms and the date of the filings potentially contributes to the gradual reduction of the number of insolvency and restructuring filings in 2020 and 2021. In the subsample of firms that completed three months of overdue credit in February 2020 and that had insolvency or restructuring filings in the subsequent months, the average difference between being overdue and the filing was 7.8 months.

Figure 3 repeats the exercise from Figure 2 but separates insolvency filings from restructuring filings. The evolution in the number of filings is similar for insolvencies and restructurings. In 2020 there was no significant increase in the number of filings, while in 2021 the number of filings dropped consistently below the historical average.

Figure 2 estimates equation (2), measuring the difference in the number of filings between the periods before and after the pandemic. Consistent with the previous results,

6. $log(1 + filings)$ is used instead of $log(filings)$ because there are weeks when the number of restructuring filings is 0.

7. Economic activity decelerated in the week of the state of emergency and in the previous week (see Lourenço and Rua (2021))

8. Average gross domestic product growth between 2017 and 2019 was 3% in Portugal and 2% in the Euro Area (source: Eurostat and the author's own calculations).

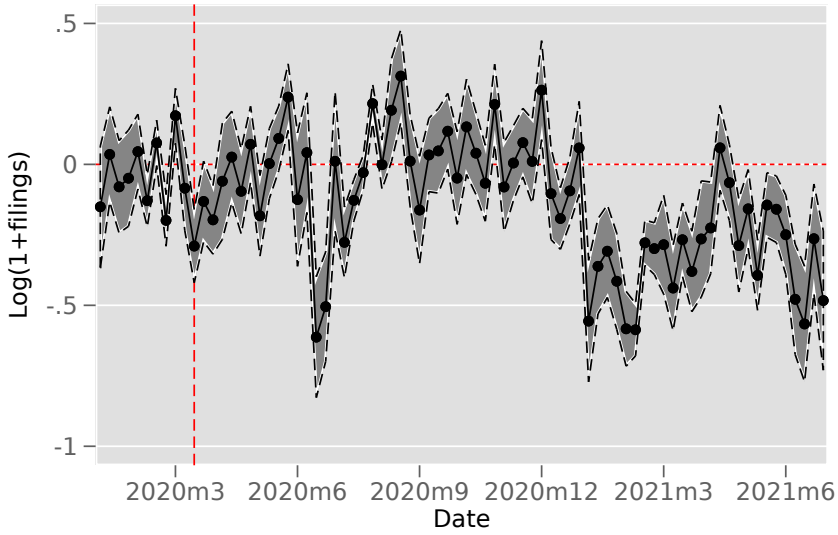
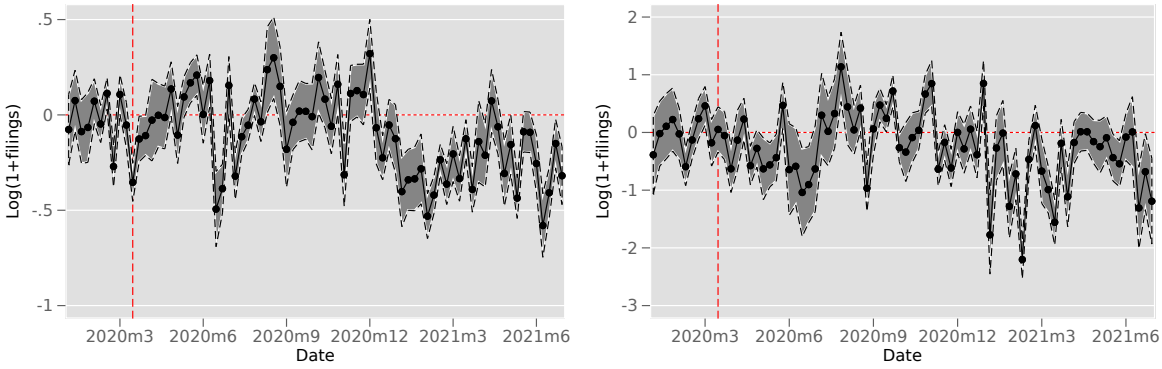


FIGURE 2: Weekly evolution of the number of corporate insolvency and restructuring filings

Note: this figure depicts the coefficients estimated in equation (1). Bands show 95% confidence intervals obtained with Newey-West confidence intervals (4 lags). The red dashed line denotes the week when the first state of emergency associated with the pandemic was declared in Portugal (March 19 2020).
Source: Citius and the author's own calculations.



(A) Insolvency (B) Restructuring

FIGURE 3: Weekly evolution of the number of filings, by type of filing.

Notes: this figure shows the coefficients from equation (1). Panel A shows coefficients for insolvency filings. Panel B shows coefficients for restructuring filings. Bands show 95% confidence intervals obtained with Newey-West errors (4 lags). The red dashed line denotes the declaration of the first state of emergency associated with the pandemic (March 19 2020).
Source: Citius and the author's own calculations.

the number of filings in the 2020 weeks affected by the pandemic was not significantly different from the historical average. In 2021, the number of filings was lower than the historical average. Obtaining an approximation to the percent change in the number of

filings from Table 2 estimates,[9] average weekly filings dropped 27% in 2021 (-24% for insolvencies and -43% for restructurings).[10]

	All filings (1)	Insolvency (2)	Restructuring (3)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2020}$	-0.015	0.005	-0.083
	(0.032)	(0.031)	(0.096)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2021}$	-0.313***	-0.270***	-0.568***
	(0.038)	(0.032)	(0.125)
Effect 2020	-1.5%	0.5%	8.0%
Effect 2021	-26.9%	-23.7%	-43.3%
R-squared	0.508	0.480	0.216
Observations	234	234	234

TABLE 2. Effect of the pandemic on insolvency and restructuring cases

Notes: this table estimates coefficients from equation (2). In Column the dependent variable is the logarithm of one plus the number of insolvency and restructuring filings. In Column 2, the dependent variable is the logarithm of one plus the number of insolvency filings. In Column 3, the dependent variable is the logarithm of one plus the number of restructuring filings. The table reports Newey-West standard errors in parentheses (4 lags). Values for rows *effect 2020* and *effect 2021* are obtained by transforming coefficient estimates using the formula $\frac{\Delta x}{x} = exp(\hat{\beta}) - 1$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant results at the 10%, 5% and 1% levels.
Source: Citius and the author's own calculations.

5.2. Mechanisms

This section analyzes four mechanisms that potentially affect the evolution of the number of insolvency and restructuring filings during the pandemic. First, it measures the effect of the economic slowdown, comparing firms in the sectors that were the most exposed to the pandemic to firms from other sectors. Second, it analyzes the effect of suspending the obligation to file for insolvency, comparing the number of insolvency filings initiated by the debtor with the number of other filings. Third, it uses a natural experiment to measure the effect of the credit moratorium on the probability of insolvency and restructuring. Finally, it measures the impact of the state of emergency periods on the number of filings.

9. The approximation is given by $\frac{\Delta x}{x} = exp(\hat{\beta}) - 1$ (e.g., Graham *et al.* (2019)).

10. In the online appendix, Table A.2 assumes that the number of filings follows a Possion or negative binomial distribution or uses the the absolute number of filings as the dependent variable. Results are similar.

5.2.1. Economic activity

Table 3 estimates equation (2) separately for the sectors that were the most exposed to the pandemic and for the remaining sectors.[11] In the most exposed sectors, the number of filings increased 28.4% above the historical average in 2020 and was not significantly different from the historical average in 2021. In the other sectors, the number of filings was below the historical average in 2020 and 2021 (-11.2% and -35.1%, respectively). In Column 3, the difference in the number of filings between sectors diverged both in 2020 and 2021. The difference between the most exposed sectors and the least exposed sectors is significant: 40 pp in 2020 and 37 pp in 2021.

	Most exposed sectors (1)	Other sectors (2)	Difference (3)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2020}$	0.250***	-0.119***	0.369***
	(0.061)	(0.037)	(0.072)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2021}$	0.020	-0.432***	0.452***
	(0.053)	(0.047)	(0.067)
Effect 2020	28.4%	-11.2%	39.6 p.p.
Effect 2021	2.0%	-35.1%	37.1 p.p.
R-squared	0.227	0.532	0.271
Observations	234	234	234

TABLE 3. Effect of the pandemic on insolvency and restructuring filings, by sector

Notes: this table depicts estimation results for equation (2). In Column 1, the dependent variable is the logarithm of one plus the number of insolvency and restructuring filings in the most exposed sectors. In Column 2, the dependent variable is the number of insolvency and restructuring filings in the remaining sectors. In Column 3, the dependent variable is the difference between the dependent variable from Column 1 and the dependent variable from Column 2. The table reports Newey-West standard errors in parentheses (4 lags). Values for rows *effect 2020* and *effect 2021* are obtained by transforming coefficient estimates using the formula $\frac{\Delta x}{x} = exp(\hat{\beta}) - 1$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant results at the 10%, 5% and 1% levels.
Source: Citius and the author's own calculations.

Figure 4 estimates equation (2), with the dependent variable being the difference between the logarithm of filings in the most exposed and the least exposed sectors ($\Delta log(1 + filings) = log(1 + filings_{affected,t}) - log(1 + filings_{other,t})$). $filings_{affected,t}$ is the number of filings in the most affected sectors and $filings_{other,t}$ is the number of filings in other sectors. The difference in the number of filings between the most and the least affected firms was consistently positive in 2020 and 2021.

11. The most exposed sectors are the sectors from Decree-law 78-A/2020. Results are similar using sectors from Decree-law 22-C/2021 and exposed sectors from the *Retomar* program.

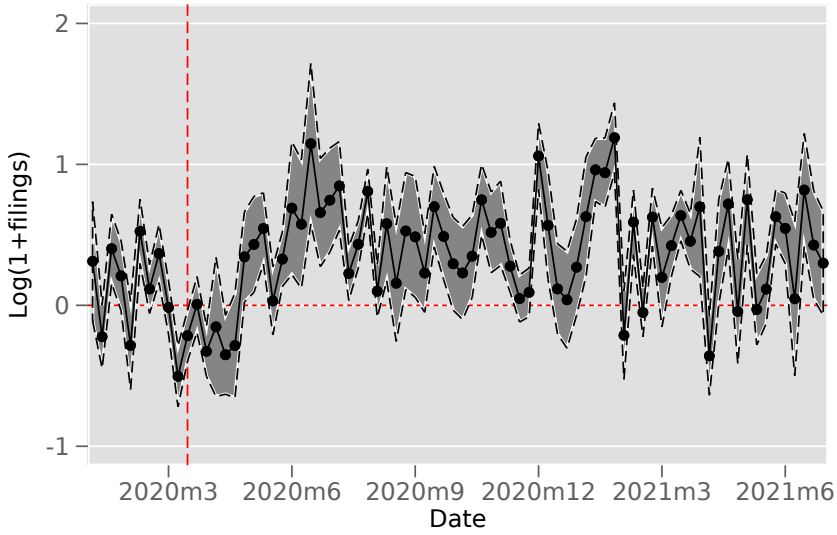


FIGURE 4: Filings in the most exposed vs. the least exposed sectors

Notes: this figure shows coefficients estimated using equation (1). The dependent variable is the difference between the logarithm of one plus the number of filings in the sectors that were the most exposed to the pandemic and one plus the number of filings in the remaining sectors. Bands show 95% confidence intervals obtained with Newey-West standard errors (4 lags). The red dashed line denotes the week of the declaration of the first state of emergency in Portugal associated with the pandemic (March 19 2020).
Source: Citius, IES and the author's own calculations.

5.2.2. *Suspension of the deadline to file for insolvency*

As mentioned in Section 2, debtors that are unable to comply with their debt obligations or that have assets significantly lower than liabilities must file for insolvency. This deadline was suspended during the pandemic, which might explain the drop in the number of insolvency and restructuring filings.

Table 4 contrasts the evolution of the number of insolvency filings submitted by debtors with the evolution of the other insolvency and restructuring filings. The suspension of the deadline to file for insolvency only affected insolvency filings submitted by debtors. If the drop in the number of filings were explained by the suspension of the deadline to file for insolvency, then one would expect the reduction in the number of filings to be concentrated in insolvencies filed by debtors. However, this pattern does not happen. The number of filings submitted by debtors increased 9.7% in 2020 and dropped 19.1% in 2021. The number other filings always changed negatively, dropping by 9.5% in 2020 and by 27.2% in 2021.

5.2.3. *Credit moratorium*

Support measures adopted during the pandemic allow for the continuation of economic activity and discourage resource reallocation (Caballero and Hammour (1996)). Assessing all measures is not doable, since there are many parallel measures with simultaneous effects on firms. This section uses a natural experiment to assess the existence of a causal relationship between one of the support measures –

	Suspended deadline (1)	Other filings (2)	Difference (3)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2020}$	0.093**	-0.112**	0.205***
	(0.040)	(0.044)	(0.057)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2021}$	-0.212***	-0.317***	0.105*
	(0.051)	(0.029)	(0.056)
Effect 2020	9.7%	-9.5%	19.3 pp
Effect 2021	-19.1%	-27.2%	8.1 pp
R-squared	0.300	0.416	0.165
Observations	234	234	234

TABLE 4. Insolvency and restructuring filings affected by the deadline suspension

Notes: this table presents results from the estimation of equation (2). In Column 1, the dependent variable is the logarithm of one plus the number of insolvency filings submitted by the debtor. In Column 2, the dependent variable in the logarithm of one plus the number of insolvency filings requested by debtors and restructuring filings. In Column 3, the dependent variable is the difference between the logarithm of one plus the number of insolvency filings submitted by the debtor and the logarithm of one plus the number of insolvency filings requested by debtors and restructuring filings. The table reports Newey-West standard errors in parentheses (4 lags). Values for rows *effect 2020* and *effect 2021* are obtained by transforming coefficient estimates using the formula $\frac{\Delta x}{x} = exp(\hat{\beta}) - 1$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant results at the 10%, 5% and 1% levels.
Source: Citius and the author's own calculations.

credit moratoriums – and the probability of insolvency and restructuring. A natural experiment is an empirical analysis in which firms from the sample are exposed to the variables of the study in an approximately random manner because of external factors.

The study focuses on credit moratoriums for three reasons. First, moratoriums have a large impact on the insolvency process. With the moratoriums, firms do not have the immediate obligation to reimburse creditors, hence avoiding one of the conditions for being insolvent (being unable to comply with overdue debt obligations). Second, moratoriums affect the relationships between firms and creditors directly, who are the main recipients of the funds that are disbursed through insolvency and restructuring procedures. Finally, the design of the moratoriums in Portugal allows testing for the existence of a causality relationship between the corporate support measures and the probability of insolvency and restructuring.

The credit moratorium introduced in March 2020 excluded firms with overdue loans for more than 90 days.[12] This exclusion leads to a natural experiment because it affects firms with overdue credit in different ways. This exercise considers two groups of firms that were affected by the regulations in different ways. The control group contains firms that are overdue for two subsequent months in January 2020.[13] These loans cannot access the moratorium to avoid being overdue for three months because the moratorium does

12. For legal purposes, credit is overdue only if it complies with the materiality criteria from the Banco de Portugal Regulation 2/2019 and from the European Central Bank Regulation (EU) 2018/1845.

13. The study adopts an overdue credit criteria that is consistent with the criteria used by the legislation that introduces the credit moratorium. A given firm has two months of overdue credit if it has overdue

not apply in February 2020. The treatment group contains all firms that become overdue for two months in February 2020. Among firms in the control group, firms whose loans are less than 90 days overdue on March 18 2020 have access to the moratorium, therefore they can use the moratorium and avoid being three months overdue. The sample includes firms with overdue credit events before the events included in the analysis and firms with more than one overdue credit event. These exclusions avoids having firms both in the control group and in the treatment group.

The study measures the effect of the moratorium on these firms using a differences-in-differences specification. The *pre* period presents the probability of insolvency or restructuring up to the month when the firm has two months of overdue credit. The *post* period presents the probability of insolvency or restructuring in the periods after the month when the firm completes two months of overdue credit.

The specification is given by:

$$\mathbb{1}_{filing,i,t} = \alpha + \beta_1 \mathbb{1}_{treatment,i} + \beta_2 \mathbb{1}_{post,t} + \beta_3 \mathbb{1}_{treatment,i} \times \mathbb{1}_{post,t} + \epsilon_{i,t} \quad (3)$$

$\mathbb{1}_{filing,i,t}$ is an indicator that is equal to 1 when the firm has an insolvency or a restructuring filing in period t. $\mathbb{1}_{treatment,i}$ is an indicator equal to 1 if the firm is part of the treatment group (two months of overdue credit in February 2020). $t \in \{0, 1\}$, where 0 is the *pre* period and 1 is the *post* period.

Table 5 depicts estimates for coefficients in equation (3). The moratorium law causes a 2.6 pp difference between the treatment and the control group. This effect represents a reduction in the probability of corporate insolvency or restructuring of 34.7%.[14] Even though the coefficient has a considerable economic impact, the analysis contains a high level of statistical noise, as results are statistically significant only at the 10% level. From the 2.6 pp increase in the probability of a new insolvency or restructuring filing, 2.5 pp arise from the increase in the probability of insolvency. This effect represents a reduction of -39.1% in the probability of insolvency. The effect on restructurings is smaller (-14.3%) and statistically not significant at the 10% level.

The natural experiment has as its main advantage requiring a minimal set of econometric assumptions. However, the natural experiment is a partial equilibrium analysis, studying only firms included in the sample and abstracting itself from the effect of the moratorium on the economy. In general equilibrium, i.e. considering the effect of the moratorium on all economic agents and the interactions between agents, it is likely that the moratorium also reduces the probability of insolvency for other firms. With the moratorium, previously healthy firms that were affected by the pandemic could avoid becoming overdue and insolvent. Additionally, the shocks that affect some firms propagate to other firms through supply chains (Carvalho *et al.* (2021)). The moratorium reduced the effect of the pandemic by blocking the propagation of shocks through supply chain networks.

credit for two subsequent months in the CRC and the overdue amount each month is greater than €500 and represents more than 1% of total credit.

14. This value originates from the formula $\frac{\hat{\beta_3}}{\hat{\alpha}+\hat{\beta_1}+\hat{\beta_2}}$ using estimates from equation (3).

	(1) All cases	(2) Insolvency	(3) Restructuring
$\mathbb{1}_{treatment,i} \times \mathbb{1}_{post,t}$	-0.026*	-0.025**	-0.001
	(0.013)	(0.012)	(0.007)
$\mathbb{1}_{treatment,i}$	0.006	0.008	-0.002
	(0.008)	(0.007)	(0.004)
$\mathbb{1}_{post,t}$	0.035***	0.031***	0.005
	(0.010)	(0.009)	(0.005)
Constant	0.034***	0.025***	0.010***
	(0.006)	(0.005)	(0.003)
R-squared	0.004	0.004	0.001
Observations	4,198	4,198	4,198

TABLE 5. The effect of the pandemic on insolvency and restructuring filings

Notes. this table depicts results from estimating equation (3). In Column 1, the dependent variable is an indicator equal to one if there is a new insolvency or restructuring case. In Column 2, the dependent variable is an indicator equal to one if the firm starts an insolvency process. In Column 3, the dependent variable is an indicator equal to one if the firm starts a restructuring process. The table reports heteroskedasticity-robust standard errors. $^{*}\ p < 0.1$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$ denote statistically significant results at the 10%, 5% and 1% level, respectively.
Source: Citius and the author's own calculations.

Table 6 uses the percentage of creditors from the financial sector[15] in each filing to split the sample between firms whose share of creditors from the financial sector is above or below the median. There was a more significant reduction in the number of filings by firms with exposure to the financial sector greater than the median. These estimates corroborate results from Table 5. Moratoriums allow firms with exposure to financial creditors above the median to stop reimbursing their loans, which reduces the probability that these firms file for insolvency or restructuring.

5.2.4. State of emergency

This section analyzes the effect of state of emergency declarations on the number of insolvency and restructuring filings. There were two periods with state of emergency declarations. The first period happened in the beginning of the pandemic between March and the beginning of May 2020. The second period happened between November 2020 and April 2021. In these periods, there were restrictions to regular court operations, including the completion of some proceedings using remote work tools and the suspension of other proceedings.

15. Creditors belong to the financial sector if their institutional sector (ESA 2010) starts by S.12.

	Exposure > median (1)	Exposure ≤ median (2)	Difference (3)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2020}$	-0.138***	0.093***	-0.231***
	(0.040)	(0.033)	(0.037)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2021}$	-0.394***	-0.224***	-0.170**
	(0.059)	(0.044)	(0.070)
Effect 2020	-12.9%	-8.9%	-20.6%
Effect 2021	-32.6%	-20.1%	-15.6%
R-squared	0.407	0.404	0.195
Observations	234	234	234

TABLE 6. Effect of the pandemic on insolvency and restructuring filings, firms whose share of financial creditors is above or below the median.

Notes: this table presents results from estimating equation (2). In Column 1, the dependent variable is the logarithm of one plus the number of insolvency and restructuring filings for firms whose share of financial creditors is above the median. Column 2 repeats the exercise for the remaining firms. In Column 3, the dependent variable is the difference bteween the dependent variable in Column 1 and the dependent variable in Column 2. The table reports Newey-West standard errors in parentheses (4 lags). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant results at the 10%, 5% and 1% levels.
Source: Citius and the author's own calculations.

The following equation assesses the effect of state of emergency declarations:

$$y_t = \alpha + \beta_1 \mathbb{1}_{emergency_1,t} + \beta_2 \mathbb{1}_{emergency_2,t} + \beta_3 \mathbb{1}_{post,t} \times \mathbb{1}_{year=2020,t} + \beta_4 \mathbb{1}_{post,t} \times \mathbb{1}_{year=2021,t} + \gamma_{week} + \gamma_{month} + \gamma_{days} + \epsilon_t \quad (4)$$

$\mathbb{1}_{emergency_1,t}$ is equal to 1 in the weeks when there is an ongoing state of emergency for at least one day between March and May 2020 (first state of emergency period). $\mathbb{1}_{emergency_2,t}$ is equal to 1 in the weeks when there is an ongoing state of emergency for at least one day between November 2020 and April 2021 (second state of emergency period). The analysis includes the variables $\mathbb{1}_{post,t} \times \mathbb{1}_{year=2020,t}$ and $\mathbb{1}_{post,t} \times \mathbb{1}_{year=2021,t}$ in the equation. β_1 and β_2 measure the change in the number of filings in the weeks of the state of emergency, controlling for the average change in the number of filings in 2020 and 2021 after the beginning of the pandemic.

Table 7 measures the effect of the state of emergency periods on the number of insolvency and restructuring filings. The first state of emergency period caused a 10.1% reduction in the number of filings. This reduction was relatively small when compared to the drop in in-person activity at courts, which might reflect the fact that urgent court cases (such as insolvencies and restructurings) were still processed during the state of emergency or the continuation of procedures using remote work tools. Payments in courts dropped by 54.3%. [16] The drop in in-person court activity reflected lower movement at other establishments in Portugal, as one can see in Columns 3 and 4 from Table 7. The second state of emergency period had a relatively smaller effect on

16. Payments at establishments with sector code 84230 (legal activities) are classified as court payments. However, this sector includes other establishments such as jails.

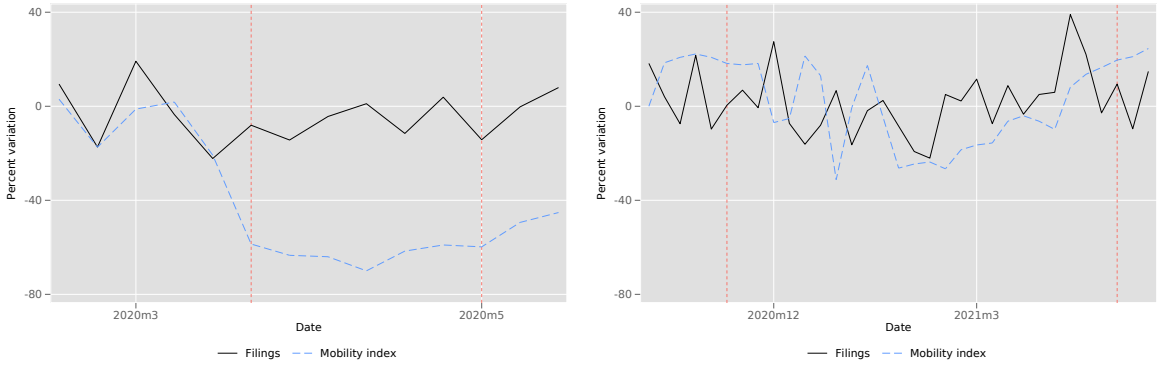
mobility. The results do not corroborate the existence of a reduction in the number of filings during this period.

	Filings (1)	Payments (courts) (2)	Payments (3)	Mobility (4)
$\mathbb{1}_{emergency_1,t}$	-0.106*	-0.784***	-0.333***	-0.516***
	(0.055)	(0.150)	(0.072)	(0.097)
$\mathbb{1}_{emergency_2,t}$	-0.000	0.036	-0.120***	-0.272***
	(0.054)	(0.137)	(0.031)	(0.083)
$\mathbb{1}_{post} \times \mathbb{1}_{year=2020}$	0.004	0.015	-0.046**	
	(0.042)	(0.089)	(0.022)	
$\mathbb{1}_{post} \times \mathbb{1}_{year=2021}$	-0.318***	-0.174	-0.010	
	(0.048)	(0.129)	(0.033)	
Effect emergency 1	-10.1%	-54.3%	-28.3%	-40.3%
Effect emergency 2	0.0%	-3.5%	-11.3%	-23.8%
Effect 2020	0.4%	1.5%	-4.5%	
Effect 2021	-27.2%	-16.0%	-1.0%	
R-squared	0.513	0.425	0.860	0.692
Observations	234	182	182	72

TABLE 7. Effect of the state of emergency

Notes: the table presents results from estimating equation (4). In Column 1, the dependent variable is the logarithm of 1 plus the number of restructuring and insolvency filings. In Column 2, the dependent variable is the logarithm of the number of payments at establishments from sector 84230 (legal activities), correcting for a linear trend. In Column 3, the dependent variable is the logarithm of the total number of payments in all establishments, correcting for a linear trend. In Column 4 the dependent variable is the weekly average (excluding weekends) of the Google Mobility Reports mobility index for the *workplace* variable. Table 2 explains the method to retrieve annual and state of emergency effects. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ denote statistically significant results at the 10%, 5% and 1% levels.
Source: Citius, Google Mobility Reports, SIBS and the author's own calculations.

Figure 5 tracks residuals from equation (2) during state of emergency periods. In Panel A, between February and May 2020, residuals were negative. Even though results are consistent with a reduction in the number of filings during this period, this reduction is much smaller than the drop in the mobility index. In Panel B, between September 2020 and May 2021, residuals were not consistently smaller than 0.



(A) First stage of emergency period (B) Second state of emergency period

FIGURE 5: Effect of the state of emergency periods on insolvency and restructuring filings

Notes: this figure shows residuals from equation (2) during state of emergency periods transformed into percent changes. Panel B reindexes the mobility index to have value 0 in the first week. Vertical lines depict the beginning and end of the state of emergency periods.
Fonte: Citius, Google Mobility Reports and the author's own calculations.

6. Conclusion

This study analyzes the evolution of the number of corporate insolvency and restructuring filings in Portugal during the COVID-19 pandemic. In Portugal, firms have access to an insolvency system that typically leads to liquidation, and to PER, which allows firms to negotiate with creditors and to restructure without capital structure unanimity. The pandemic affected insolvency and restructuring mechanisms directly by suspending the obligation to file for insolvency, introducing incentives to restructuring and reducing court costs. Indirectly, the credit moratorium, one of the corporate support measures approved in Portugal, allowed firms to avoid insolvency.

Even though there is a historical and negative relationship between corporate economic activity and insolvency and restructuring filings, the number of new filings did not increase during the pandemic. Filings stayed around the historical average in 2020 and dropped consistently below the historical average in 2021.

The study analyzes the factors that affected the evolution of the number of filings. First, the study analyzes the effect of lower economic activity associated to the pandemic on the number of insolvency and restructuring filings, comparing the number of filings at the most and least exposed sectors to the pandemic. Exposure to the pandemic led to an increase in the number of insolvency and restructuring filings. In the sectors that were the most exposed to the pandemic, the number of filings was above the historical average in 2020 and stayed at the historical average in 2021. In the remaining sectors, the number of filings was below the historical average in 2020 and 2021. Second, the study analyzes the effect of the corporate support measures on the number of filings. The suspension of the obligation to file for insolvency does not explain the drop in the number of filings, since the number of filings that were not affected by this suspension also went down. The results from a natural experiment suggest that

the credit moratorium avoided new insolvency filings, even though the analysis has a high level of statistical noise.

Finally, the study shows that temporary restrictions to court operations introduced by the state of emergency had a negative but small impact on the number of filings. The negative impact was concentrated on the first state of emergency period, between March and May 2020, but was significantly lower than the reduction of mobility in Portugal in the same period.

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Non-technical summary

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On the aggregate and distributional effects of carbon taxation in Portugal

Zeina Hasna, Nuno Lourenço and Cezar Santos

As the economic effects of climate change unfold, countries face increasing pressure to adopt effective policies aimed at curbing greenhouse gas emissions and accelerate the transition towards a low-carbon economy. A widely discussed policy prescription involves pricing carbon emissions to incentivise businesses and households to shift towards greener practices.

We investigate the aggregate and distributional effects of a carbon tax for Portugal, by resorting to the multi-sector model introduced by Cavalcanti *et al.* (2021). The model integrates the workers' skill distribution with the economy's sectoral composition. It also features endogenous occupational choice and human capital accumulation. Individuals take into account their sector-specific productivities to choose their sector of work and invest in schooling.

The production side of the economy consists of various sectors, including four energy-producing activities: oil, coal, natural gas and green. In the policy experiments, we introduce a carbon tax on the "dirty" energy sectors: oil, coal and natural gas. Given the intersectoral linkages in the economy, carbon taxation induces changes in relative prices, thus leading to reallocation of inputs across sectors. In the analysis, four different revenue-recycling schemes are considered, where revenues are either: (i) wastefully spent, i.e. not rebated back to the economy ("Wasteful spending"); (ii) used to subsidise green energy, for example wind energy projects ("Green subsidy"); (iii) used to subsidise all non-dirty sectors ("Useful spending"); or (iv) used to subsidise education expenditures for all non-dirty sectors in the economy ("Education subsidy").

We estimate that a carbon tax of 32.9% is needed to achieve Portugal's original Paris Agreement pledge of 35% emissions reduction (Table 1, Panel A).

This carbon tax costs the Portuguese economy at most a 1.7% drop in GDP, which is the worst-case scenario when the government does not rebate its tax revenues back to the economy. If the government uses the carbon tax revenue to subsidise the green sector, the fall in GDP is dampened to only 0.9%. Despite the relatively small impact on GDP and welfare, the carbon tax has non-trivial distributional effects at the sectoral and individual levels. Our analysis points to asymmetric effects across sectors and individuals; workers with a comparative advantage in dirty energy sectors who do not reallocate experience

Panel A: 32.9% carbon tax		
Scenario	GDP	Welfare
Wasteful spending	-1.7	-3.3
Green subsidy	-0.9	-1.0
Useful spending	-1.5	-0.7
Education subsidy	0.4	-1.1
Panel B: 80.4% carbon tax		
Scenario	GDP	Welfare
Wasteful spending	-7.5	-10.7
Green subsidy	-5.8	-6.6
Useful spending	-7.1	-6.0
Education subsidy	-4.1	-7.1

TABLE 1. Long-run effects of a carbon tax in Portugal for different revenue-recycling schemes. | Welfare is measured with the consumption equivalent variation.

the largest welfare loss. In particular, these workers suffer a welfare loss almost five times larger than workers in non-dirty sectors, however they account for less than 0.5% of the Portuguese labour force.

As the Paris Agreement targets have been revised over time, we also target the carbon tax needed for Portugal to achieve a 70% decline in emissions, which stands at 80.4% (Table 1, Panel B). The results with an 80.4% carbon tax are qualitatively similar to those leading to a 35% emissions reduction, but amplified. Under this policy experiment, workers with a comparative advantage in dirty energy production are still the hardest hit, but now constitute only 0.2% of the Portuguese labour force.

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On the aggregate and distributional effects of carbon taxation in Portugal

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Abstract
Drawing on the model developed by Cavalcanti *et al.* (2021), we quantify the aggregate and distributional effects of a carbon tax in Portugal. Carbon taxation induces changes in relative prices and reallocation of inputs, including labour. We target a decline in emissions of a 30 to 40%, required for Portugal to achieve its original Paris Agreement pledge. This entails at most a 1.7% drop in output. As the Paris Agreement targets have been revised over time, we also estimate the carbon tax needed for Portugal to achieve a 70% decline in emissions, which stands at 80.4%. We find that the effects are asymmetric across sectors and individuals, with those workers with a comparative advantage in dirty energy sectors who do not reallocate being hit harder. (JEL: E13, H23, J24.)

1. Introduction

Triggered by a high concentration of carbon dioxide and other greenhouse gases (GHG) in the atmosphere, climate change is arguably the largest global negative externality in the world. It affects ecosystems worldwide by causing global warming, rising sea levels or more frequent extreme weather events. Its economic effects are surrounded by heightened uncertainty, and are long-lasting and heterogeneous across geographies.

The 2015 Paris Agreement set the stage for the international response to climate change by bringing several parties to adopt policies to limit global warming to well below 2, later revised to 1.5 degrees Celsius compared to pre-industrial levels. Countries have thus submitted their plans for climate action known as nationally determined contributions (NDCs), where they communicated the intended actions to reduce GHG

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emissions. Portugal was no exception. A long-term strategy for carbon neutrality by 2050 was designed, consisting of the identification of the main decarbonisation vectors in all sectors, the policy options and the emission reduction path to achieve this end across different socio-economic scenarios.[1]

Given that there is scientific consensus that global temperatures are rising, it is almost unanimous that governments lie at the root of the transition to a greener economy. In fact, one of the policy prescriptions to address climate change has been known for more than a century, since the work of Pigou (1920). By imposing a tax on GHG emissions at the source that must be equal to the total marginal damage the polluter is not paying for, it provides incentives to producers to shift their operations to a less carbon-intensive direction. A second policy prescription for climate change mitigation drawing on the work of Coase (1960) lies in the implementation of tradable carbon permits (e.g. European Union Emissions Trading System). As carbon dioxide spreads fast in the atmosphere, the damages are identical regardless of where pollution occurs.

In this paper, we assess the aggregate and distributional effects of a climate change mitigation policy in Portugal, in particular a tax on GHG emissions, inspired by the line of research highlighting the effectiveness of carbon taxes in reducing emissions (see for example, Golosov *et al.* (2014), Hassler *et al.* (2018) and Hassler *et al.* (2021)). The carbon tax will induce a change in factor prices that then spreads to the rest of the economy and causes sectoral reallocation of inputs, in particular labour. To do so, we resort to the model introduced in Cavalcanti *et al.* (2021) featuring heterogeneity in the workers' skill distribution and the economy's sectoral composition.

In our policy experiments, we analyse the economic impacts of introducing a carbon tax to the "dirty" energy producers.[2] Our model-based estimates needed for Portugal to achieve its Paris Agreement pledges of a 35 and a 70% reduction in emissions point to a 32.9 and an 80.4% carbon tax, respectively.[3] We find that the carbon tax is an effective tool for Portugal to reduce emissions and achieve its climate targets laid down in the Paris Agreement. We also show that the effects will be conditional on the magnitude of the tax and how the tax revenues are rebated back to the economy. For instance, we estimate that a 32.9% (80.4%) carbon tax costs the Portuguese economy at most a 1.7% (7.5%) drop in output, which is the worst-case scenario when the government does not rebate tax revenues back to the economy. Moreover, the carbon tax has non-trivial distributional effects at the sectoral and individual levels. Our analysis points to asymmetric effects across sectors and individuals; workers with a comparative advantage in dirty energy sectors who do not reallocate experience the largest welfare loss.

1. See `https://descarbonizar2050.apambiente.pt/en/documents/` for an overview of the documents that have been released following the Paris Agreement.

2. The "dirty" energy sectors refer to oil, coal and natural gas sectors, whereas the "non-dirty" energy sector refers to the green sector.

3. A reduction target of 30 to 40% by 2030, below 2005 levels was originally pledged by Portugal. Later on, Portugal assumed a reduction target of 65 to 75% by 2040, below 2005 levels. Hence, in our experiments we target the mid-points of these intervals, respectively, 35 and 70%. See `https://files.dre.pt/1s/2020/07/13300/0000200158.pdf` for details (in Portuguese only).

The remainder of the paper is structured as follows. Section 2 describes the model. Section 3 details the aggregate results and Section 4 presents the sectoral- and individual-level results of the policy scenarios. Section 5 concludes.

2. The model

We follow the multi-sectoral model developed by Cavalcanti *et al.* (2021), in which the workers' skill distribution is integrated with the economy's sectoral composition. As in Hsieh *et al.* (2019), the framework features endogenous occupational choice and human capital accumulation, where individuals live for two periods. In the first period, individuals take into account their sector-specific productivities to choose the sector they work for and their investment in human capital.[4] In the second period, individuals work and consume. The production side of the economy consists of sectors producing differentiated intermediate goods, including four energy types: oil, coal, natural gas and green. There is also a final good sector. A carbon tax is introduced to the dirty energy producers, which in turn affects their prices. Given the intersectoral linkages in the economy, these changes in relative prices induce reallocation of inputs across sectors, including labour. The model environment is described in what follows.

2.1. Households

Individuals work in each one of the J intermediate sectors and are endowed with two units of time: one unit when they are "young", which is allocated between leisure and schooling; and one unit when they are "old", when they supply their labour inelastically to one of the intermediate goods sectors. There is a continuum of measure one of those individuals.

Each individual derives utility from consumption, c, and leisure, $1-s$, according to the following function:

$$U = c^{\gamma}(1-s),\ \gamma > 0,$$

where s denotes time spent on schooling in the first period of life and γ controls the relative weight of consumption in the individual's utility.

Human capital for sector j depends on schooling time, s, and schooling resources (e.g. tuition fees), e, and is given by:

$$h_j(s,e) = s^{\varphi_j} e^{\eta}.$$

The elasticity of human capital with respect to time is sector-specific, φ_j, such that different sectors feature different returns to schooling.

The individual's labour income is the product of the wage per efficiency unit in sector j, w_j, their idiosyncratic ability draw, z_j, and their acquired human capital for sector j,

4. Ability, talent, comparative advantage and productivity are used interchangeably in the text.

$h(s,e)$:

$$I = w_j z_j h_j(s,e).$$

Individuals split income between consumption, c, and expenditures on schooling resources, e:

$$c = w_j z_j h_j(s,e) - e.$$

Given an occupational choice, wage, and idiosyncratic talent, z_j, the individual's utility maximisation problem is given by:

$$U_j(w_j, z_j) = \max_{c,s,e} c^{\gamma}(1-s) \text{ subject to } c = w_j z_j h_j(s,e) - e. \tag{1}$$

The solution of this problem reads as follows:

$$s_j^* = \frac{1}{1 + \frac{1-\eta}{\gamma\varphi_j}}, \tag{2}$$

$$e_j^*(z_j) = \left[\eta w_j z_j (s_j^*)^{\varphi_j}\right]^{\frac{1}{1-\eta}}. \tag{3}$$

After plugging in equations (2) and (3) into (1), the individual's indirect utility is given by:

$$U_j^* = \left[w_j z_j s_j^{\varphi_j} (1-s_j)^{\frac{1-\eta}{\gamma}} \eta^{\eta} (1-\eta)^{(1-\eta)}\right]^{\frac{\gamma}{1-\eta}}. \tag{4}$$

2.1.1. Occupational skills

We assume that each worker is endowed with a vector of idiosyncratic abilities $\{z_j\}_{j=1}^{J}$ drawn from a multivariate Fréchet distribution, such that:

$$F(z_1, ..., z_J) = \exp\left(-\sum_{j=1}^{J} (z_j)^{-\lambda}\right), \ \lambda > 1,$$

where the parameter λ measures the dispersion of individual productivity across sectors. When λ is small, workers' abilities are more dispersed, and hence a larger change in wages is needed to get workers to reallocate across sectors. And vice versa. However, when λ is larger, skills are less dispersed, and workers' occupational choices are more sensitive to changes in wages, which makes reallocation across sectors easier.

2.1.2. Occupational choice

Heterogeneous abilities interact with the endogenous components of an individual's utility in (4) and drive self-selection. As such, workers supply their labour to the sector which offers them the highest relative returns given their vector of ability, i.e. the highest utility $\max_j\{U_j\}$.

The share of workers in each sector can be derived using the tractability afforded by the Fréchet distribution, given the decision rule behind workers' occupational choice (see Cavalcanti *et al.* (2021) for details). Each worker's occupational choice is driven

by *relative* returns instead of *absolute* returns. Having calculated the labour supply for each sector, we can compute the efficiency units of labour supplied (i.e. effective labour supply) in each sector.

Average worker quality in each sector can be computed by taking the ratio of efficiency units of labour supplied over the units of labour supplied. Average quality is therefore inversely related to the labour share in each sector, which captures a selection effect.

2.2. Production

As alluded before, the economy consists of J intermediate goods sectors and one final good sector. These are now described.

2.2.1. Intermediate goods

The production setup is similar to trade models such as Eaton and Kortum (2002). There are J sectors, each producing a differentiated intermediate good. Among these, there are four energy sectors (oil, coal, natural gas and green), from which the first three are polluting, i.e. dirty energy sectors. The fourth sector is the clean energy sector. The technology to produce each intermediate good $j \in \{1, 2, ..., J\}$ is represented by a Cobb-Douglas function with constant returns to scale:

$$Y_j = L_j^{\beta_j} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}},\ \beta_j, \nu_{jk} \in [0,1]; \textit{and}\ \beta_j + \sum_{k=1}^{J} \nu_{jk} = 1,$$

where L_j corresponds to effective labour input and β_j is the labour share in sector j. The variable x_{jk} denotes the quantity of intermediate input k used in the production of good j. The parameter ν_{jk} determines the relative importance of good k in the production of sector j. The inclusion of intersectoral linkages allows for a more detailed analysis of the general equilibrium effects of adding a carbon tax (Jones 2011; Acemoglu *et al.* 2012; King *et al.* 2019).

The representative firm in the intermediate goods sector j chooses labour L_j and intermediate inputs $\{x_{jk}\}_{k=1}^{J}$ to maximise:

$$\pi_j = \max_{L_j, x_{jk}} \left\{ P_j L_j^{\beta_j} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}} - w_j L_j - \sum_{k=1}^{J} P_k x_{jk} \right\}, \tag{5}$$

where P_j is the price of intermediate good j and w_j is the wage rate paid in sector j. Inputs are paid according to their marginal products, such that:

$$\beta_j P_j L_j^{\beta_j - 1} \prod_{k=1}^{J} x_{jk}^{\nu_{jk}} = w_j,$$

$$\nu_{jk} P_j L_j^{\beta_j} x_{jk}^{\nu_{jk}-1} \prod_{k \neq s} x_{js}^{\nu_{js}} = P_k,\ \forall x_{jk},\ k \in \{1, 2, ..., J\}.$$

2.2.2. *Final good*

A production function using differentiated intermediate goods, $\{Y_j^F\}_{j=1}^J$, yields the final good, Y_f, according to the following aggregator:

$$Y_f = \prod_{j=1} \left(Y_j^F\right)^{\sigma_j},\ \sigma_j \in [0,1) \text{ and } \sum_{j=1}^{J} \sigma_j = 1.$$

The final good is the numéraire, i.e. $P_f = 1$. The optimisation problem of the representative firm in the final good sector is to choose each input $\{Y_j^F\}_{j=1}^J$ to maximise:

$$\pi_f = \max_{Y_j} \left\{ \prod_{j=1} \left(Y_j^F\right)^{\sigma_j} - \sum_j P_j Y_j^F \right\}, \tag{6}$$

and the optimal demand for each input satisfies:

$$Y_j^F = \sigma_j \frac{Y_f}{P_j},\ \forall j \in \{1, 2, ..., J\}.$$

2.3. *Equilibrium*

The stationary competitive equilibrium consists of individual choices $\{c, s, e\}$, individual occupational choices, efficiency units of labour input in each sector $\{L_j\}_{j=1}^J$, intermediate goods $\{Y_j\}_{j=1}^J$, final output Y_f, wages $\{w_j\}_{j=1}^J$ and prices of intermediate goods $\{P_j\}_{j=1}^J$. In the economy, individuals maximise their utility and supply labour to the sector that provides them the highest income according to their abilities. Firms producing intermediate goods and the representative firm of the final good are profit-maximisers. Finally, all markets clear.

2.4. *Carbon taxation*

A carbon tax affects the prices of energy inputs, particularly the more polluting types. Therefore, the burden of the tax on the price of each energy type should depend on the carbon content of that particular energy type. Following Golosov *et al.* (2014) and Hassler *et al.* (2018), we differentiate between the four energy inputs according to their carbon content (intensity of carbon emissions to the atmosphere). Denote this content by g_j, such that $g_j \in [0, 1]$. Green energy types (such as wind and solar) are not associated with any climate externality, so $g_{green} = 0$. The carbon tax rate on each energy type is given by $\tau_j = \tau g_j, \forall j$. Note that $\tau_{green} = 0$ since $g_{green} = 0$.

We introduce the carbon tax as a sales tax to each energy type j, such that profits in energy type j, in the presence of such a tax, are given by:

$$\pi_j = (1 - \tau_j) P_j Y_j - w_j L_j - \sum_{k=1}^{J} P_k x_{jk}.$$

In our simulations, we consider different ways to rebate revenues raised with carbon taxes and adjust the equilibrium conditions accordingly. For instance, in one

counterfactual experiment, we consider the use of tax revenues in dirty energy sectors to subsidise the green energy sector. In that experiment, the green subsidy is designed such that the carbon tax is revenue neutral (i.e. $\sum_{j=1}^{J} \tau_j P_j Y_j = 0$), which implies that $\tau_{green} < 0$.

The parameterisation of the model is conducted by disciplining the parameters with detailed micro-data for Portugal. Some of the model parameters can be directly observed in the data (e.g. the relative importance of each input in the production of intermediate goods). Others will be estimated to match key moments of the data. For example, the expenditure shares in the final good (σ_j) are estimated to map sectoral value added. Returns of schooling in sector j (φ_j) are calibrated to target average relative wages, whereas the dispersion of productivities (λ) are calibrated to map the coefficient of variation in earnings. A detailed discussion of the data sources used and on how the model parameters are disciplined is provided in the Appendix.

3. The aggregate effects of a carbon tax

We assess how the economy reacts to a climate change mitigation policy by introducing a carbon tax to the dirty energy producers. In the analysis, four different revenue-recycling schemes are considered, where revenues are either:

1) wastefully spent, i.e. not rebated back to the economy ("Wasteful spending");
2) used to subsidise green energy, for example wind energy projects ("Green subsidy");
3) used to subsidise all non-dirty sectors ("Useful spending") or;
4) used to subsidise education expenditures for all non-dirty sectors in the economy ("Education subsidy").[5]

Subsidies in the schemes 2 – 4 are designed such that the government budget balances.

Emissions do not affect production or consumption, so the model does not feature emissions as an externality (as in King *et al.* (2019)). We take a positive approach rather than normative, in the sense that our goal is not to derive the optimal policy but to understand the aggregate and distributional effects of imposing a carbon tax aimed at curbing emissions consistent with the Paris Agreement climate targets.

We consider two experiments in which we increase the tax rate on oil, coal and natural gas energy production sectors from $\tau = 0\%$ to $\tau = 32.9\%$ and from $\tau = 0\%$ to $\tau = 80.4\%$.[6] In its original Paris Agreement pledge, Portugal's intended NDCs entailed an emissions reduction target of 30 to 40% by 2030, below 2005 levels. A tax rate of 32.9% yields the mid-point of the interval (a 35% reduction). NDCs have been revised over time, thus we also consider a 70% emissions reduction, for which a tax rate of 80.4% is needed.

5. The subsidy in the useful spending scenario and in the education subsidy scenario applies to all non-dirty sectors, which include the 14 non-energy intermediate goods and the green energy sector.

6. Adding a 32.9% (80.4%) value added tax translates into a tax $\tau_{oil} = 27.8\%$ (68%) on oil sales, $\tau_{coal} = 23.6\%$ (57.6%) on coal sales, and $\tau_{gas} = 24.1\%$ (59%) on natural gas sales upon adjusting for the carbon content of each energy input. This tax rate is equivalent to 53 (129.5) euros per ton of CO_2 in Portugal.

The main aggregate results for these analyses are displayed in Table 1. Panel A reports the results on emissions (total and fossil), GDP, consumption and welfare of introducing a 32.9% carbon tax.[7] Panel B displays the results for a 80.4% carbon tax. Welfare includes everything that individuals value, that is, consumption and leisure and is measured by a consumption equivalent variation from adding the carbon tax relative to the baseline. We detail the results for the different types of revenue-recycling schemes.

Panel A: 32.9% carbon tax					
Scenario	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-35.0	-37.7	-1.7	-4.0	-3.3
Green subsidy	-26.2	-28.4	-0.9	-0.9	-1.0
Useful spending	-33.6	-36.3	-1.5	-1.5	-0.7
Education subsidy	-35.0	-37.7	0.4	-2.0	-1.1
Panel B: 80.4% carbon tax					
Scenario	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-70.0	-75.5	-7.5	-11.6	-10.7
Green subsidy	-61.8	-66.8	-5.8	-5.8	-6.6
Useful spending	-68.8	-74.4	-7.1	-7.1	-6.0
Education subsidy	-70.0	-75.5	-4.1	-8.4	-7.1

TABLE 1. The effects of a carbon tax under all recycling schemes (% change).

By construction, the model yields a 35% reduction in total emissions (Panel A) in the wasteful spending scenario. Since the dirty energy sectors pollute more than the other activities, the drop in fossil emissions is larger (37.7%). A detailed breakdown of emissions by fossil fuel type is presented in Table 2. As energy becomes more expensive, the economy contracts and GDP falls by 1.7%. With the tax, reallocation of resources and fall in output, aggregate welfare decreases.

Panel A: 32.9% carbon tax							
Scenario	%Δ oil emissions	%Δ coal emissions	%Δ natural gas emissions	%Δ green emissions	%Δ non-energy emissions	%Δ total fossil fuel emissions	%Δ total emissions
Wasteful spending	-32.3	-51.0	-43.3	-	-2.0	-37.7	-35.0
Green subsidy	-28.6	-28.4	-27.5	-	-0.4	-28.4	-26.2
Useful spending	-31.0	-49.4	-41.5	-	-0.3	-36.3	-33.6
Education subsidy	-32.3	-51.0	-43.3	-	-2.0	-37.7	-35.0
Panel B: 80.4% carbon tax							
Scenario	%Δ oil emissions	%Δ coal emissions	%Δ natural gas emissions	%Δ green emissions	%Δ non-energy emissions	%Δ total fossil fuel emissions	%Δ total emissions
Wasteful spending	-71.7	-85.9	-78.2	-	-3.8	-75.5	-70.0
Green subsidy	-68.8	-63.6	-63.1	-	-0.8	-66.8	-61.8
Useful spending	-70.7	-84.8	-76.8	-	-0.6	-74.4	-68.8
Education subsidy	-71.7	-85.9	-78.2	-	-3.8	-75.5	-70.0

TABLE 2. Percentage change in CO_2 emissions by source and recycling scheme.

7. Total emissions in the economy include emissions from fossil fuel sectors plus emissions from non-energy sectors. The effects on GDP and consumption are "long-run" effects. There is no dynamics in the model and comparisons are made across two steady states.

If the government uses the carbon tax revenue to subsidise the green sector, the fall in GDP is dampened to only 0.9%. With more economic activity, emissions actually decline by less than with wasteful spending even with subsidies to the clean sector. An alternative is to subsidise all non-dirty sectors ("Useful spending"). Again, the fall in GDP is dampened relative to the wasteful spending scenario, but emissions do not fall by as much.

When tax revenues are used to finance education subsidies, Portugal GDP rises by 0.4%. Individuals invest more in education with this policy, increasing individual productivity and therefore aggregate output.

The estimated effects of a 32.9% carbon tax on aggregate output are not sizeable. This happens because the dirty energy sectors constitute a small fraction of the gross output in the economy (see Table B.1 in the Appendix for details). Panel B of Table 1 also displays the results for a higher tax rate (80.4%). The results are qualitatively similar, but amplified.[8] In order to achieve a 70% emissions reduction, GDP is expected to decline at most 7.5%. In this scenario, welfare losses can be sizeable.

3.1. Cross-country analysis

Given that economies differ in their production structures and labour force characteristics, the impact of carbon taxes is likely to vary across countries. Cavalcanti *et al.* (2021) find that for the United States to achieve its original Paris Agreement pledge of 26% reduction in emissions, it will need a 32.3% carbon tax and it will suffer at most a 0.6% drop in GDP (Table 3). In the case of China, their results indicate that to achieve a similar emission reduction target, it would need a 25.4% carbon tax and it would come with at most a 1.5% reduction in GDP. This is due to the fact that China is more reliant on dirty energy than the United States (see Cavalcanti *et al.* (2021) for details).

Applying the same emission reduction target of 26% for Portugal, we find that Portugal would need a 23.2% carbon tax and it will come with at most a 1% drop in GDP. In Portugal, the non-energy sectors contribute relatively more to national emissions than in the United States and China. Hence, to achieve the same emission reduction target, a lower carbon tax must be implemented in Portugal.

Meanwhile, the GDP losses of the United States, Portugal, and China associated with a 26% drop in emissions are in line with the relative shares of dirty energy sectors in each economy's total sales: 2.4%, 3.3% and 5.1%, respectively.

8. The amplification effect of increasing the tax rate to 80.4% is highly non-linear. This results from the law of diminishing returns, whereby the marginal product increases as the input quantity declines.

Panel A: 23.2% carbon tax					
Portugal	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-28.0	-1.0	-2.8	-2.2
Green subsidy	-18.6	-20.2	-0.4	-0.4	-0.5
Useful spending	-24.7	-26.8	-0.9	-0.9	-0.3
Education subsidy	-26.0	-28.0	0.6	-1.2	-0.5
Panel B: 32.3% carbon tax					
United States	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-26.8	-0.6	-1.7	-1.1
Green subsidy	-24.3	-25.0	-0.3	-0.3	-0.3
Useful spending	-25.3	-26.1	-0.5	-0.5	0.1
Education subsidy	-26.0	-26.8	0.4	-0.7	0.1
Panel C: 25.4% carbon tax					
China	Total emissions	Fossil emissions	GDP	Consumption	Cons. Equiv.
Wasteful spending	-26.0	-27.5	-1.5	-4.7	-3.6
Green subsidy	-20.6	-21.8	-0.7	-0.7	-1.2
Useful spending	-23.4	-24.8	-1.3	-1.3	-0.1
Education subsidy	-26.0	-27.5	1.0	-2.2	-1.0

TABLE 3. Effects of a carbon tax targeting a 26% reduction in emissions by country (% change).

4. The distributional effects of a carbon tax

Carbon taxes have non-trivial distributional effects at the sectoral and individual levels. These are now documented.[9]

4.1. Sectoral-level analysis

Introducing a carbon tax on oil, coal and natural gas energy sectors makes them more expensive relative to other sectors. As a result, these sectors shrink and labour demand and wages fall. Workers reoptimise their occupational decisions and some switch sectors. Figure 1 shows the changes in equilibrium labour by sectors. Employment in the oil, coal and natural gas sectors drops, with losses ranging from 20 to 40%, depending on the revenue-recycling scheme. With the subsidy to clean energy, inputs are reallocated from the dirty energy sectors to the green sector to equalise marginal returns. This yields an increase in employment in this sector of more than 30%. With an education subsidy, human capital rises because education becomes relatively cheaper, reinforcing the increase in effective labour to the sectors not directly affected by the carbon tax.

The occupational decision of workers is driven by their innate abilities and the wage in each occupation. Marginal workers with relatively low productivity in the dirty energy sectors reallocate to other sectors of the economy. Workers with a high

9. The results of this section are based on a comparison across two different steady states. We use terms like "switchers" and "stayers" when discussing the results for the sake of readability. But we emphasise that the comparisons are made across the steady states.

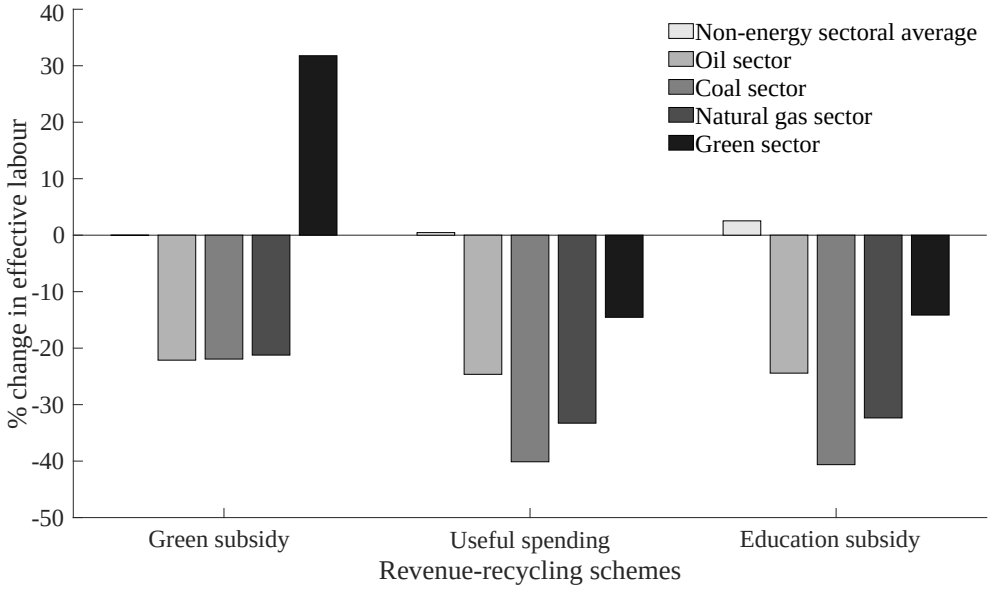

FIGURE 1: Percentage change in effective labour upon increasing the carbon tax from 0% (benchmark) to 32.9%.

comparative advantage in the dirty energy sectors remain in these sectors after the policy change. Therefore, due to a selection effect, the average productivity of workers in the taxed sectors rises (see Figure 2). In the green subsidy scenario, average productivity drops by 10% in the green sector due to the larger prevalence of workers in this sector, as depicted in Figure 1.[10]

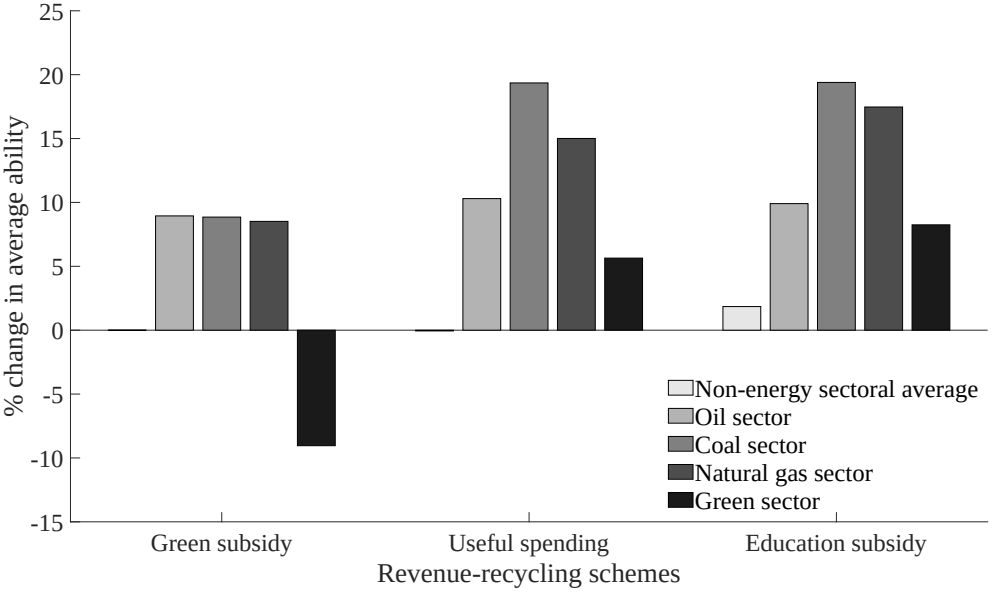

FIGURE 2: Percentage change in average productivity upon increasing the carbon tax from 0% (benchmark) to 32.9%.

10. For the sake of space, the figures for $\tau = 80.4\%$ are not reported but are available from the authors upon request. The effects across sectors and tax rebate schemes are qualitatively similar, but amplified.

4.2. Individual-level analysis

We now assess the distributional effects at the individual-level that arise after the introduction of a carbon tax. Workers are split into four categories: (i) those who remain in the non-dirty energy sectors; (ii) those who reallocate from non-dirty energy sectors; (iii) those who remain in dirty energy sectors; and (iv) those who reallocate from dirty energy sectors. We then track how their welfare changes after the implementation of the policy. As stated earlier, welfare is measured by the consumption equivalent variation from adding the carbon tax relative to the baseline.

Panel A: 32.9% carbon tax								
	Wasteful spending		Green subsidy		Useful spending		Education subsidy	
	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)
Non-dirty sectors, stayers	-3.5	98.7	-0.3	98.8	-1.0	98.9	-1.3	98.7
Non-dirty sectors, switchers	-3.3	0.4	3.2	0.3	-0.7	0.3	-1.1	0.4
Dirty sectors, stayers	-16.8	0.5	-9.7	0.6	-14.5	0.5	-14.9	0.5
Dirty sectors, switchers	-9.7	0.3	-5.2	0.2	-7.3	0.3	-7.6	0.3
Aggregate	-3.3	100.0	-1.0	100.0	-0.7	100.0	-1.1	100.0
Panel B: 80.4% carbon tax								
	Wasteful spending		Green subsidy		Useful spending		Education subsidy	
	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)	CE (%)	LFP (%)
Non-dirty sectors, stayers	-11.1	98.4	-5.2	98.4	-6.5	98.7	-7.6	98.4
Non-dirty sectors, switchers	-10.7	0.8	1.2	0.8	-6.0	0.5	-7.1	0.8
Dirty sectors, stayers	-41.8	0.2	-30.3	0.3	-38.6	0.2	-39.4	0.2
Dirty sectors, switchers	-23.4	0.6	-17.0	0.6	-19.3	0.6	-20.3	0.6
Aggregate	-10.7	100.0	-6.6	100.0	-6.0	100.0	-7.1	100.0

TABLE 4. Welfare analysis. | CE denotes consumption equivalent variation; LFP stands for labour force participation.

Table 4 shows that workers who remain in the dirty sectors (oil, coal and natural gas) experience the largest decline in welfare. Take Panel A as an example. In the wasteful spending scenario, the welfare of stayers in the dirty sectors declines by 16.8%. This loss is almost twice as much as the one experienced by those who managed to switch from the dirty sectors (9.7%) and almost five times the loss witnessed by non-dirty workers (stayers and switchers). However, these workers who are most affected account for less than 0.5% of the Portuguese labour force. This decline in welfare is due to the reduction in labour demand and wages in the taxed sectors. Due to general equilibrium effects, labour reallocation also takes place in the non-dirty sectors.

In the face of a higher carbon tax (Panel B), workers who stay in the dirty sectors are hit harder and experience welfare losses ranging from 30 to 42%, compared to 17 to 23% welfare loss by workers who managed to reallocate out of the dirty sectors and -11 to 1.2% by workers not in the dirty energy sectors. As such, workers with a comparative advantage in dirty energy production are still the hardest hit, but now constitute only 0.2% of the Portuguese labour force.

5. Concluding remarks

As the economic effects of climate change unfold, there is a growing pressure for governments to adopt more aggressive environmental policies. In fact, the costs of delayed action can be substantial. In this paper, we unveil the aggregate and distributional effects of the carbon tax Portugal needs to meet its Paris Agreement pledges.

We estimate that a carbon tax of 32.9% is needed for Portugal to achieve its original Paris Agreement pledge of 35% emissions reduction. This carbon tax costs the Portuguese economy at most a 1.7% drop in GDP, which is the worst-case scenario when the government does not rebate tax revenues back to the economy. Despite the small impact on GDP and welfare, carbon taxes have non-trivial distributional effects at the sectoral and individual levels. Workers with a comparative advantage in dirty energy sectors who do not reallocate suffer a welfare loss five times higher than workers in non-dirty sectors, but constitute less than 0.5% of the labour force.

As NDCs have been adjusted over time, we also target the carbon tax needed for Portugal to achieve a 70% decline in emissions. The results point to a 80.4% carbon tax, with the effects being qualitatively similar to those leading to a 35% emissions reduction, but amplified. Under this policy experiment, workers with a comparative advantage in dirty energy production experience the largest welfare loss, but now constitute only 0.2% of the Portuguese labour force.

While the experiments in this study have focused on Portugal, the framework outlined here can be easily replicated to other countries to inform policy responses. This is of particular interest as climate change mitigation policies have heterogeneous responses across individuals, sectors, as well as geographies.

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Appendix A: Data and calibration

This section outlines the data sources used in the model calibration to assess the aggregate and distributional effects of a carbon tax policy. Table A.1 lists the two main data sources used: the World Input-Output Database (WIOD) and the Labour Force Survey (LFS). We also resort to the World Development Indicators (WDI).

Data	Year	Source
Input-Output table	2014	WIOD
Environmental Accounts	2009	WIOD
CO_2 emissions	2009	WIOD
Sectoral labour force participation	2014	WIOD
Sectoral labour compensation	2014	WIOD
Income earnings	2019	LFS
Education attainment by sector	2019	LFS
Public expenditure on education (% GDP)	2018	WDI
Total labour force participation rate (%)	2018	LFS

TABLE A.1. Data sources.

Although we have prior information about some of the model parameters (e.g. importance of each input in the production of intermediate goods), others will be estimated internally to match key moments of the data. Table A.2 lists all model parameters.

Parameter	Externally calibrated parameters	Data source
J	Number of sectors	WIOD
ν_{jk}	Input-output shares	WIOD
β_j^L	Labour shares	WIOD
$g_{\text{oil}} = 84.6\%$	Carbon intensity of oil	Golosov *et al.* (2014)
$g_{\text{coal}} = 71.6\%$	Carbon intensity of coal	Golosov *et al.* (2014)
$g_{\text{natural gas}} = 73.4\%$	Carbon intensity of natural gas	Garg *et al.* (2006)
$g_{\text{green}} = 0\%$	Carbon intensity of green	Golosov *et al.* (2014)
γ	Consumption weight in the utility function	Mincerian estimate using LFS data
η	Expenditure on education (% GDP)	WDI
	Internally calibrated parameters	**Moment(s) targeted**
σ_j	Expenditure shares in final good	Sectoral value added from WIOD data
φ_j	Returns of schooling in sector j	Average relative wages using WIOD data
λ	Fréchet dispersion parameter	Coefficient of variation in earnings from LFS data

TABLE A.2. List of parameters.

External Calibration. To set values for J, β_j, and ν_{jk}, we use data from the WIOD. This is a comprehensive database containing national input-output tables, data on sectoral labour force participation rates, labour compensation and environmental accounts. We use data on inter-sectoral sales to compute ν_{jk} and set $\beta_j = 1 - \sum_{k=1}^{J} \nu_{jk}$. First, we collapse the 35 sectors in the WIOD tables to the top-level International Standard Industrial Classification (ISIC) Rev. 4 classification as outlined in the first column of Table A.3. Second, we aggregate these 21 sectors into the 15 sectors presented in the LFS database. Since the focus is on taxing dirty energy producing sectors in the economy, we create an aggregate energy sector by merging "Mining and quarrying" and "Electricity"

sectors (second column of Table A.3). Third, we split the aggregate energy sector (Total energy: B, D) into oil, coal, natural gas and green energy production based on the energy input mix of each of the intermediate sectors, according to the WIOD environmental accounts on energy use by sector and energy type. This yields 18 intermediate goods sectors overall. To save on space, the 18 sectors are not included in Table A.3.

	Sectors ($J = 21$) **ISIC Rev. 4: Top-level aggregation**		**Sectors ($J = 15$)** **LFS aggregation**
A	Agriculture, hunting, forestry and fishing	A	Agriculture, hunting, forestry and fishing
B	Mining and quarrying	C	Manufacturing
C	Manufacturing	E	Water supply
D	Electricity, gas, steam and air conditioning supply	F	Construction
E	Water supply; sewerage, waste management and remediation activities	G	Wholesale and retail trade
F	Construction	H, J	Transport, storage and communications
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	I	Accommodation and food service activities
H	Transportation and storage	K	Financial and insurance activities
I	Accommodation and food services activities	L, M, N	Real estate, renting and business activities
J	Information and communication	O	Public administration and defence
K	Financial and insurance activities	P	Education
L	Real estate activities	Q	Health and social work
M	Professional, scientific and technical activities	R, S, U	Arts and other service activities
N	Administrative and support service activities	T	Private household services
O	Public administration and defence; compulsory social security	B, D	Total energy
P	Education		
Q	Human health and social work activities		
R	Arts, entertainment and recreation		
S	Other service activities		
T	Activities of households as employers; undifferentiated goods - and services-producing activities of households for own use		
U	Activities of extraterritorial organisations and bodies		

TABLE A.3. Intermediate goods sectors.

We then calculate the input-output matrix ν which represents intersectoral elasticities, such that each entry ν_{jk}:

$$\nu_{jk} = \frac{\text{Input of sector } k \text{ into sector } j}{\text{Sales of sector } j}$$

β_j^L is calculated by adhering to the constant returns to scale characteristic of the production function, such that $\beta_j^L + \sum_{k=1}^{J} \nu_{jk} = 1$.

With the environmental accounts data on CO_2 emissions by sector and energy type we calculate the effect of taxes on emissions. Note that the model abstracts from the feedback effects of emissions on the economy. In order to discipline the magnitude of the carbon tax we compute the change in CO_2 emissions.

The sectoral carbon content, g_j, is based on Golosov *et al.* (2014): $g_{oil} = 0.846$ and $g_{coal} = 0.716$. We replicate their methodology and calculate $g_{gas} = 0.734$ using estimates from Garg *et al.* (2006).

We follow Hsieh *et al.* (2019) to calibrate η and γ. From the WDI, we compute η, which is the public expenditure on education (as a percentage of GDP) normalised by labour force participation. To calibrate γ, we take average earnings in sector j, $\bar{w}_j = w_j \mathbb{E}[h_j z_j] = (1-s)^{\frac{-1}{\gamma}} \eta^{\frac{\eta}{1-\eta}} \Gamma(1 - \frac{1}{\lambda}\frac{1}{1-\eta})$. Drawing on the micro-data from the LFS for Portugal, we calculate the average years of schooling divided by a pre-work time endowment of 25 years, $\bar{s}$, and estimate the Mincerian return to schooling across sectors, ξ, from a regression of log average wages on average schooling across sectors. With $\bar{s}$ and ξ, we calculate $\gamma = \frac{1}{\xi(1-\bar{s})}$. The values for η and γ are 0.080 and 0.645, respectively.

Internal Calibration. The remaining parameters σ_j, φ_j and λ are disciplined by solving the model and targeting certain data moments. In particular, we calibrate the expenditure shares σ_j such that the sectoral value added shares in the model match those in the data (Table A.4).

Sector	VA_j (%)	σ_j
1. Agriculture, hunting, forestry and fishing	2.3	0.020
2. Manufacturing	13.2	0.231
3. Water supply	1.2	0.007
4. Construction	4.5	0.066
5. Wholesale and retail trade	14.7	0.097
6. Transport, storage and communications	8.2	0.056
7. Accommodation and food service activities	5.1	0.070
8. Financial and insurance activities	5.2	0.036
9. Real estate, renting and business activities	19.6	0.119
10. Public administration and defence	7.9	0.091
11. Education	6.2	0.063
12. Health and social work	6.0	0.087
13. Arts and other service activities	2.1	0.029
14. Private household services	0.8	0.007
15. Oil energy production	1.4	0.010
16. Coal energy production	0.1	0.000
17. Natural gas energy production	0.2	0.001
18. Green energy production	1.2	0.008

TABLE A.4. Intermediate goods sectors: Value-added and final expenditure shares.

We follow the methodology in Hsieh *et al.* (2019) to estimate φ_j and λ. To estimate φ_j, we use data from WIOD on the number of persons engaged and labour compensation to calculate the average wage in each sector. This yields the relative sectoral wages, which determine the relative values for φ_j. To find the absolute values of φ_j, we take the ratio of the average wages relative to Agriculture. We calculate average schooling in Agriculture, s_{Agri}, and then use equation (2) to solve for φ_{Agri}. With this, we pin down the remaining φ_j by targeting the ratio of each sectoral wage relative to Agriculture.[11] Data on the relative ratios of sectoral wages and the values for φ are presented in Table A.5.

11. Given the lack of information on the individual energy sectors, we target the ratio of average wage in the aggregate energy sector relative to Agriculture.

Sector	$\frac{w_j}{w_{Agri}}$	φ_j
1. Agriculture, hunting, forestry and fishing	1.0	0.580
2. Manufacturing	1.8	0.740
3. Water supply	2.0	1.968
4. Construction	1.8	1.073
5. Wholesale and retail trade	1.8	0.694
6. Transport, storage and communications	3.1	1.770
7. Accommodation and food service activities	1.7	0.934
8. Financial and insurance activities	5.1	3.583
9. Real estate, renting and business activities	2.0	0.727
10. Public administration and defence	3.4	2.044
11. Education	2.9	1.815
12. Health and social work	2.4	1.400
13. Arts and other service activities	2.0	1.599
14. Private household services	1.0	0.852
15. Energy average (weighted by LFP)	3.7	3.698

TABLE A.5. Relative sectoral wages and sector-specific elasticity of human capital accumulation to schooling years.

Finally, to estimate λ, we use micro-data on individual wages to fit the distribution of residuals from a cross-sectional regression of log income earned on age-industry dummies. We then match the coefficient of variation of sectoral residual wages. The values of the estimated Fréchet parameter and model's estimate of the coefficient of variation of wages are 3.915 and 0.247, respectively.

Appendix B: Additional statistics

Sector	Sales (%)	VA_j (%)	Int. Cons. (%)	LFP (%)
1. Agriculture, hunting, forestry and fishing	2.6	2.3	2.7	11.3
2. Manufacturing	26.1	13.2	38.2	15.3
3. Water supply	1.3	1.2	1.4	0.9
4. Construction	5.9	4.5	7.3	6.3
5. Wholesale and retail trade	11.5	14.7	8.5	14.7
6. Transport, storage and communications	9.5	8.2	10.4	5.2
7. Accommodation and food service activities	4.4	5.1	3.5	6.0
8. Financial and insurance activities	4.7	5.2	4.3	1.9
9. Real estate, renting and business activities	12.9	19.6	6.5	10.8
10. Public administration and defence	5.4	7.9	3.0	6.4
11. Education	3.5	6.2	1.0	6.8
12. Health and social work	5.0	6.0	4.0	7.7
13. Arts and other service activities	1.9	2.1	1.7	3.3
14. Private household services	0.4	0.8	0.0	2.9
15. Oil energy production	2.1	1.4	2.8	0.2
16. Coal energy production	0.5	0.1	0.9	0.0
17. Natural gas energy production	0.7	0.2	1.2	0.1
18. Green energy production	1.7	1.2	2.3	0.2

TABLE B.1. Sectoral breakdown of output, value-added (VA), intermediate consumption and labour force participation (LFP) in the zero-tax benchmark.

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Non-technical summary

July 2022

Pandemic shocks

Paulo Júlio and José R. Maria

The 2020-21 period was marked by the pandemic crisis. Lockdowns and social distancing inflicted unprecedented damages to economic agents.

In Portugal, the lockdown period in the first half of 2020 triggered a gigantic decline in Gross Domestic Product (GDP) totaling nearly 20 percent. Impacts were partially reverted in the second half, but the new lockdown phase, which came into force by the end of 2020 and beginning of 2021, triggered a new downfall in output. The ensuing quarters were characterized by a gradual recovery, but GDP was still 1.5 percent below the pre-pandemic level by the end of 2021.

This article devises a strategy to identify and quantify the economic driving forces and properties that lay behind the Portuguese pandemic crisis, under the lens of an estimated general equilibrium model. We enrich the model with three pandemic-specific fluctuation sources. The first one is a supply-side effect. Under this shock, firms across the globe became unable to produce the same amount of goods and services as compared with the pre-pandemic period, as some productive capabilities were halted. The second is a domestic demand-side effect. Households became unable to consume some goods and services. The third is an external demand-side effect. Foreign agents became unable to buy some domestic goods and services, triggering a decline in export penetration.

Our results suggest that 2020 is marked by worldwide supply-side perturbations (Table 1) *i.e.* an inability of firms across the globe to produce the same amounts of goods and services as before. Due to its global nature, this shock explains the coordinated downfall of domestic and euro area GDP, impacting all demand components alike. Demand-side impacts, both domestic and external, also had important contributions to GDP developments. Hence, the inability of domestic and foreign agents to consume domestically produced goods and services also played an important role.

Output volatility throughout 2021 was due more heavily to demand-side disturbances, against a background characterized by a gradual supply-side recovery. We observe a large decline in private consumption and a subsequent recovery *vis-à-vis* other demand components and euro area GDP during the first half of the year. This suggests that the concomitant pandemic wave was associated with an inability of domestic households to consume some goods and services. The second half of 2021 was marked by a large recovery in exports, to values above the pre-pandemic level. The impacts

	2020Q1	Q2	Q3	Q4	2021Q1	Q2	Q3	Q4
GDP (%)	-4.8	-16.9	14.7	-0.4	-3.4	4.4	2.9	2.1
Pandemic shocks (pp)								
LD-Supply	-2.0	**-8.7**	**8.4**	-1.3	-0.1	1.4	2.1	-0.4
LD-Demand	0.0	-4.8	2.4	0.5	**-2.0**	**2.5**	-0.3	0.4
LD-External	-0.5	-4.9	3.7	0.2	-0.4	-0.8	2.0	1.6
Non-pandemic shocks (pp)								
O-Domestic	-1.5	3.1	-0.6	-0.7	-0.7	1.1	-0.9	0.0
O-External	-0.6	-2.2	1.1	0.8	-0.2	0.0	-0.4	0.2
ME+IC	-0.1	0.6	-0.3	0.0	0.1	0.1	0.3	0.3

TABLE 1. Historical decomposition of GDP growth

Sources: Statistics Portugal and authors' calculations.

Notes: GDP growth, measured in percentage (%), is approximated by quarter-on-quarter log changes. Pandemic and non-pandemic shocks refer to contributions to GDP growth, measured in percentage points (pp). ME denotes measurement errors and IC Initial Conditions. Pandemic shocks LD-Supply, LD-Demand and LD-External pinpoint exogenous changes that only took place over 2021-2021, namelly on the unit root labor-augmenting technology shared by Portugal and the euro area (moving average of second order with *iid* shocks), household preferences (*iid* shock) and external demand (*iid* shock). The aggregate O-Domestic includes the contribution of 20 shocks (nominal, financial, etc) and the agregate O-External of 5 shocks (euro area interest rate, inflation, etc), none of them directly related with the lockdown peridod. The pandemic and non-pandemic contributions approximately add up to the rate of change of GDP.

driven by the inability of foreign agents to consume domestically produced goods seem to have come to an end. It should be noted that the model does not independently address developments in tourism exports.

In contrast with the results obtained for economic activity, inflation over the 2020-21 period was not driven by the pandemic-specific fluctuation sources, which pushed price changes downwards. Inflation was mostly determined by non-pandemic disturbances, particularly by cost-push shocks.

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Pandemic shocks

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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

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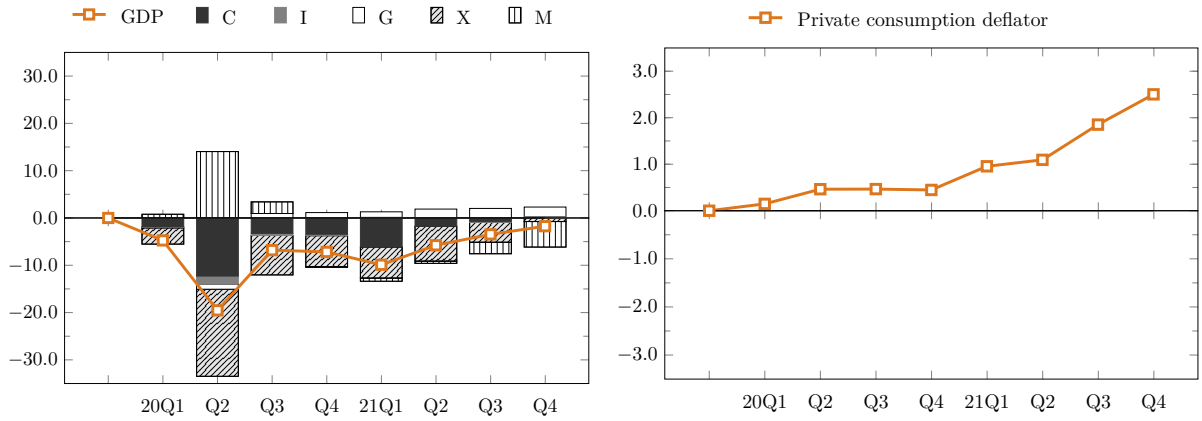


(A) GDP and demand components.

(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.

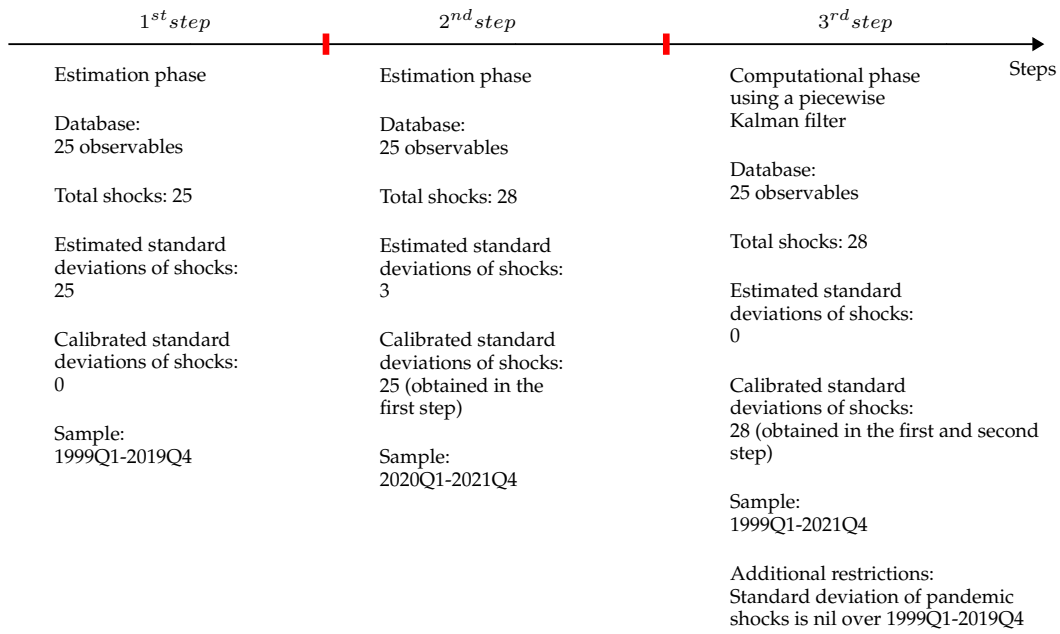


FIGURE 2: Estimation and computational phases.

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 $\log\left(T_t/T_{t-1}\right) = g_t^{\mathrm{NP}} + g_t^{\mathrm{P}}$ 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 $\tilde{\varepsilon}_t^{g,\mathrm{P}}$. 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

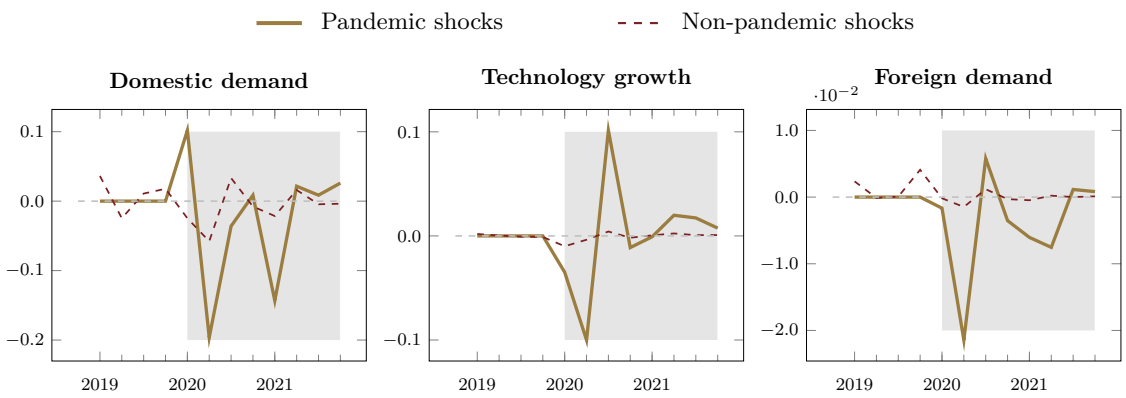


FIGURE 3: Selected smoothed shock processes during the pandemic crisis.

Sources: The authors.

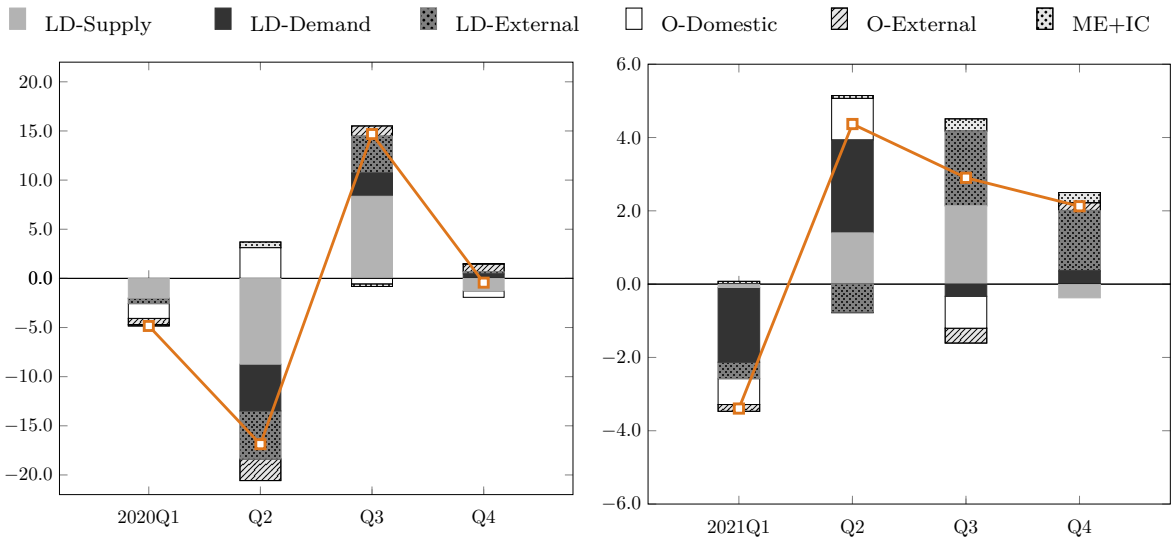
Notes: Non-pandemic shocks were identified by the piecewise linear Kalman filter using parameters estimated for the pre-pandemic period. They can be interpreted as the part of the shock that has some resemblance with the past.

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.

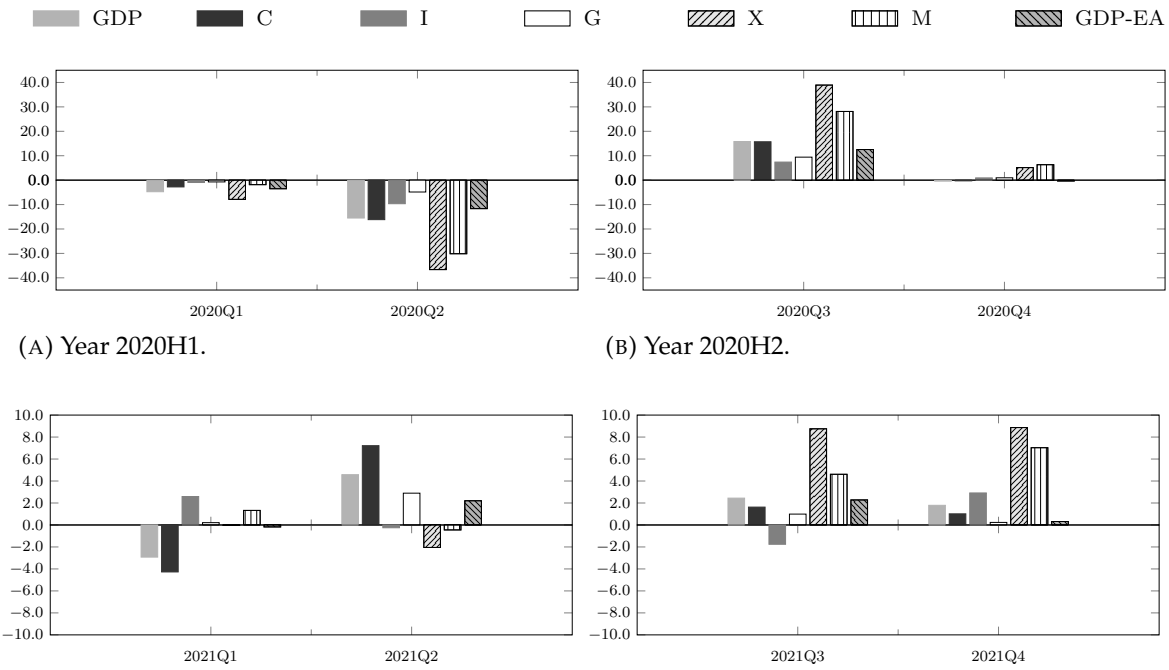
Sources: The authors.

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.

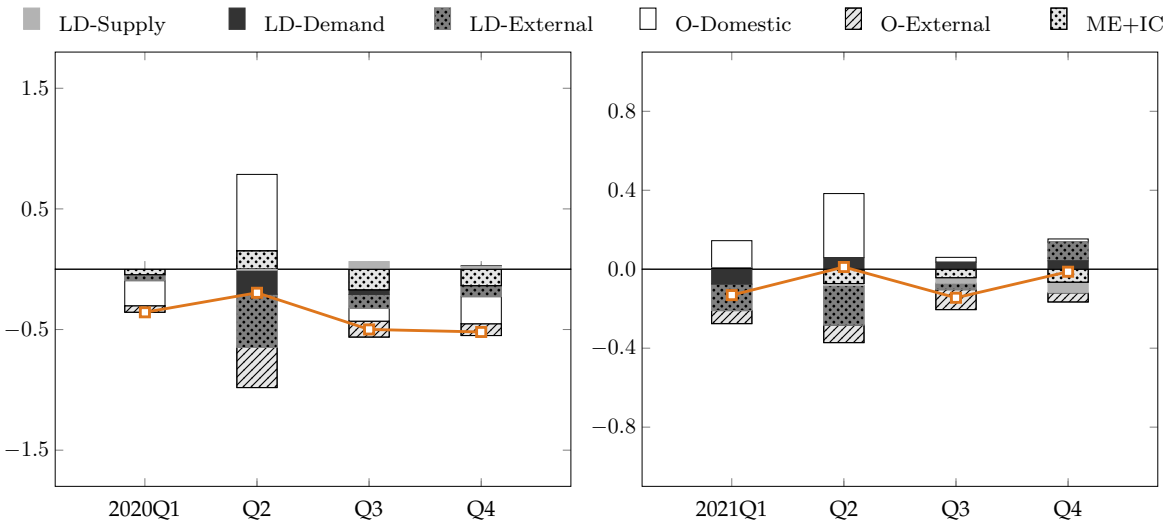
FIGURE 5: GDP, selected demand components, and Euro Area GDP growth.

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.

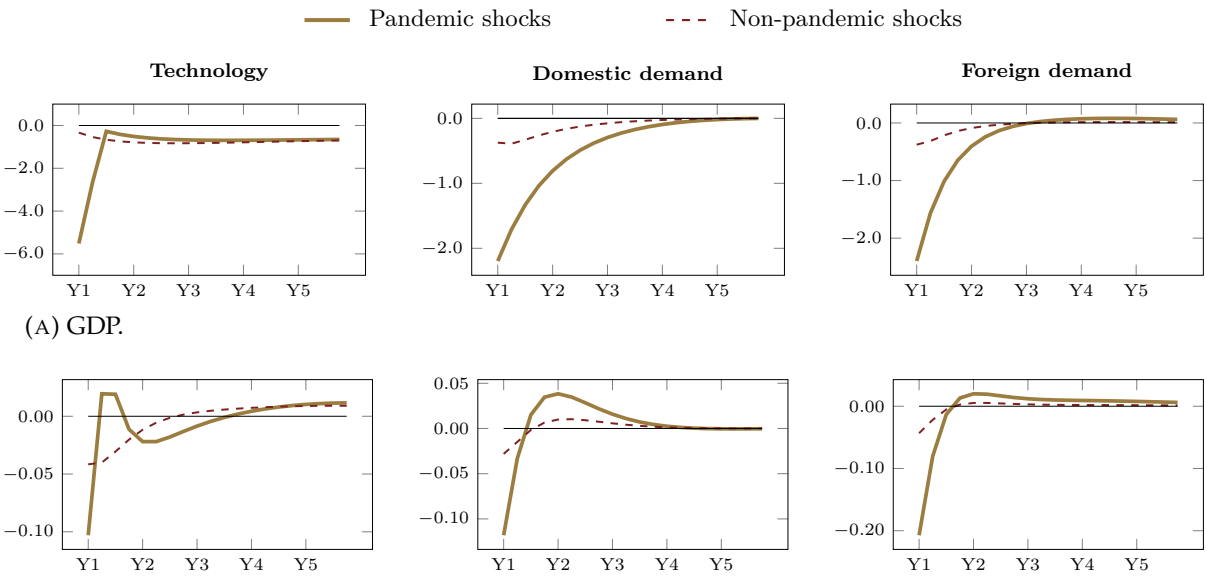
FIGURE 6: Historical decomposition of inflation .

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.

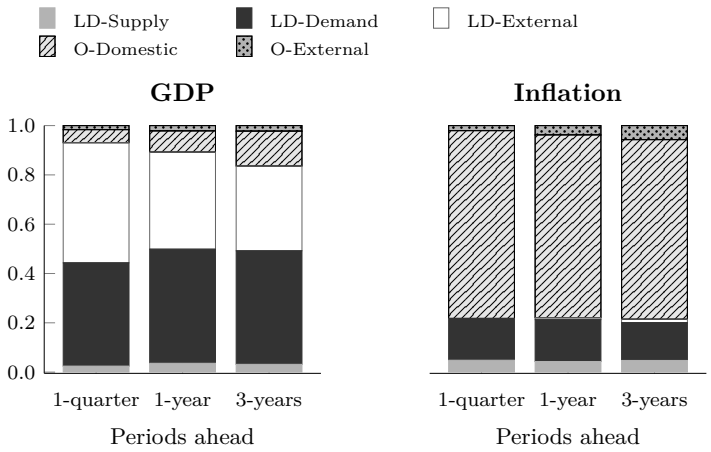


FIGURE 8: Forecast error variance decomposition for GDP and inflation.

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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Non-technical summary

July 2022

Economic Synopsis
On the solvency and credibility of a central bank

José Miguel Cardoso da Costa

Can a central bank become insolvent? Can uncertainty around a central bank's profitability affect monetary policy credibility? Under what conditions may a central bank's financial situation reach a level that jeopardises the ability to fulfil its mandate? These questions are not new in the economic literature and the history is full of examples of emerging and underdeveloped economies whose currencies lost economic agents' confidence. These examples are typically characterised by a strong depreciation of the currency value, or even hyperinflation. In these cases, even if a central bank is able to fulfil its nominal obligations through the issuance of new currency, in practice it becomes unable to achieve its objectives, falling in a situation that the literature classifies as 'policy insolvency'.

Even though these episodes are unknown in the recent history of advanced economies, the strong expansion of central banks' balance sheets observed in the past decade left them vulnerable to income losses. The potential negative impact of such losses on public finances, together with the general increase of public debt also recently observed, has reignited the debate on the interactions between monetary and fiscal policies. While the likelihood of central bank insolvency is very small in advanced economies, it is still important to understand the conditions that ensure a central bank's credibility, in order to guarantee an adequate institutional framework for both monetary and fiscal policy. This is relevant as the balance sheet exposures will likely persist for some years to come.

The economic literature has identified two fundamental conditions for the credibility of monetary policy in fulfilling a price stability mandate. The first condition recommends a separation of roles between monetary and fiscal policies, where the fiscal authority is responsible for ensuring the sustainability of public finances, while the central bank acts independently in the pursuit of well-defined policy objectives. This condition is well established in the economic literature and there is a large consensus on the advantage of maintaining an independent institutional framework, as reflected in the statutes of most central banks. More recently, the literature has also suggested a second condition that stresses the need to ensure some form of fiscal support of the central bank in case of deterioration of its financial situation. In the absence of an explicit

mechanism of fiscal support, the central bank may face financial vulnerabilities that could potentially put at risk the ability to fulfil its objectives and undermine monetary policy credibility.

A central bank is always policy solvent when its assets are mainly short-term and interest-bearing reserves are inexistent or residual. Things may be potentially different when interest-bearing reserves are leveraged to finance a large set of assets with a substantially different risk-return profile, but the available estimates suggest that the likelihood of policy insolvency is still very small. For example, in the case of a high exposure to long-duration assets and short-term liabilities a central bank may incur losses if interest rates increase significantly. However, these scenarios are typically followed by an increase of future profits (from the higher seignorage revenues associated with the increased interest rates) and hence any potential losses would be temporary and would not undermine monetary policy credibility.

In the case of a monetary union, the existence of several national central banks sharing the same currency, but whose capital is owned by different fiscal authorities, increases the complexity of the problem from an institutional standpoint. In the current euro area arrangement, without a complete monetary union, the conditions for the solvency of the common currency are safeguarded by fiscal policies guaranteeing public debt sustainability at the national level, as well as by the existence of mechanisms that ensure each national central bank's credibility.

With the increase of central banks' exposures to interest rate risk and sovereign credit risk observed in the past decade, the realisation of income losses in some periods is possible, but the evidence suggests that the likelihood of policy insolvency is very small. Nonetheless, it remains important to monitor underlying risk factors and to understand whether they could compromise credibility in the future. It is important to have mechanism in play to ensure that monetary policy decisions continue to be guided by the central bank's mandate and not by concerns with its financial situation. These mechanisms may imply maintaining sufficient financial buffers, through adequate dividend policies and provisioning rules, or by setting up explicit recapitalisation arrangements. A better understanding of these issues contributes to guarantee that episodes of policy insolvency remain only a theoretical possibility.

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Economic Synopsis
On the solvency and credibility of a central bank

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Abstract
This synopsis discusses the financial boundaries of central banks' actions. Under extreme conditions, a weak financial situation could interfere with monetary policy objectives, but the literature suggests that the likelihood of such an event occurring in an advanced economy is very low. Currently high balance sheet exposures leave central banks vulnerable to income losses, but this does not need to affect monetary policy credibility. This discussion is at the core of monetary and fiscal policies interactions. Understanding these mechanisms is important to ensure that episodes of policy insolvency remain only in the realm of a theoretical possibility. (JEL: E52, E58, E63, H63)

Keywords: Central bank balance sheet, monetary-fiscal interactions, central bank independence, monetary policy credibility.

"As recent events should have taught us, historically abnormal events do occur in financial markets, and understanding in advance how they can arise and how to avert or mitigate them is worthwhile."
Del Negro and Sims (2015)

1. Introduction

Can a central bank go bankrupt? For a central bank whose liabilities are denominated in nominal terms and in the domestic currency the simple answer is no. Any central bank in these circumstances can simply issue additional

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currency to cover its nominal financial obligations.[1] This answer may erroneously lead to the conclusion that central banks are not confronted with financial restrictions in the pursuit of their activities. This is certainly not the case. This synopsis discusses precisely the financial boundary of central banks' actions and the conditions under which a central bank may become unable to fulfil its mandate due to a lack of financial resources, i.e. it becomes 'policy insolvent'.

A central bank may be policy insolvent if it departs from its objectives to satisfy its financial obligations, e.g. by allowing inflation to increase above its target. In extreme cases, this may result in a loss of confidence in the currency, leading to hyperinflation and strong depreciation. There are several historical examples of such episodes, in European countries in the 1920s (e.g. Germany) or Latin American countries more recently (e.g. Argentina and Brazil in the 1980s or Venezuela since 2015).[2] The literature has related these episodes with unsound interactions between monetary and fiscal policies.[3]

While there is no evidence that such a chain of events may occur in the near future in any advanced economy, the issue regained relevance in the past decade, as central banks' balance sheets increased significantly in size and risk exposure. Figure 1 presents the evolution of central banks' total assets in the four major advanced economies and figure 2 a decomposition of the balance sheet in the cases of the Eurosystem and the Federal Reserve. Until the global financial crisis in 2008, central banks' balance sheets were relatively small and the asset side mainly comprised collateralised short-term credit operations with financial institutions (in the case of the Eurosystem) and US Treasury bills and bonds mostly with short duration (in the case of the Federal Reserve). Since then, balance sheets increased significantly and their composition tilted towards longer-term operations, leaving central banks more exposed to interest rate risk and sovereign credit risk. On the liability side, before the financial crisis operations were mainly financed through currency. Since 2008, interest-bearing reserves played an increasing role and currently represent a substantially higher portion of central banks' liabilities.

As it will probably take some time before central banks' balance sheets return to the pre-2008 configuration, this evolution has raised concerns over central banks' profitability in the coming years, namely in the event of higher policy rates. Can the materialisation of these risks lead to policy insolvency? Can the potential impact of monetary policy measures on a central bank's net income influence its decisions? It

1. The answer would be different for a central bank with real liabilities (e.g. indexed to inflation or denominated in a foreign currency). In such cases, formal insolvency is possible. Throughout the analysis we will focus on the more interesting case of central banks that mainly issue nominal liabilities denominated in the domestic currency, where 'formal insolvency' is not an issue, but 'policy insolvency' could still occur.

2. See Quinn and Roberds (2016) for an earlier example of a reserve currency (the Dutch florin in the 18th century) that lost its status in the aftermath of accommodative policies that resulted in substantial financial losses for the central bank.

3. See Kehoe and Nicolini (2021) for a thorough discussion of monetary and fiscal policy interactions in Latin America since 1960 and its implications for inflation and economic well-being.

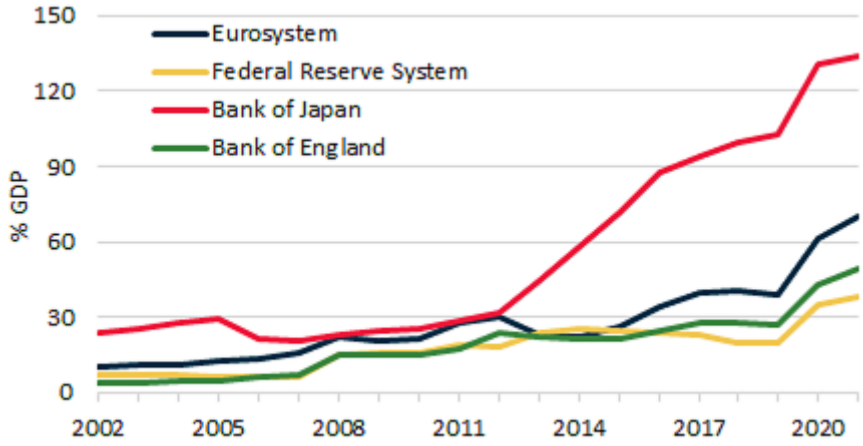
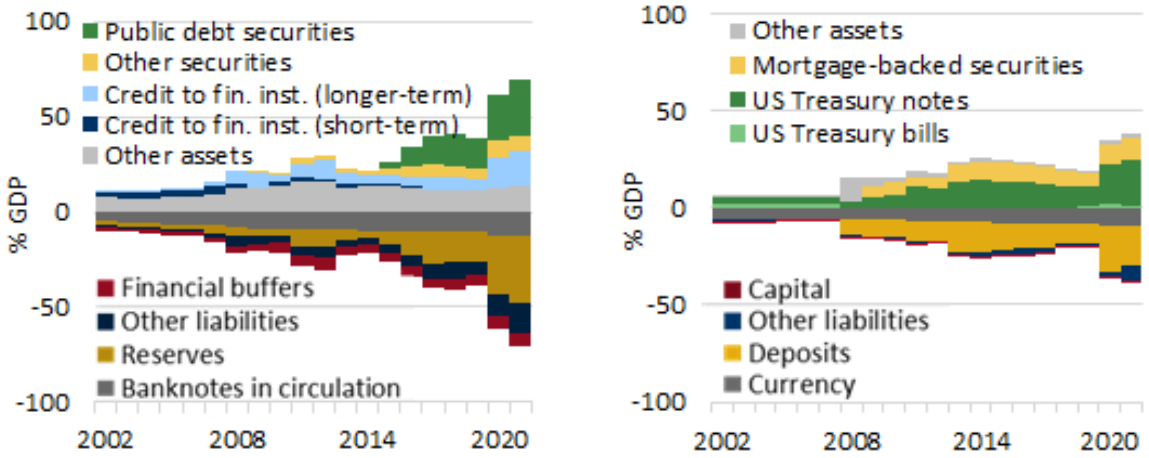


FIGURE 1: Central banks' total assets in selected advanced economies

Notes: Positions at the end of each calendar year. | Latest observations: 2021.
Sources: European Central Bank, Federal Reserve System, Bank of Japan and Bank of England.



(A) Eurosystem (B) Federal Reserve System

FIGURE 2: Composition of the balance sheet in the Eurosystem and the Federal Reserve System

Notes: Credit to financial institutions (longer-term) includes all operations with maturity greater than or equal to three months. | Latest observations: 2021.
Sources: European Central Bank and Federal Reserve System.

should not. Hence, understanding the conditions that could lead to policy insolvency is crucial to ensure the credibility of monetary policy.

We start by discussing how the literature has dissected the fundamental interactions of monetary and fiscal policies. In section 2, the two necessary conditions to ensure that monetary policy can sustain a price stability objective are clearly identified: (i) fiscal policy needs to guarantee public debt sustainability for any given level of prices ('monetary dominance'); (ii) the fiscal authority ensures the recapitalisation of the central bank in case of need ('fiscal support').

When the second condition is not met, the central bank needs to satisfy an autonomous budget constraint that can serve as a reference for the definition of the central bank's solvency. This is discussed in section 3 for the case of a single central bank and a single fiscal authority, where we lay out some general principles suggested by the literature. The consensus is that the likelihood of central bank insolvency is negligible when the central bank's assets are mainly short-term, carrying little interest rate or credit risk, and interest-bearing reserves are inexistent or residual. Things could change when a large amount of interest-bearing reserves is issued to finance a large set of assets with a substantially different risk-return profile. In any case, the available estimates suggest that this likelihood is very small.

In a monetary union, the issue poses additional challenges, given the complex web of interactions between national central banks (NCB) and national fiscal authorities. This is discussed in section 4. While the credibility of the single monetary policy still hinges on a similar solvency constraint at the aggregate level, understanding how national level concerns may or may not spill over to the aggregate level is important. Section 5 briefly discusses proposed alternative mechanisms to support the financial strength of a central bank in case of absence of an explicit 'fiscal support' and explores in some detail the institutional arrangements observed in major advanced economies. In the case of the Eurosystem this is mainly achieved by increasing capital or financial provisions.[4]

Section 6 provides some concluding remarks. The likelihood of central bank insolvency in an advanced economy is very small from an intertemporal perspective. However, any eventual pressure to maintain positive dividends could raise doubts on whether monetary policy decisions would be guided by concerns over the central bank's financial situation. The conduct of monetary policy ought to be guided by the central bank's mandate. Hence, the institutional framework should continue enforcing mechanisms to ensure the central bank's independence.

2. Fundamental interactions between monetary and fiscal policies

The literature has long understood that monetary and fiscal policies interact in several dimensions. In a seminal contribution, Sargent and Wallace (1981) show how this relationship is inextricably linked by the consolidated budget constraint of the public sector (i.e. including the central bank and the rest of the government). In their setting, if the fiscal authority significantly increases the budget deficit and public debt without any intention to offset that by raising taxes or reducing spending in the future ('dominant fiscal policy'), then the monetary authority has no option but to raise seignorage revenues (and inflation) if it cares about the solvency of the public sector. This result suggests the need for fiscal policy to ensure the sustainability of public debt for any given price level in order for monetary policy to be able to fulfil a price stability

4. The ECB's risk management principles (European Central Bank 2015) stress the importance of using the risk capacity of the Eurosystem in the most efficient way (i.e. aiming to achieve the policy objectives with the lowest possible risk) and explicitly acknowledge that "the ECB and the NCBs need to have enough net equity – in case of losses – in order to minimise reliance on capital injections".

objective. Henceforth we will denote this condition by 'monetary dominance' (or 'no fiscal dominance'), following the terminology used by Sargent and Wallace (1981).[5]

To understand this, consider the following simplified version of the flow budget constraint of the public sector:

$$B_{t-1} + M_{t-1} \leq \frac{1}{1+i_t} B_t + M_t + P_t \tau_t \tag{1}$$

where B_t are one-period government bonds held by the private sector outstanding at the end of period t, issued at discount with a nominal risk-free interest rate i_t, M_t is currency in circulation at the end of period t, P_t is the price level in period t and τ_t is the real primary surplus of the government in period t.

Following Benigno and Nisticò (2020), we define the flow of real seignorage revenues as $s_t = \frac{i_t}{1+i_t} \frac{M_t}{P_t}$, which represents the interest saved by issuing money balances that carry no nominal cost. Then, the flow budget constraint can be rewritten as:

$$B_{t-1} + M_{t-1} \leq \frac{1}{1+i_t} (B_t + M_t) + P_t \tau_t + P_t s_t \tag{1a}$$

The interpretation is simple: in every period, the public sector must finance its liabilities with the issuance of new liabilities or the resources obtained either from primary surpluses or from seignorage revenues.

Iterating forward and assuming a condition that prevents the public sector from sustaining an ever increasing value of liabilities (likewise a Ponzi scheme),[6] we can obtain the following intertemporal budget constraint for the consolidated public sector:

$$\frac{B_{t-1} + M_{t-1}}{P_t} \leq E_t \left[\sum_{T=t}^{\infty} v_{t,T} (\tau_T + s_T) \right] \tag{2}$$

where $E_t[.]$ represents an expectation based on the set of information available at the end of period t and $v_{t,T}$ is the real stochastic discount factor between periods t and T. In a setting with risk-free nominal assets, the real stochastic discount factor can be given by $v_{t,t} = 1$ and $v_{t,T} = \prod_{j=t+1}^{T} [\frac{1+\pi_j}{1+i_{j-1}}]$, for $T \geq t+1$, where π_t is price inflation between periods $t-1$ and t.[7] Under rational expectations, agents are assumed to know the model and policy rules that govern these stochastic variables, so the expectation in the right-hand side of condition (2) would be consistent with fundamental model specificities.

5. The literature has used different terminologies for similar conditions. Leeper (1991) defines 'passive' fiscal policy (as opposed to 'active') as one that raises taxes sharply when public debt increases. Woodford (2001) defines a 'Ricardian' fiscal policy as one that ensures that the intertemporal government budget constraint holds for any given price level and relates this with the 'fiscal requirements' embedded in the Stability and Growth Pact of the Economic and Monetary Union (EMU). More generally this may be ensured by a proper set of 'fiscal rules' (see Blanchard *et al.* 2020).

6. The so-called transversality condition can be rationalised from the optimising behaviour of private agents and asset market clearing conditions, which should prevent the public sector from engaging in Ponzi schemes: $\lim_{T \to \infty} E_t[v_{t,T} (\frac{B_T + M_T}{P_{T+1}})] \leq 0$.

7. In a standard general equilibrium micro-founded model this can be replaced by $v_{t,T} = \beta^{T-t} \frac{u'(c_T)}{u'(c_t)}$, where β is the subjective discount factor and $u'(c_t)$ is the marginal utility of consumption in period t.

Under an optimal behaviour of private agents, condition (2) will hold with equality, so the initial price level or the present discounted value of future primary surpluses and seignorage revenues may need to adjust to satisfy the constraint, if the value of nominal liabilities increases.

This intertemporal budget constraint is often presented in a slightly different version that uses a definition of seignorage revenues as the period increase in real money balances $\sigma_t = \frac{M_t - M_{t-1}}{P_t}$:

$$\frac{B_{t-1}}{P_t} \leq E_t\left[\sum_{T=t}^{\infty} v_{t,T}(\tau_T + \sigma_T)\right] = E_t\left[\sum_{T=t}^{\infty} v_{t,T}(\tau_T)\right] + E_t\left[\sum_{T=t}^{\infty} v_{t,T}(s_T)\right] - \frac{M_{t-1}}{P_t} \quad \text{(2a)}$$

The sum of the last two terms is generally considered the total value of seignorage: the present discounted value of future seignorage revenues minus the initial real money balances. This decomposition clarifies that the central bank may increase total seignorage using two alternative policies. First, it may increase the present discounted value of seignorage revenues, which is typically achieved by raising the long-run level of inflation (e.g. raising the inflation target) and thus the long-run level of the nominal interest rate.[8] Second, the central bank may engineer an increase of the initial price level P_t, thereby reducing the real value of initial money holdings (and also other nominal liabilities).

From an intertemporal perspective, uncertainty around the central bank's ability to sustain a given inflation objective may arise if the present value of future primary surpluses and future seignorage is perceived to be lower than the current level of public sector liabilities. If the public debt increases without a corresponding increase of the present value of future primary surpluses, either the central bank gives in and increases seignorage revenues (and average inflation), or the initial price level needs to adjust.[9] This shows that the ability of a central bank to meet a certain inflation objective crucially hinges on satisfying a condition that is inextricably linked with the conduct of fiscal policy.

In general, condition (2) is compatible with multiple equilibria, i.e. there may exist alternative policies governing the trajectories of the stochastic variables that satisfy this budget constraint. If agents question the willingness or ability of the government to generate sufficiently high primary surpluses in the future to pay the initial level of public debt, the public sector may be vulnerable to expectations-driven debt crises.

8. This positive relation between the nominal interest rate and inflation in the long run follows from the Fisher equation that defines the real interest rate as the difference between the nominal interest rate and inflation ($r_t = i_t - E_t[\pi_{t+1}]$) and from the assumption that the real interest rate in the long run is independent from inflation or the nominal interest rate. We are also assuming that we are on the increasing part of the Laffer curve and hence postulate a positive relationship between inflation and seignorage revenues.

9. The latter is akin to the fiscal theory of the price level (see Cochrane 2022, for a thorough discussion). If, at any moment, public debt holders raise concerns about the verification of this constraint, they may be willing to exchange government bonds and domestic currency for other financial assets (leading to the reduction of the market value of debt) or for goods and services (leading to higher inflation).

Corsetti and Dedola (2016) show that the central bank can eliminate these bad equilibria, by acting as a backstop for government funding, i.e. issuing monetary liabilities in exchange of public debt securities. If risks are not fundamental (i.e. if there are still possible trajectories of primary surpluses, inflation and interest rates compatible with the authorities' objectives that satisfy the budget constraint), such policy actions may reduce the interest rate on public debt and comply with the budget constraint, without generating higher inflation. Arguably, this may have justified at least part of the increase of central banks' balance sheet exposures observed over the past decade.

With the advent of 'independent' central banks tasked with specific objectives (e.g. price and macroeconomic stability) that may conflict with the desires of fiscal authorities, the financial situation of a central bank may affect its ability to fulfil its mandate and complicate monetary-fiscal interactions. Stella (1997, 2002) was one of the first to study the implications of a central bank's financial strength for achieving low and stable inflation. He analysed several episodes of central banks that incurred large capital losses, mainly in emerging and developing economies, and discussed the implications for the conduct of monetary policy. Stella and Lonnberg (2008) examined in further detail the laws governing the financial interaction between central banks and fiscal authorities in a large set of countries and showed that often the fiscal authority leaves the central bank dependent on seignorage to finance their operations, in practice leading to policy insolvency. These findings suggest that it is reasonable to model the two institutions separately.[10]

In a setting where the monetary and fiscal authorities are autonomous institutional bodies, each of them will need to satisfy an independent budget constraint. However, the two budget constraints will still be linked by financial transfers between the two entities. Usually these transfers take the form of dividend payments from the central bank to the Treasury, but in general they could also be negative, if the Treasury recapitalises the central bank. Defining these transfers in real terms as d_t, we have the following flow budget constraint for the fiscal authority

$$B_{t-1}^G \leq \frac{1}{1+i_t} B_t^G + P_t \tau_t + P_t d_t \tag{3}$$

and for the central bank[11]

$$M_{t-1} - B_{t-1}^{CB} \leq \frac{1}{1+i_t} \left(M_t - B_t^{CB} \right) + P_t s_t - P_t d_t \tag{4}$$

where B_t^G represents total government issued by the fiscal authority and B_t^{CB} represents government bonds held by the central bank.

10. The implications of this setting are discussed in detail in a recent growing literature. See Bassetto and Messer (2013), Del Negro and Sims (2015), Hall and Reis (2015), or Benigno and Nisticò (2020).

11. For simplicity the budget constraint abstracts from the central bank's administrative costs, as these are typically dwarfed in comparison with seignorage revenues.

Again iterating forward each equation and using similar transversality conditions,[12] one can obtain the following intertemporal budget constraints for the fiscal authority and the central bank, respectively:

$$\frac{B_{t-1}^G}{P_t} \leq E_t \left[\sum_{T=t}^{\infty} v_{t,T}(\tau_T + d_T) \right] \tag{5}$$

$$\frac{M_{t-1} - B_{t-1}^{CB}}{P_t} \leq E_t \left[\sum_{T=t}^{\infty} v_{t,T}(s_T - d_T) \right] \tag{6}$$

The first condition highlights again the need for monetary dominance: if the fiscal authority does not ensure a sustainable fiscal policy, the present value of future central bank's dividends would need to increase, putting pressure on the monetary authority to achieve this through higher seignorage and inflation. Additionally, the second condition suggests that, in certain circumstances, the ability to control inflation may also depend on 'fiscal support', i.e. the existence of a financial transfer from the fiscal authority to guarantee the central bank's solvency ($d_t < 0$). If the fiscal authority is committed to provide fiscal support whenever needed and there is no fiscal dominance, then the central bank is always independently solvent. In practice, this may be implemented with a rule that transfers all central bank's profits – including negative profits – to the fiscal authority. In this case, and using $B_t = B_t^G - B_t^{CB}$, only the consolidated budget constraint (2) will be relevant and monetary policy will be able to independently achieve a certain inflation objective.

Fiscal support mechanisms have not been made explicit in many advanced economies[13] and may be difficult to guarantee in practice. Moreover, if the central bank's profits are usually positive and tend to grow large, the fiscal authority may be tempted to commit to a certain level of public expenditure and be reluctant to accept a negative transfer. Without fiscal support, the possibility of central bank insolvency arises. In this case, the fiscal and monetary authorities will need to satisfy separate budget constraints. We turn next to this case in more detail.

3. Solvency in the case of a single central bank for a single government

In this section we discuss a setting in which an explicit commitment of the fiscal authority to recapitalise the central bank in case of need is not available. In the absence of such mechanism, the central bank will need to satisfy its budget constraint using its own resources.

12. While the transversality condition on private sector's holdings of government debt follows directly from consumers' optimising behaviour, in principle there is nothing ruling out the possibility that the central bank's holdings of the public debt follow an explosive path. In that case, $\lim_{T\to\infty} E_t[v_{t,T}(\frac{B_T^{CB}}{P_{T+1}})]$ could be positive or negative and would show up on the right-hand side of equation (5) and left-hand side of equation (6). However, in the absence of political economy conflicts between the two entities, this position would be immaterial.

13. See Archer and Moser-Boehm (2013) and Bunea *et al.* (2016). See also the discussion in section 5.

3.1. Intertemporal insolvency

From an intertemporal perspective, slightly rearranging (6), the central bank's budget constraint imposes that the present value of future dividends does not exceed the current central bank's net worth (the real value of assets minus liabilities) plus the present value of seignorage revenues:

$$E_t\left[\sum_{T=t}^{\infty} v_{t,T}(d_T)\right] \leq \frac{B_{t-1}^{CB} - M_{t-1}}{P_t} + E_t\left[\sum_{T=t}^{\infty} v_{t,T}(s_T)\right] \tag{6a}$$

In the simple setting discussed thus far, where the central bank's assets include only nominal risk-free bond holdings and liabilities comprise only non-interest bearing money balances, it is virtually impossible to violate this condition. Assuming no fiscal dominance, Bassetto and Messer (2013) and Benigno and Nisticò (2020) show that the central bank's intertemporal constraint is satisfied for any price level under general conditions, if the central bank pays no interest on reserves or, when interest-bearing reserves are introduced, if it holds only short-term assets with the same risk-return characteristics of reserves.

This setting was coined 'old-style central banking' by Hall and Reis (2015), in contrast to the 'new-style central banking' observed since the great financial crisis, where central banks hold large sums of financial assets that may carry considerable risks financed by a significant leverage on interest-bearing reserves. Under this setting, the possibility of central bank insolvency can no longer be completely ruled out.

To understand this, it is instructive to introduce these features explicitly in our setting. Consider that the central bank buys in period t a portfolio of risky financial assets, summarised by A_t, that pays a nominal return ι_{t+1} only observed in period $t+1$. This portfolio may include government bonds and other financial assets that may carry different sources of risk (e.g. interest rate, credit, and exchange rate risk). Consider also that the central bank now issues interest-bearing reserves H_t at discount that pay the same nominal risk-free return of one-period government bonds, i_t. Then, the central bank's budget constraint reads as follows:

$$M_{t-1} + H_{t-1} - (1+\iota_t)A_{t-1} \leq M_t + \frac{1}{1+i_t}H_t - A_t - P_t d_t \tag{4a}$$

Again, iterating forward, we obtain the following intertemporal constraint:

$$E_t\left[\sum_{T=t}^{\infty} v_{t,T}(d_T)\right] \leq \frac{(1+\iota_t)A_{t-1} - M_{t-1} - H_{t-1}}{P_t} + E_t\left[\sum_{T=t}^{\infty} v_{t,T}(s_T)\right] \tag{6b}$$

The right-hand side of this condition gives an upper bound for the central bank's dividend payments. This can be interpreted as the value of the franchise of the central bank. If fiscal support is not available, then a minimal requirement is that the present value of future dividends is not negative, which leads to the following intertemporal solvency condition for the central bank:

$$\frac{(1+\iota_t)A_{t-1} - M_{t-1} - H_{t-1}}{P_t} + E_t\left[\sum_{T=t}^{\infty} v_{t,T}(s_T)\right] \geq 0 \tag{7}$$

The first term of this condition corresponds to the difference between the market value of the central bank's assets and liabilities, a measure of the central bank's net worth in real terms: $N_t^{CB} = \frac{(1+\iota_t)A_{t-1} - M_{t-1} - H_{t-1}}{P_t}$. The second term represents the present value of real seignorage revenues, which is typically positive and large, if monetary policy is credible. Hence, a central bank can be solvent even if its current net worth is negative, as long as the present value of future seignorage is able to cover such position. For a better assessment of the central bank's solvency, we should then adopt a broader measure of net worth that includes this second term. The literature has often called this the central bank's 'comprehensive net worth': $W_t^{CB} = N_t^{CB} + E_t[\sum_{T=t}^{\infty} v_{t,T}(s_T)]$.

Under 'new-style' central banking, the mismatch between the risk of central bank's assets and that of interest-bearing reserves raises the possibility of central bank insolvency. This would arise if losses in the central bank's assets ($\iota_t < 0$), arising for instance from a lower market value of long-term bonds or from credit impairments, were so large as to deplete its net worth by more than the present value of seignorage revenues.[14] If agents anticipated such scenario and there existed no mechanism to recapitalise the central bank, then agents could be reluctant to continue holding central bank's liabilities, which could lead to high inflation.

When the source of risk stems only from the duration mismatch between assets and liabilities, the likelihood of intertemporal insolvency is small. The simulations presented by Del Negro and Sims (2015) suggest that this investment strategy typically provides a sort of natural hedging. Shocks that reduce the real value of the central bank's assets (higher long-term interest rates, if the central bank's portfolio has a long duration) tend to be positively related with inflation expectations and hence may be accompanied by an increase of the present value of seignorage revenues.

The prospect of intertemporal insolvency increases if it involves a shock that reduces net worth without sufficiently increasing future seignorage. This may arise if the central bank's financial assets carry non-diversified credit risk, for instance.[15] This kind of exposure is arguably more prone to jumps that may have an abrupt negative impact on net worth, while being less directly related with the business cycle and inflation and thus having no compensating effect on the present value of seignorage.

Del Negro and Sims (2015) offer another interesting possibility. They describe the effects of introducing 'inflation scares' as defined by Goodfriend (1993), i.e. shocks to

14. As central banks' assets are typically held to maturity, these are often booked at nominal value or amortised cost in the financial statements. Nonetheless, from an economic perspective, the market value is still the relevant metric. Considering the case of duration mismatch, even if an increase in interest rates does not directly affect the book value of fixed-rate long-term assets, it will still lead to losses if the financing cost increases sufficiently.

15. The early example of the Bank of Amsterdam in the 18th century discussed by Quinn and Roberds (2016) is an interesting case in point, as the Bank's losses mainly resulted from the large concentration of investments in the Dutch East India Company, a large government-sponsored enterprise that became insolvent.

inflation expectations that have a positive impact on long-term nominal interest rates without affecting the central bank's inflation objective. These shocks reduce the market value of central bank's assets ($\iota_t < 0$) without major implications on the present value of seignorage revenues. If the effect is large enough, it would require either a capital injection or higher inflation. The latter would confirm agents' inflation scare, opening the door to the existence of multiple self-fulfilling equilibria. As discussed above, the central bank's credibility is crucial to eliminate such equilibria.

3.2. Alternative definitions of central banks' insolvency

The last example suggests that there can be uncertainty regarding the verification of the intertemporal budget constraint. Moreover, it is also possible that the central bank's shareholders demand a certain level of positive dividends that may imply the verification of other more stringent conditions of a central bank's solvency.

Reis (2015) proposes two alternative, more restrictive, definitions of central bank solvency that result from different institutional arrangements between the central bank and the fiscal authority. First, 'period insolvency' assumes an extreme lack of fiscal support where the fiscal authority refuses to compensate, now or in the future, any losses of the central bank. This would imply that the central bank would become insolvent as soon as it posts a negative profit. Hence, in order to remain solvent under this definition, the central bank would need to post positive profits ψ_t in every period: $\psi_T > 0, \forall_{T \geq t}$.

Second, 'rules insolvency' would be an intermediate case that relies on the central bank staying committed to the dividend distribution rule foreseen in its relationship with the Treasury. This would be equivalent to period insolvency if the rule implied that dividends could never be negative and that profits could not be used to offset previous losses. But it would be equivalent to intertemporal insolvency if the rule allowed to build a deferred account of accumulated losses – to be compensated by future profits –, up to the level of the central bank's comprehensive net worth. Hall and Reis (2015) discuss how a measure of 'rules insolvency' may differ depending on the dividend distribution policies or the accounting principles followed by the central bank.

3.3. Quantitative assessment of central banks' solvency in advanced economies

The principles laid out above suggest that the central bank's net worth may not be the best metric to assess the likelihood of insolvency, especially if there is a substantial risk-return mismatch between assets and liabilities. Under 'new-style' central banking, this mismatch has increased significantly, as shown in Figure 2 above. While this increases the likelihood of central banks posting losses, leaving them vulnerable to a negative net worth position, the intertemporal solvency of any central bank may still be solid if the present value of seignorage revenues more than compensates a potentially negative net worth.

The literature has attempted to estimate this component of central banks' comprehensive net worth. Most estimates tend to be large, suggesting a small likelihood

of insolvency, but results differ substantially depending on model specifications. Table 1 reports a sub-sample of those estimates:

(All values as percentage of GDP)	Country (scenario)	**Total seignorage**	**Comprehensive net worth (2021)**	*p.m. Total CB's assets (2021)*
Del Negro and Sims (2015)	US (baseline)	114	127	38
	US (higher rates)	18	29	38
Reis (2016)	US (market-based)	33	42	38
	US (historical)	14	23	38
Buiter and Rahbari (2012)	US	21	30	38
	Euro area	40	59	70
	Japan	40	65	134
	UK	11	15	49

TABLE 1. Estimates of central banks' comprehensive net worth found in the literature

Notes: Most of these papers only present estimates for the value of total seignorage: $E_t[\sum_{T=t}^{\infty} v_{t,T}(\sigma_T)] = E_t[\sum_{T=t}^{\infty} v_{t,T}(s_T)] - \frac{M_{t-1}}{P_t}$. As comprehensive net worth is given by $W_t^{CB} = N_t^{CB} + E_t[\sum_{T=t}^{\infty} v_{t,T}(s_T)]$, we can proxy it by adding reported equity and currency in circulation to the estimated value of total seignorage. The table reports W_t^{CB} using currency in circulation and equity reported for the end of 2021, except for Del Negro and Sims (2015), who directly report a measure of comprehensive net worth for their calibration of the US economy. Reis (2016) reports estimates for a number of alternative model settings and discount rates; this table reports the upper and lower bounds of those estimates. Buiter and Rahbari (2012) provide estimates of the value of total seignorage for alternative steady state levels of the nominal discount rate and GDP growth rate; this table reports estimates using 4% and 1.5%, respectively.

In the table, the estimate provided by Del Negro and Sims (2015) in their baseline calibration of a general equilibrium model for the US economy stands out, as they report an estimate of comprehensive net worth that is a multiple of the level of the central bank's assets. This is mainly the result of considering a very low discount rate of 0.25%. Still, even under higher discount rates, and taking into account uncertainty around seignorage revenues, as in Reis (2016), alternative estimates for the US economy point to a level of comprehensive net worth that is of the same order of magnitude of the current historically high level of total central banks' assets. Buiter and Rahbari (2012) provide estimates for other central banks and reach similar conclusions. This means that, from an intertemporal perspective, central banks would be able to cope with a very substantial negative shock on the market value of its assets, without the need for recapitalisation.[16]

These estimates suffer from a number of limitations. First, they are very sensitive to assumptions on the discount rate, which is reflected in the range of estimates presented for the US.[17] Second, they depend significantly on the relationship between inflation and seignorage. Similarly to other taxes, the real seignorage revenues may be subject to a Laffer curve, meaning that above some level higher inflation actually implies a reduction of seignorage revenues. Third, estimates also depend crucially on money demand functions, which may be on the verge of a structural change, given increased

16. The difference between comprehensive net worth and the total value of seignorage (in columns 4 and 3 of Table 1) gives a measure of net worth plus currency in circulation. The fact that this is significantly lower in the cases of the US, and especially the UK, reflects the different mechanisms put in place to offset any potential losses. See discussion in section 5.

17. See also the sensitivity analysis provided by Buiter and Rahbari (2012) for other countries.

competition from external alternatives and the possible introduction of central bank digital currencies. Still, the more conservative estimates suggest that the likelihood of intertemporal insolvency in any of these economies is very small.

Hall and Reis (2015) assess alternative more stringent metrics of central banks' solvency that take into consideration the accounting standards and dividend policies of three major central banks. They characterise the main sources of risk for the Federal Reserve (interest rate risk), the Eurosystem (sovereign credit risk) and the Swiss National Bank (exchange-rate risk) and find that in most adverse scenarios these central banks would be able to avoid high inflation and continue paying dividends in most periods. In the case of the US, Carpenter *et al.* (2015) and more recently Cavallo *et al.* (2019) simulate the effect of different scenarios for the Federal Reserve's normalisation policies on net income and remittances to the Treasury and find that the likelihood of an accumulation of substantial losses is extremely remote. While these estimates were obtained before the most recent increase of central banks' balance sheets size and exposures, they still seem to suggest that the financial situation of central banks in advanced economies is sufficiently strong to cope with large shocks.

4. The case of a monetary union

The existing literature has mainly focused on the case of a single monetary authority issuing liabilities in domestic currency. While many of the conclusions obtained from such setting can be extended to the case of a monetary union, this environment raises additional challenges that deserve a careful discussion. As monetary policy is decided at the aggregate level and does not depend on the idiosyncratic decision of a single national authority, one may be led to conclude that the independence of monetary policy with respect to any potential external pressures is higher in a monetary union. Nonetheless, understanding the complex web of interactions between NCB within the system and with each national fiscal authority is important, in particular whether concerns on the financial situation of a national fiscal authority or a NCB may have implications to the aggregate level.

The first important question is on how to ensure the conditions for 'monetary dominance' and 'fiscal support' in a monetary union. Sims (1999) was probably one of the first to highlight some of the difficulties that this institutional arrangement could entail, focusing on the specific case of the EMU. In what regards monetary dominance, he speculated that the commitment to fiscal rules on the part of several fiscal authorities would be feeble, which could lead to fiscal free-riding and financial stress in some countries that could threaten the EMU credibility.

Bergin (2000) was another early contribution. He showed that, in the absence of a mechanism that ensured monetary dominance, an unsustainable fiscal policy in a single country could lead to a higher price level in the currency area. On a more positive note, he also showed that monetary dominance could be achieved under different policy arrangements. One common proposal would be for each national government to ensure its own public debt sustainability, which provides some justification for

the fiscal restrictions foreseen in the EMU's Stability and Growth Pact. But, more generally, monetary dominance could be guaranteed by a central fiscal authority defining national fiscal policies under a commonly agreed framework, or even by any national government taking actions at the national level to ensure public debt sustainability at the aggregate level. However, the latter arrangement could result in diverging paths for national public debt levels, which would probably raise questions on the stability of the monetary union.

In what regards the fiscal support condition, this could also be envisaged under centralised or decentralised arrangements. But, in the absence of an explicit mechanism, fears of capital losses could limit NCB's actions. Corsetti *et al.* (2019) discuss the need for coordinated stabilisation policy in the context of the EMU, supporting the role of the central bank as a lender of last resort and backstop for government funding. As discussed above, the central bank's actions under these roles may eliminate non-fundamental self-fulfilling equilibria and from that perspective be themselves crucial to control inflation expectations.[18] However, they typically imply assuming higher financial risks. In order to ensure the central bank's ability to accomplish these endeavours without endangering the price stability objective, the authors propose some institutional changes to the euro area, including the need for fiscal support of the Eurosystem at the aggregate level.

In the absence of explicit fiscal support, there is the need to satisfy a solvency condition like (7) at the aggregate level. Moreover, if there is limited risk sharing within the monetary system, each NCB will need to satisfy a separate budget constraint. An immediate application of condition (7) suggests that a NCB's solvency will depend on its own net worth and its share in the present value of future seignorage revenues, but this conclusion abstracts from potential financial linkages between the different NCB.

Bassetto and Caracciolo (2021) have recently formalised this setting, suggesting that the solvency of each NCB is important to sustain the credibility of the common monetary policy. Even if a large capital loss of an individual NCB does not threat the aggregate solvency condition, if there were no fiscal support from the national fiscal authority, the loss would be eventually covered by the whole system. This could imply either an implicit transfer of resources between members of the monetary system or the acceptance of higher seignorage revenues (and inflation).[19] In this context, ensuring the solvency of each NCB may be important to guarantee an ecosystem of mutual trust within a common monetary system that preserves the credibility of monetary

18. See Cardoso da Costa and Gomes (2021).

19. In the case of the Eurosystem, this would contradict Article 125 of the EU Treaty. Buiter (2020) discusses the specific case of the Eurosystem, stressing the risk of insolvency for NCB stemming from the non-shared exposure to own government default risk. In such circumstances, it is unlikely that the national fiscal authority would be able to provide fiscal support, which increases the risk of spilling over to the Eurosystem as a whole.

policy.[20] A formal discussion of the setting developed by Bassetto and Caracciolo (2021) is presented in an Appendix.

5. Mechanisms to support central bank solvency

The previous sections present a theoretical framework that helps us understand the financial boundary of central banks' actions. In the absence of a credible mechanism of fiscal support, it remains in the central bank's hands the ability to ensure its own solvency. The literature has discussed different mechanisms to minimise the likelihood of policy insolvency, often building on the institutional arrangements observed in practice.

Sims (2004) suggests that central banks should diversify their portfolio of assets and invest in sound and stable entities, while building up net worth (i.e. capital buffers) through retained earnings.[21] Similarly, Goodfriend (2014) suggests that central banks with large long-duration balance sheets should avoid the carry trade and retain part of their income in the beginning of a quantitative easing process to hedge against financial risks that may materialise when policy rates start to increase. Hall and Reis (2015) discuss the use of deferred assets, whereby central banks losses would be offset by future profits. The authors also suggest other risk management mechanisms that may be useful for specific exposures, such as mark-to-market accounting and repurchase agreements (in case of exposure to default risk) or exchange rate pegs (in case of exposure to foreign currency risk). Finally, Reis (2015) discusses examples of central banks that segregate part of their financial investments in specific facilities to shield the balance sheet from any potential losses. If the fiscal authority fully indemnifies these facilities, it is providing an explicit mechanism of fiscal support for the risks associated with that specific portfolio.[22]

Having this said, reviewing the institutional arrangements observed in the major advanced economies is instructive, as they cover a large spectrum of the mechanisms proposed in the literature.

5.1. Institutional arrangements in major advanced economies

The Federal Reserve System relies mainly on the establishment of deferred assets. Under the Federal Reserve's accounting standards, when earnings are insufficient to cover the operational costs, thus implying a net income loss, remittances to the Treasury are

20. In the case of the EMU, the Agreement on Net Financial Assets, which has been set up to limit the impact of decisions unrelated with monetary policy on the aggregate balance sheet, may also serve as a mechanism to minimise the likelihood of such negative spillovers.

21. At the same time, the author cautions that building large financial buffers may also put pressure on the central bank's independence, as it may raise political pressure to use accumulated reserves. Moreover, the central bank may also be tempted to enlarge its mission to justify the maintenance of additional buffers, exposing the bank to other risks.

22. This arrangement may be less credible if such facility is particularly exposed to sovereign credit risk, which is yet another reminder that the condition of monetary dominance remains necessary.

suspended until cumulative earnings are sufficient to cover the losses accumulated in the deferred asset account.[23] The 'deferred asset' is booked as a negative liability, thus insulating the central bank's capital. This arrangement, if credible and applied with no limit, would in fact satisfy a full fiscal support mechanism from an intertemporal perspective. However, as Carpenter *et al.* (2015) note, there has never been a deferred asset of significant size, so there is no guidance on how large that limit could be. The accounting standards provide that deferred assets should be periodically reviewed for impairment, which suggests that the limit may be lower than the present value of future seignorage. Nonetheless, the simulations of Hall and Reis (2015) and Carpenter *et al.* (2015) suggest that the accumulation of losses resulting in a very large deferred asset would be extremely unlikely.

The Bank of England currently has two complementary mechanisms that provide substantial fiscal support, without the need to rely on a large capital buffer. On one hand, the Bank established in 2009 the 'Bank of England Asset Purchase Facility Fund', which holds all asset purchases conducted for monetary policy purposes and is fully indemnified by the HM Treasury. In February 2021 the loan to this Facility represented more than 80% of the central bank's assets, which significantly dwarfs the central bank's unbacked exposures. On the other hand, in 2018 the Bank of England and the HM Treasury agreed on a new framework for the central bank's capital, establishing a target, a floor and a ceiling for the level of loss-absorbing capital, that serve of reference to determine the proportion of earnings to be distributed. If the Bank's capital falls below the floor, the HM Treasury is mandated to recapitalise the Bank in an amount that brings the level back to target. Otherwise, the Bank of England may or may not pay dividends, depending on the comparison with the target and the ceiling.[24]

Finally, the Bank of Japan and the Eurosystem mainly rely on building financial buffers to pre-emptively ensure sufficient capital to cover any potential losses. This may be done through different mechanisms: (i) retaining part of net profits as capital or reserves; (ii) building financial provisions for specific or general purposes;[25] or (iii) maintaining revaluation accounts for unrealised capital gains.[26] In the case of the Eurosystem, these three layers of financial buffers serve as different lines of defence of the ECB's and NCB's net worth against possible losses. Revaluation accounts are

23. See Federal Reserve Board (2022), p. 56.

24. See HM Treasury (2018). Since the implementation of this memorandum of understanding, the Bank of England was recapitalised in 2019 and did not pay dividends to the Treasury in 2021 nor in 2022.

25. The Bank of Japan has separate provisions for possible losses in bond transactions and foreign exchange transactions, for example. Within the Eurosystem the capital policy followed by De Nederlandsche Bank since 2019 is a good example of how different financial buffers may be built for different purposes. In the 2019 Annual Report, the DNB draws a clear "distinction between buffers to cover temporary risks (the provision for financial risks) and buffers to cover structural and hidden risks (capital)". See De Nederlandsche Bank (2020).

26. In the case of the Eurosystem, unrealised capital gains/losses have an asymmetric accounting treatment: gains are used to build revaluation accounts that show up as a positive liability in the balance sheet, while losses may have an impact on earnings (and hence capital), if they surpass the respective revaluation account.

reduced first, if and only if part of the unrealised gains are reversed. Additional losses may be covered by a reduction of financial provisions (if available), or may directly affect earnings and capital.

Over the past decade, financial buffers in the Eurosystem increased significantly, mainly driven by the evolution of revaluation accounts related with the market value of gold reserves. Excluding this component, however, financial buffers still increased at a higher pace than nominal GDP, especially through the build up of financial provisions since the great financial crisis, accompanying part of the increase of balance sheet size and exposures. This evolution has been broad-based across NCB, but the level of financial buffers still reveals substantial heterogeneity within the Eurosystem that may reflect different balance sheet exposures, but also different mechanisms regarding the relationship between the monetary and fiscal authorities at the national level, namely in what regards dividend distribution policies.

6. Concluding remarks

This synopsis discusses the financial boundaries of central banks' actions. The literature has developed an appropriate theoretical framework that clarifies the importance of this discussion and shows that it lays at the core of the interactions between monetary and fiscal policies. In order to ensure that the central bank has the power to sustain an inflation objective, the fiscal authority needs to guarantee public debt sustainability and should also be ready to provide fiscal support to the central bank in case of need. In the absence of the latter, the central bank needs to satisfy an autonomous solvency condition.

The current sizeable exposure of central banks' balance sheets in advanced economies, especially vulnerable to interest rate and non-diversified sovereign credit risk, leave them susceptible to incur some losses. These exposures result from policies that may have contributed to eliminate non-fundamental self-fulfilling equilibria and hence do not necessarily pose a fundamental threat of insolvency from an intertemporal perspective. While policy decisions going forward should not be contaminated by concerns over potential short-term losses, it is crucial that the institutional framework (including central banks' accounting policies and rules governing the distribution of dividends or the need of capital injections) guarantees the pursuit of fiscal and monetary policies that avoid any fundamental concerns.

The evidence suggests that the possibility of policy insolvency of central banks in advanced economies is extremely unlikely. Nonetheless, history showed that abnormal unexpected events occur, so it is paramount to continue enforcing the necessary mechanisms to ensure that such episodes remain only in the realm of a theoretical possibility. Maintaining an active and transparent debate about these issues contributes to the understanding of how to properly design such mechanisms.

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Appendix: Budget constraint of a NCB in a monetary union and possible implications for monetary policy

In a recent effort to understand the implications of a central bank's solvency for the credibility of monetary policy within a monetary union, Bassetto and Caracciolo (2021) define separate budget constraints for each national fiscal authority and each NCB. Focusing on the budget constraint of an individual NCB, the main difference with respect to condition (6b) in the main text, is that now we need to consider the possibility of financial linkages (claims and liabilities) between members of the monetary system.[27] We define X_t^n as the intra-union claims (liabilities) of the NCB of country n with respect to the other members of the system whenever $X_t^n > 0 (< 0)$. Assuming that these positions are issued at discount with a nominal interest rate i_t, just like common interest-bearing reserves, and that they exist in zero net supply ($\sum_n X_t^n = 0$), the flow budget constraint for the NCB of country n can be written as:

$$M_{t-1}^n + H_{t-1}^n - X_{t-1}^n - (1+\iota_t^n)A_{t-1}^n \leq M_t^n + \frac{1}{1+i_t}(H_t^n - X_t^n) - A_t^n - P_t d_t^n \tag{A.1}$$

Then, following directly Bassetto and Caracciolo (2021), the intertemporal budget constraint of NCB of country n can be written as:

$$\begin{aligned} E_t\left[\sum_{T=t}^{\infty} v_{t,T}(d_T^n)\right] \leq \frac{(1+\iota_t^n)A_{t-1}^n + X_{t-1}^n - H_{t-1}^n - M_{t-1}^n}{P_t} + E_t\left[\sum_{T=t}^{\infty} v_{t,T}(s_T^n)\right] - \\ - \lim_{T\to\infty} E_t\left[v_{t,T}\frac{X_T^n}{P_{T+1}}\right] \end{aligned} \tag{A.2}$$

The main difference with respect to condition (6b) is the presence of intra-union positions, which show up in the initial net worth and also in the final limiting term. The presence in the initial net worth is immaterial, given the assumption that these claims pay the same interest as reserves. Some NCB may issue reserves that are then used to purchase assets by a second NCB in a different jurisdiction, which would imply that the former NCB would hold an intra-union claim over the system, while the latter would have a liability. It is only relevant the level of interest-bearing liabilities net of these positions: $(H_{t-1}^n - X_{t-1}^n)$.

27. In the Eurosystem these claims and liabilities are mainly reflected in the TARGET positions of each NCB vis-à-vis the ECB that serves as the direct counterpart (i.e. the positions are not directly defined between any two NCB, but between each NCB and the ECB). These balances increased significantly during the global financial crisis, as the money market dried up and the Eurosystem stepped in to intermediate funding between commercial banks, often from different jurisdictions. Balances also increased significantly with the implementation of large-scale asset purchases since 2015, as often NCB buy securities held by foreign investors. In either case, the increase of these balances resulted from the regular functioning of monetary policy, simply reflecting the fact that the reserves issued by one NCB may be used to finance commercial banks of a different jurisdiction. For a primal explanation, see: https://www.ecb.europa.eu/ecb/educational/explainers/tell-me-more/html/target2_balances.en.html.

The final term is more interesting (and controversial). The presence of this term reflects the possibility of an explosive path on the intra-union positions, with one NCB constantly rolling over an ever-increasing liability vis-à-vis the monetary system ($\lim_{T\to\infty} E_t\left[v_{t,T}\frac{X_T^n}{P_{T+1}}\right] < 0$), which would imply that some other NCB would accept maintaining an ever-increasing intra-union claim ($\lim_{T\to\infty} E_t\left[v_{t,T}\frac{X_T^n}{P_{T+1}}\right] > 0$). As discussed in the main text, typically these diverging paths are excluded by the assumption of some transversality condition that can be rationalised from the optimising behaviour of the agent that would hold these positions: a private household would always prefer to increase consumption than to accumulate ever-increasing assets. Bassetto and Caracciolo (2021), however, argue that the same reasoning cannot be applied between two NCB, as these entities are not maximising consumption and thus nothing prevents them from accumulating exploding amounts of financial claims.

The presence of this term would mean that it would be straightforward for any individual NCB to satisfy its intertemporal constraint, an apparent symptom of the irrelevance of NCB solvency. But it also would mean that, under some equilibria, the constraint of other NCB would be affected. In particular, the creditor NCB would either need to accept a reduction in the present value of dividends to be paid to its national authority, or accept a higher inflation to generate a proportional increase of seignorage revenues. Hence, under this setting, the credibility of the common monetary policy could be affected by the materialisation of risks in an individual NCB.

However, the possibility of equilibria with such diverging paths of intra-union positions, which would effectively imply a transfer between two jurisdictions, is not consensual in the literature. For instance, Bergin (2000) has discussed the possibility of equilibria with explosive paths of government bond holdings across different fiscal authorities, but these equilibria have been considered unappealing, as they would imply a welfare loss of the individuals in the country whose government would accept to hold such positive positions.

The same reasoning could be used to rule out the equilibria with diverging paths of intra-union positions within a monetary system. Most likely, such equilibria would be difficult to sustain politically. Nonetheless, it is instructive to understand the potential implications of a capital loss in an individual NCB.

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