The Role of Adverse Supply Shocks in the Post-Pandemic Euro Area Inflation Surge: a DSGE Approach

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Abstract of the master's thesis

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Abstract

The economy has faced unprecedented shocks during the past four years as the world was first shaken by the Covid-19 pandemic and shortly after the Russian invasion of Ukraine. These shocks created a difficult environment for policymakers to act in and eventually most central bankers failed to predict the resulting inflation surge.

This thesis aims to add to the on-going discussion on the drivers of the inflation surge by examining the inflationary effects of adverse supply shocks that the economy faced as a consequence of the pandemic and war. This thesis will examine this through a linear New Keynesian dynamic stochastic general equilibrium (DSGE) model adapted from Harding et al. (2023). The model is calibrated to represent the euro area in the beginning of 2021, a time when the initial lockdowns had begun to ease, increasing demand but supply constraints remained and inflation began to increase.

Through the DSGE simulations, this thesis is able to show that two types of adverse supply shocks, a negative productivity shock and positive cost-push shock, both create a positive inflation response. The simulations highlight the role of cost-push shocks in euro area inflation. To test the robustness of the results, the persistence of the shocks are varied. Furthermore, in light of the policy implications, this thesis briefly explores and highlights the trade-off between inflation and the output gap that monetary policy encounters when faced with adverse supply shocks.

Keywords DSGE model, Covid-19, productivity shock, cost-push shock, monetary policy

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Euroalueen talous on kohdannut suuria shokkeja viimeisen neljän vuoden aikana, kun ensin maailmaa ravisteli Covid-19-pandemia ja pian tämän jälkeen Venäjän hyökkäyks Ukrainaan. Nämä shokit loivat päätöksentekijöille vaikean toimintaympäristön, ja lopulta useimmat keskuspankkiirit eivät pystyneet ennustamaan siitä johtuvaa inflaation kiihtymistä.

Tämän tutkielman tavoitteena on lisätä ymmärrystä inflaation kiihtymisen ajureista tarkastelemalla pandemian ja sodan aiheuttamien tarjontahäiriöiden inflaatiovaikutuksia. Tässä tutkielmassa tarkastellaan tätä lineaarisen uuskeynesiläisen dynaamisen stokastisen yleisen tasapainon (DSGE) mallin avulla, joka on mukautettu Harding et al. (2023) tutkimuksesta. Malli kalibroidaan kuvaamaan euroaluetta vuoden 2021 alussa, jolloin pandemiasta johtuneet liikkumisrajoitteet olivat alkaneet helpottaa ja näin myös kysyntä oli lähes palautunut. Tästä huolimatta tarjontarajoitteet säilyivät ja inflaatio alkoi kiihtyä.

DSGE-simulaatioiden avulla tämä tutkielma pystyy osoittamaan, että kahdenlaiset tarjontashokit, negatiiviset tuottavuusshokit sekä positiiviset kustannusshokit, vaikuttavat molemmat positiivisesti inflaation. Simulaatiot korostavat kustannusshokkien roolia euroalueen inflaatiossa. Tulosten vahvuutta testataan herkkyysanalyysilla, jossa vaihdellaan shokkien kestoa. Lisäksi poliittisen päätöksenteon näkökulmasta, tämä tutkielma tarkastelee lyhyesti inflaation ja tuotantokuilun välistä kompromissia, jonka rahapoliittiset päättäjät kohtaavat tarjontashokkien valossa.

Avainsanat DSGE-malli, Covid-19, tuottavuusshokki, kustannusshokki, rahapolitiikka

Preface

I want to thank Prof Seppo Honkapohja for his guidance. I would also like to extend a special thank you to Prof Mathias Trabandt, Dr Martin Harding and Dr Jesper Lindé for providing their paper's replication package as well as their guidance in solving the model. Lastly, I would like to thank my family and friends for their unwavering support.

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Contents

1 Introduction

During the past four years, the world economy has experienced vast unprecedented shocks, starting with the Covid-19 pandemic and shortly followed by the Russian invasion of Ukraine. These events resulted in simultaneous demand and supply shocks (Baqaee & Farhi, 2022), which created a difficult environment for central banks to act in and eventually most central bankers and economists failed to predict the consequence of these shocks - the sharp increase in inflation (Bernanke & Blanchard, 2023). The surge was persistent since only now, four years after the outbreak, inflation has nearly returned back to the European Central Bank's (ECB) target of two percent (ECB, 2024).

Since the sharp rise in inflation caught most by surprise, economists have been attempting to unravel the mechanisms and key drivers of this surge. Majority of the on-going discussion has been on whether demand or supply shocks were the driving force since a key characteristic of this economic crisis has been the simultaneous occurrence of both supply and demand shocks. First economies shut down as lockdowns were imposed, limiting demand and causing supply chain issues. Then economies begun to open and demand had pent up whilst supply constraints remained and the energy crisis begun.(Di Giovanni et al., 2022) Distinguishing the inflationary roles of these two different types of shocks is crucial for policy makers as the optimal policy response depends on the drivers of the surge (Baqaee & Farhi, 2022).

This thesis aims to add onto the discussion by expanding the understanding of the role of negative supply shocks on inflation in the euro area. According to Bandera et al. (2023), economists have argued that in the coming decades, the economy will experience more and larger adverse supply shocks. Hence, through expanding the understanding of the inflationary effects of negative supply shocks, future similar economic disturbances can be better navigated through appropriate policy responses. The focus of this thesis will be on the year 2021, as this was a time period when initial restrictions were eased and demand had nearly rebounded to pre-pandemic levels but supply disruptions remained and inflation began to rise (Ascari, Bonomolo, et al., 2023).

Therefore, the main question that this paper aims to answer is: What were the inflationary effects of the negative supply shocks in 2021 in the euro area? The secondary question relates to the monetary policy response, which is the policy implication of this thesis: What are the implications of such adverse supply shocks for monetary policy? These questions will be mainly answered through an empirical simulation but the analysis will also be supported by a theoretical analysis. More specifically, the main research question will be answered through a theoretical overview as well as an empirical analysis of two different types of negative supply shocks experienced during the pandemic - a negative productivity shock and a positive cost-push shock. The theoretical overview will utilize two different frameworks, the basic an aggregate demand and aggregate supply framework, as well as the 3-equation framework. The empirical analysis will use a linear dynamic stochastic general equilibrium model (DSGE) provided by Harding et al. (2023). The analysis will contain an impulse response analysis and a scenario analysis with varied persistence of the shocks. The secondary question will be briefly explored theoretically using the 3-equation model and empirically through a brief analysis of different monetary response scenarios.

The findings of this thesis show the positive inflationary effects of both types of adverse supply shocks. The theoretical analysis shows that according to the two theoretical frameworks, both negative supply shocks cause an increase in inflation. The empirical findings are consistent with the theoretical findings. The simulations show that in the euro area in 2021, both types of negative supply shocks increased inflation. The cost-push shock having clearly larger inflationary effects than productivity shocks, which highlights the importance of cost-push shocks such as the surge in energy prices in the euro area. The sensitivity analysis also highlights the role of cost-push shocks as a persistent cost-push shock caused a four-fold inflation response in the simulations. Furthermore, this thesis briefly examines the monetary response and finds through the 3-equation framework, that policy rate should respond to adverse supply shocks by an increase in policy rates. Empirically, this thesis however highlights the trade-offs faced by monetary policy during such adverse supply shocks and finds that choosing the monetary response scheme has large implications for either keeping inflation at target or avoiding large output losses.

The structure of this thesis is the following. Section 2, will give a brief overview of the economic environment created by the pandemic and Russian invasion of Ukraine. Section

3 will present findings from existing literature on the drivers of the inflation surge, focusing on literature on the inflationary effects of supply shocks from three different perspectives - global findings, findings from the United States and findings from the euro area. Section 3 will also briefly introduce existing literature on the monetary response to adverse supply shocks. Section 4, will present a theoretical analysis of the effects of the two negative supply shocks on inflation through two theoretical frameworks. Section 5 will introduce the linear DSGE model used for the empirical analysis. Section 6 will explain the calibration of the model to represent the euro area economy in the beginning of 2021. Section 7 will employ the stylized and calibrated model into MATLAB and present simulation results of a negative productivity shock and a positive cost-push shock as well as a sensitivity analysis on the effects of varying the persistence of the shocks. Section 7 will also present a brief empirical analysis on three different monetary policy scenarios. Finally this thesis will be concluded in Section 8.

2 Background

This section summarizes the evolution of the pandemic induced economic shocks, monetary response and the surge in inflation. In the beginning of the pandemic, in 2020, world GDP collapsed as supply chain disruptions began and lockdowns limited demand (Di Giovanni et al., 2022). Euro area GDP fell by 6.1 percent in 2020 (De Santis & Stoevsky, 2023). To combat this economic downturn, central banks and governments quickly engaged in large expansionary monetary and fiscal measures. The European Central Bank (ECB) engaged in quantitative easing measures through the Pandemic Emergency Purchase Program in early 2020, which lasted until March 2022 (ECB, n.d.). Against expectations, the economy rebounded quickly (Reis, 2022) but despite the fast recovery, the economic environment remained difficult to navigate as Covid-19 differed from past crises in several ways.

One significant difference was that it affected sectors heterogeneously, which created demand-supply imbalances and resulted in supply chain bottlenecks. In the beginning of the pandemic, contact-intensive sectors experienced both negative supply and demand shocks. (Di Giovanni et al., 2022) During this early phase, supply shocks arose from the shut down of factories, scarcity in various factors of production such as imported intermediate products and the restrictions on the amount of workers at workplaces. These shocks led to a decrease in productivity. Negative demand shocks arose as countries limited individuals' movement to avoid contamination. (Di Giovanni et al. 2023; Ascari, Bonomolo, et al. 2023) Other less contact-intensive sectors (such as online shops) experienced positive demand shocks as there was a shift in demand between services and goods sectors. In late 2020 and early 2021, once the initial lockdowns were lifted and vaccinations begun, sectors experienced fast but asymmetric recoveries. (Di Giovanni et al., 2022) Initially, service sectors recovered slowly as there were repeated shocks caused by different variants of the virus. Manufacturing sectors recovered faster due to the demand shift from services to goods consumption. (Di Giovanni et al., 2022) Demand had pent up but supply chains were still constrained as new waves of the pandemic caused boarders to close, global supply chain bottlenecks to remain and shortages of intermediate goods and labor to persist. This caused further pressure on supply chains as demand exceeded supply. (Di Giovanni et al. 2022; Ascari, Bonomolo, et al. 2023; Reis 2022) This increased demand led to the increase of global energy prices, which was further exacerbated by the Russian invasion of Ukraine. The euro area imports most of it's energy and between December 2020 and December 2021, the import price of energy more than doubled in the euro area. This was unexpected as energy prices do not usually change by more than 30 percent in a year. In 2022, energy prices further increased as deliveries of gas was suspended from Russia. This resulted in record high electricity prices in the euro area. (European Council, 2024)

In addition to sectors having asymmetric recovery, countries did as well. Governments' responses to the pandemic varied both in how they implemented contamination policies as well as monetary and fiscal policies. (Di Giovanni et al., 2022) The constantly changing epidemiological situation caused by various variants of the virus, resulted in varied containment measures globally (De Santis & Stoevsky 2023; Di Giovanni et al. 2022). This resulted in unsynchornized easing and tightening of containment measures (such as lockdowns), which combined with the existing supply constraints further increased bottlenecks in global supply chains. (De Santis & Stoevsky, 2023) For example in 2022, when demand was surging in various western countries, China's economy was still in shutdown, leading to bottlenecks in food and manufacturing sectors (Lane, 2024).

Eventually as a result of these unprecedented economic shocks, euro area inflation, which had briefly dipped in the beginning of the pandemic, began to increase in early 2021. Inflation rose above ECB's medium-term target of two percent in July 2021. As stated by Lane (2024), throughout 2021, the ECB saw that the supply shocks were temporary and that energy prices would normalize without effecting the medium-term inflation outlook. Hence, it was seen that monetary accommodation was the appropriate monetary response since inflation had not affected medium-term price pressures such as wage growth and long term inflation expectations. However, by December 2021, inflation had already risen to five percent in the euro area, which led to the announcement that PEPP net purchases would end in 2022Q1 and overall net asset purchases would be decelerated throughout 2022. Still no indications were made that policy rates would increase. In July 2022, new inflation projections led the ECB to raise it's policy rates for the first time (ECB, 2022). Inflation reached it's peak at 10.6 percent in October 2022 and eventually interest rates were raised ten consecutive times until October 2023 (Lane, 2024).

3 Literature Review

This section presents findings from existing literature on the drivers of the inflation. Since the surge in inflation, research has tried to understand the drivers behind the persistent increase. A significant amount of literature has focused on distinguishing between demand and supply shocks. This has been a key focus since differentiating between demand and supply shocks is crucial for determining the optimal policy responses. The optimal monetary and fiscal policy responses differ depending on the kind of shock. For example, policies that boost demand, amplify negative supply shocks, causing further shortages as well as inflation. (Baqaee & Farhi, 2022) Researchers have examined this globally as well as in various economic areas using various econometric methods such as regression analysis, VAR models and DSGE models. This section will summarize key findings of this literature, focusing on the most relevant strand of literature, literature on negative supply shocks, from three perspectives; papers examining this globally, papers focusing on the United States and finally papers examining the euro area. To aid the policy implication discussion of this thesis, this section will also briefly present literature on monetary policy responses to adverse supply shocks.

3.1 Supply Constraints Globally

Literature that has explored the phenomenon globally or in multi-country studies find that supply shocks played a key role in the sharp rise in inflation. Examining the inflation surge globally, both Celasun et al. (2022) and Carrière-Swallow et al. (2023) find that global supply shocks explain a large portion of surging inflation in the 2020s. Celasun et al. (2022) conduct a comprehensive analysis of supply chain disruptions and their effects on inflation in 2021 globally. Using a Vector Auto Regression (VAR) approach, they find that globally supply shocks were largely caused by shut downs, labor shortages and inadequate infrastructure as well as severe weather and industrial accidents, leading to shortage of microchips. Out of these causes, Celasun et al. (2022) saw in 2022 that labor shortages and issues with logistics infrastructure could lead to more persistent supply shortages. More specifically, they find that supply constraints explain a large portion of producer price inflation (PPI) but the finding varies between countries; e.g., in the euro area around 50 percent of PPI, 60 percent in Germany, 45around 50 percent in the United States and United Kingdom. They find that the rest of the inflation can be mostly explained by high demand of goods. Carrière-Swallow et al. (2023) find similar results using a panel study of 46 countries to examine the rise of shipping costs witnessed in 2020. Shipping costs raised by over 500 percent from pre-pandemic levels due to rise in demand and constrained shipping capacity caused by pandemic disruptions to logistics. Like Celasun et al. (2022), they examine effects on PPI inflation and find that this specific type of adverse supply shock, the rise in shipping cost, caused a rise in PPI. Furthermore, they find that headline and core inflation as well as inflation expectations increased in response to the spike in shipping costs.

Papers by Di Giovanni et al. (2022) and Di Giovanni et al. (2023) have focused on comparing the effects between countries through New Keynesian dynamic stochastic general equilibrium (DSGE) models. Di Giovanni et al. (2022) examine the role of demand shocks caused by expansionary policies and supply shocks, focusing on the euro area and the United States. More specifically, they examine shocks to labor supply and set their model with an assumption that there were no productivity shocks. They find that initially in 2020-2021 negative supply shocks sparked inflation and then in 2021-2022 positive demand shocks, caused by expansionary fiscal and monetary policy amplified inflation. More specifically, Di Giovanni et al. (2022) find that that in the euro area global supply bottlenecks played a larger role in the inflation surge than domestic demand shocks did. They find that supply chain bottlenecks explain around 50 percent of euro area inflation. Conversely, demand shocks played a larger role in the U.S. as supply chain bottlenecks explain only around 30 percent of the U.S. inflation. Di Giovanni et al. (2022) argue that one reason for this is the differing governmental response in the two regions and another the differences in consumption behaviour in the two regions.

In a more recent paper, Di Giovanni et al. (2023) examine these dynamics in four different regions; the United States, euro area, Russia and an aggregate of the rest of the world including China. They find that globally pandemic-related supply shocks (labor supply, factors of production and intermediate inputs) were the origin of the inflation surge and it was further increased in 2021-2022 by the demand stimulating expansionary monetary and fiscal policies. This created a supply demand imbalance, which led to inflation. In addition to these shocks, they find that the reallocation of consumption and energy shocks amplified the effects. Di Giovanni et al. (2023) find that the role of energy shocks in the inflation surge was more significant in the euro area than in the US.

3.2 Supply Constraints in the United States

Literature focusing on the United States alone echo the results found in global or multi-country studies. LaBelle & Santacreu (2022) and Ball et al. (2022) use regression analysis to find that adverse supply shocks had a significant impact on the U.S. inflation surge. LaBelle & Santacreu (2022) focus on examining the effects of supply chain disruptions on U.S. PPI inflation. They regress industry PPI inflation on exposure to supply constraints and find that exposure to foreign supply bottlenecks had a significant impact on the U.S. PPI inflation in 2021. More specifically, they find that if supply chain bottlenecks had followed the same path during the pandemic era as in 2019, U.S. PPI inflation would have been 20 percentage points lower in November 2021. In similar vein, Ball et al. (2022) find that in addition to a tight labor market, rises in energy prices and automobile prices, supply chain disruptions were key drivers on the increase in inflation.

The drivers of inflation in the United States have also been examined through New Keynesian DSGE models. The contributions using these models include Comin et al. (2023), Amiti et al. (2024) and Ferrante et al. (2023). Comin et al. (2023) examine the dynamics of supply constraints with other shocks such as the demand shock caused by monetary policy. More specifically, a part of their paper studies the interaction between potentially binding capacity constraints in the supply chain and monetary policy shocks. They find that in the United States expansionary monetary policy shocks trigger binding supply constraints and lead to the surge of inflation. They conclude that these binding capacity constraints explain half of the U.S. inflation surge.

Amiti et al. (2024) add to these findings by examining the effects of four different shocks: import price shock, labor disutility shock, rise in marginal cost of foreign competitors and goods-favored demand shock. They specify their model so that monetary policy is accommodative (interest rates are kept at zero) and find that overall supply-side shocks played a significant role in driving inflation during the pandemic era in the United States. This hence shows the joint effect of the accommodative monetary policy and supply disruptions. Their three key findings are; 1) supply chain disruptions played a key role in both price and wage inflation, 2) the shift from foreign to domestic producers (due to the marginal cost shock) increased domestic demand, increasing wage and price inflation, and 3) together, adverse supply chain and labor shocks amplified inflationary effects as substituting between labor (which was constrained) and imported input (which was more expensive) became less profitable. Furthermore, Amiti et al. (2024) highlight that alone the inflationary effects of demand side shift in consumption would not have been very significant, but supply chain and labor shocks amplified the effects.

In slight contrast, Ferrante et al. (2023) find that in the U.S., the shift of consumption to demand goods from services explains a large part of the inflation surge between end of 2019 and end of 2021 because of the the costs of increasing goods production. Furthermore, they find that labor supply shocks are only slightly inflationary and that sectoral productivity shocks even slightly lowered inflation in the initial phase of the pandemic due to the growth in productivity over the examination period. However, productivity growth was also negative in several sectors and can explain high inflation in goods-producing sectors in 2022.

Fornaro & Wolf (2023) on the other hand use a Keynesian growth model to examine the effect of an adverse productivity shock on the U.S. economy with a focus on the formation of persistent effects. In their model, they include scarring effects and show how these can prolong the inflationary impact of negative supply shocks. This happens because supply disruptions cause firms to reduce investment, which consequently destroys the economy's future productive capacity. This long-lasting decrease in investments and productivity leads firms to increase prices. Furthermore, they argue that the lag in investment's effect on productivity delays the rise of inflation, causing persistence.

In addition to New Keynesian DSGE and Keynesian growth models, literature has employed vector autoregressive (VAR) models to examine the effects of the adverse supply constraints. In a structural VAR model, Kabaca & Tuzcuoglu (2023) examine the effects of global supply chain shocks, shocks to labor supply and productivity, oil price shocks as well as price and wage mark-up shocks in the United States. They find that initially in 2020, supply chain shocks and labor supply shocks drove inflation whilst in 2021 oil shocks were a key contributor to inflation. Finally demand shocks as well as mark-up shocks become the main inflation drivers in 2022. Overall they find that global supply chains as well as oil price shocks were the biggest drivers of the U.S. inflation surge. In another VAR model, Gagliardone & Gertler (2023) find that the Fed's delayed response to inflation during a time of inflationary oil price shocks explains the inflation surge in the United States. They argue that the increase in oil prices affected both households and firms as it is a complement good for households and a complement input for firms.

3.3 Supply Constraints in the Euro Area

A strand of the emerging literature has focused solely on euro area supply shocks and inflation. In contrast to the papers focusing on the United States, there are less papers utilizing New Keynesian DSGE models (as of the time writing this, to the best of knowledge, the above discussed multi-country papers by Di Giovanni et al. (2022) and Di Giovanni et al. (2023) are the only ones that utilize a New Keynesian DSGE model in their analysis). Instead the euro area papers have mainly utilized VAR models and regression analysis. Using these varying methods, literature has found consistent results with the above discussed multi-country papers as well as those focused on the United States.

Contributions using VAR models include Finck & Tillman (2022), Ascari et al. (2024), Ascari, Bonomolo, et al. (2023) and Banbura et al. (2023). Finck & Tillman (2022) argue that global supply chain shocks were a main driver of the increase in consumer prices in the euro area. They find that the global supply chain shock (proxied by variables summarizing container shipping) was a key determinant of the euro area inflationary pressure; it explains around 30 percent of inflation dynamics in the euro area during a one year period. Finck & Tillman (2022) note that the reason behind this is that the euro area is largely dependent on global supply chains; in several member countries, more than half of manufacturing output crosses more than one boarder.

Ascari, Bonomolo, et al. (2023) on the other hand emphasize the role of demand shocks as well. They provide a concise analysis on the euro area inflation surge and find that the interaction between the reopening of the economy and the supply constraints led to the surge. In a VAR forecast analysis, they find that eventually in what they call the "phase III" of the inflation surge, the positive demand shock following the reopening of the economy and the accommodating policies along side the cost-push shock caused by the energy crisis led to the unexpected rise in inflation. In a more recent VAR analysis, Ascari et al. (2024) echo Finck & Tillman (2022) findings on global supply chains as they find that shocks to these global supply chains were a key driver of the euro area post pandemic inflation surge and that these effects are persistent due to the complexity of global supply chains. Hence, they can be expected to add inflationary pressure despite the easing of supply bottlenecks. Furthermore, Banbura et al. (2023) also use a VAR model to examine the role of supply shocks (e.g. shocks to oil supply, gas price, global supply chains and labor supply) and find that supply shocks can in fact largely explain the post-pandemic inflation surge in the euro area.

Some papers such as Acharya et al. (2023) and Balleer & Noeller (2023) have also examined this through regression analysis. Acharya et al. (2023) focus on how supply shocks generalize to inflation in Europe and find that the interaction between supply chain pressures, increased inflation expectations, and firm pricing power played a key role in the increase in inflation. Acharya et al. (2023) find that supply-chain disruptions (material, labor and financial disruptions) induced inflation through cost-push channels[1] as well as through elevated household inflation expectations. More specifically, they find that supply chain constraints contributed both to PPI and CPI growth due to increased production costs of e.g. raw materials (the cost-push channel). Furthermore Acharya et al. (2023) argue that both witnessing these price increases caused by supply chain disruptions as well as seeing news about supply shocks increase inflation expectations and reduce the likelihood of households decreasing consumption in response to price increases (lower price elasticity of demand).

[1] Cost-push channel inflation refers to inflation that rises from increased production costs (Acharya et al., 2023)

3.4 Monetary Response to Adverse Supply Shocks

The literature discussed in the previous subsections show clear findings on the key role of supply constraints in the inflation surge but also highlights that a key contributor was the interaction between constrained supply and the positive demand shocks induced by expansionary policies. The role of positive demand shocks is beyond the scope of this thesis but in the light of policy implications, this subsection will introduce some literature that focuses on the monetary policy response during negative supply shocks.

The search for the best policy response to adverse supply shocks has been ongoing for decades due to the inflation-output trade-off associated with it. In economic literature, the optimal monetary response to supply shocks was first studied in the early 1970s in response to the adverse commodity supply and oil shocks (Gordon, 1984). One influential paper is by Clarida et al. (2000), where they argue that the 1970's oil shocks alone did not induce the persistent inflation but accommodating monetary policy played a critical role. Clarida et al. (2000) argue that the Federal Reserve's decision to keep interest rates low as a response to the raised inflation expectations in the 1970s caused persistent inflation. This has been echoed by e.g., Collard & Dellas (2008) who evaluate Clarida et al. (2000) work through an alternative specification to include misperceptions about the economy. However in contrast, economists such as Bernanke et al. (1997) analyzed the subsequent contractionary monetary policy and emphasized its negative effects on output.

This trade-off between responding to adverse supply shocks and slowing down economic recovery resurfaced in response to the post pandemic inflation (Beaudry et al., 2023). Currently it is often stated that the standard monetary policy response is to "look through" supply shocks (Bandera et al. 2023; Reis 2022). The reasoning behind this is that the effects of monetary policy occur with a lag (delay estimates vary, but generally peak effectiveness is reached 12-18 months after according to Bandera et al. (2023)) and hence reacting to supply shocks, which are often temporary price-level changes, is not necessarily the optimal response. However current literature (e.g. Bandera et al. 2023; Reis 2022) does note that looking through supply shocks is not always the best response. Bandera et al. (2023) emphasizes the role of second-round and real-income effects. Focusing on oil price shocks, Bandera et al. (2023) point out that when there are frictions such as real wage or relative-price resistance, then the monetary policy response might need to be contractionary. Bandera et al. (2023) also emphasizes the duration of supply shocks as a key determinant for the appropriate monetary response.

The relatively widely cited discussion paper by Reis (2022) presents an overview of the interaction between supply shocks and expansionary monetary policy during the pandemic era. Reis (2022) argues that the reason the above discussed supply constraints led to high inflation was the misdiagnosis of these adverse supply shocks and too long expansionary monetary policy. To analyse this factor, Reis (2022) uses the Phillips curve framework, which states that there are three direct channels that cause deviation from steady state inflation; household and firm inflation expectations, the deviation between real activity from the potential level of output, and costs and mark up shocks that cause gaps between potential and efficient levels of output. Reis (2022) claims that central banks interpreted the negative supply shocks following the pandemic as temporary mark up shocks, i.e. the third channel. This led to central banks taking the standard monetary policy response to temporary shocks - let inflation rise above target. Reis (2022) argues that this was a misdiagnosis of the nature of the shocks. He argues that the shocks were rather shocks that affected the potential level of output and hence inflation rose through the second channel. The appropriate monetary policy to the second channel inflation would have been contractionary measures to keep inflation on target.

Furthermore, Reis (2022) argues the energy price shock also led to household inflation expectations to become de-anchored. Central banks however continued to look through this shock, which Reis (2022) argues caused the price increase to have an oversized impact on inflation expectations, further increasing inflation. The discussion on whether inflation expectations did or did not de-anchor has been divided. There is some empirical evidence for the inflationary effects of the de-anchoring of inflation expectations during the pandemic era as Ascari, Fasani, et al. (2023) find evidence that shocks that increased inflation expectations caused an increase in inflation. Bernanke & Blanchard (2023) on the other hand has argued that inflation expectations did not de-anchor in the United States but short term expectations did increase enough to induce an upward pressure on wages and prices.

In another theoretical analysis, the above discussed paper Ascari et al. (2024) comes to similar conclusions as Reis (2022) as they find that in response to the adverse supply shocks, the optimal monetary response would be a contractionary policy. Ascari et al. (2024) argue that this is the case according to the Taylor rule as it shows that interest rates should be raised in response to global supply chain shocks. They claim that the intensity of the monetary response depends on the level of global value chain participation.

This unfavorable monetary policy trade-off between taming inflation versus maintaing the output gap during the pandemic has also been examined empirically by Harding et al. (2023). Using a DSGE model to examine the U.S., Harding et al. (2023) highlight that the trade-off becomes larger when inflation is elevated since cost-push shocks have an amplified effect when inflation is high as it was post-pandemic. Furthermore their findings indicate that keeping the federal funds rate so low for an extended period of time contributed to the surge in inflation in 2021. The above discussed paper by Fornaro & Wolf (2023) disagrees with these findings slightly as they find that in the medium run contractionary monetary policy can even increase inflation since high interest rates would further decrease investment (see Section 3.2 for more detailed discussion on the mechanisms found in this paper) and hence future productive capacity. Hence, they find that a policy mix of contractionary monetary policy combined with subsidies to firms' investment to help future productive capacity, could decrease prolonged inflation.

Furthermore, in a paper published in July 2024, Giannone & Primiceri (2024) use a Structural VAR model to find that both in the United States as well as in the euro area, expansionary monetary shocks played a large role in the inflation surge. They extend their analysis to similar counterfactual monetary policy response analysis as the one done in Harding et al. (2023) and in this thesis in Section 7. They find that if the ECB had followed a policy response that completely neutralized demand shocks, inflation would have only peaked at three percent however GDP would have cumulatively fell around four percent. In a scenario where the ECB would have conducted policy that keeps inflation at target, GDP would have fallen nearly five percent. The third scenario they analyze is one where the ECB would have followed its monetary policy rule from before the pandemic and therefore would have lifted interest rates earlier. They find that this scenario would have resulted in a six percent inflation increase (around three percent lower than what happened in reality) and GDP would been lower than it was in reality. Hence, this third scenario shows that the ECB's loose monetary policy after 2021 increased inflation by roughly three percent. According to Giannone & Primiceri (2024) this three percent higher inflation is the the cost paid for the faster recovery of the economy.

This section reviewed literature on the inflationary effects of supply constraints. Overall, there are clear findings that adverse supply chain disruptions played a key role in the inflation surge. The findings seem to hold globally. However, findings on the inflationary effects of negative productivity shocks and positive cost-push shocks in the euro area remain scarce. To the best current knowledge, no paper has directly examined both of these shocks, the most similar is Di Giovanni et al. (2023) who studied energy sector-specific total factor productivity shocks fed from the Russian energy sector and thus their analysis essentially captures an energy price shock. Hence, by analysing a productivity and cost-push shock, this thesis aims to provide further understanding on the inflationary effects of adverse supply shocks. This thesis also uses different data to Di Giovanni et al. (2023). Moreover, to the best of knowledge, the only two studies in the euro area to have used a DSGE model are Di Giovanni et al. (2022) and Di Giovanni et al. (2023) and hence this paper adds to literature by using a different DSGE model. Furthermore, this section briefly introduced some papers on the optimal monetary response to supply shocks. The findings show the difficulty of monetary policy as a response to shocks, highlighting the trade-off between stabilizing inflation versus maintaining the output gap. The only known paper examining this trade-off in the euro area is the recent publication by Giannone & Primiceri (2024). This thesis hence also aims to expand the understanding of the policy implications.

4 Theoretical Framework

This section will present a general theoretical overview of the mechanisms that underpin the analysis of this thesis. This section will first define some key concepts and then give a brief overview of the relevant theory through two different models. Through the first model, the most basic aggregate demand (AD) aggregate supply (AS) framework, this section will outline the theoretical inflationary effects of the different phases of the pandemic era shocks after which this section will present a more in depth theoretical analysis using the 3-equation model with policy responses considered.

This thesis defines supply shocks according to Blinder et al. (2008) as a shock that influences aggregate supply through affecting firms' ability to produce gross domestic products and hence directly affects the prices or quantities of factors of production or the production technology. This thesis considers two types of supply shocks; a productivity shock such as decrease in productivity caused by bottlenecks and a cost-push shock such as an energy price increase. A distinctive feature of supply shocks is that they move equilibrium price level and real output in opposite directions (Blinder et al., 2008). In contrast, demand shocks move equilibrium price levels and output in the same direction (Blinder et al., 2008).

4.1 The AD-AS Framework

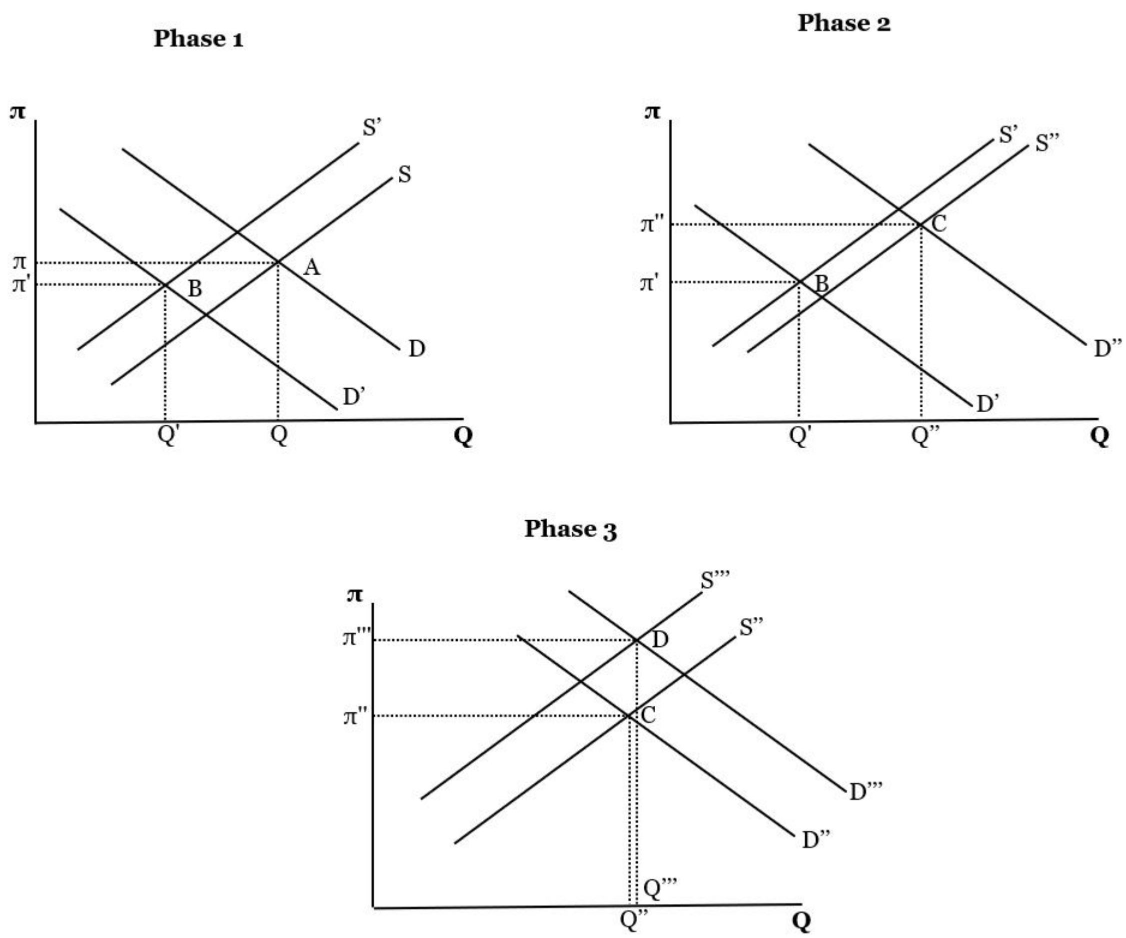
To first present a general overview of the different shocks through a theoretical lens, this subsection follows the simple analysis by Ascari, Bonomolo, et al. (2023). This framework is useful for showcasing how the interaction of the different pandemic era shocks described in the background section (see Section 2) affects inflation and output in an economy. Ascari, Bonomolo, et al. (2023) characterise the euro area pandemic shocks in to three phases: 1) the Covid shock, 2) the reopening of the economy and, 3) the post-reopening. These three phases can be seen analytically in Figure 1. In phase one the economy was hit by the simultaneous negative supply and demand shock, moving both aggregate curves to the left and the economy from point A to point B. In the euro area this translated into a slight decrease in inflation as the negative demand shock more than offset the negative supply shock as seen in the top left diagram. Phase two compromised of an increase of demand when economies reopened but with further negative supply shocks as global supply chain bottlenecks persisted. According to Ascari, Bonomolo, et al. (2023), aggregate supply recovered slightly despite remaining constrained and hence moving the AS curve towards the initial levels to S". The mismatch between constrained supply and demand caused the economy to move from B to C with increased inflation. In the final phase, phase three, global supply chains had partially recovered but in 2021 another adverse supply shock in the form of an energy shock hit the euro area and further accelerated in 2022 due to the war. This further moved the AS curve to the left while pent up demand continued to increase demand, pushing the AD curve further to the right. These shocks together moved the euro area economy into point D where inflation was even further from target. (Ascari, Bonomolo, et al., 2023)

4.2 The 3-Equation Model

As this thesis' policy implications regard the optimal monetary policy response, this subsection will expand the theoretical analysis to a framework, which includes the monetary authority. This subsection will outline a simple model through the commonly used 3-equation New Keynesian model. The 3-equations that form the model are the IS curve, which represents the demand side, the Phillips curve, which represents the supply side and the monetary policy rule (Carlin & Soskice, 2015, p.92). This subsection will first derive the basic 3-equation model according to Carlin & Soskice (2015) and then apply it the two negative supply shocks of interest; a productivity shock and a cost-push shock. As the focus of this thesis is on the latter phases of the pandemic (2021 onwards) and specifically the inflationary effects of supply shocks, this simple analysis does not take into account the effects of constrained or pent up demand but focuses on constrained supply.

In the 3-equation model, household's optimal allocation of consumption in equilibrium is modeled by the IS-curve. It depicts the negative relationship between output gap (y) and real interest rate (r) and is derived based on the assumption that interest rate negatively affects consumption and investment (Carlin & Soskice, 2015, p.18). In the formulated IS-curve (Equation (1)), it is seen that the interest rate (r_{t-1}) and exchange rate (q_{t-1}) in

Figure 1: AD-AS framework for the different shocks following the pandemic adapted from Ascari, Bonomolo, et al. (2023)



Notes: The figure shows three different phases of the pandemic era as defined by Ascari, Bonomolo, et al. (2023). It shows how over the course of the three phases, the economy moves from equilibrium in point A to point D with higher inflation.

the previous period, affect output in the current period, y_t. This is because it takes time for them to affect expenditure decisions (Carlin & Soskice, 2015, p.372). Carlin & Soskice (2015, p.324) formulates the open economy IS-curve as follows

$$y_t = A_t - ar_{t-1} + bq_{t-1}, \tag{1}$$

where A_t is exogenous demand, a determines the sensitivity to changes in interest rate and b determines how responsive aggregate demand is to exchange rate changes (Carlin & Soskice, 2015, p.18, p.342).

As stated by Carlin & Soskice (2015, p.68), the Phillips curve on the other hand depicts the relationship between inflation rate and output gap. Through the formulation of the Phillips curve below, it is seen that this period's inflation, π, is affected by the current output gap, $y_1 - y_e$, as well as last year's inflation, π_{t-1}. Hence the policy lag is visible in the Phillips curve. Carlin & Soskice (2015, p.66) formulates the PC-curve as follows

$$\pi_t = \pi_{t-1} + \alpha(y_t - y_e) \tag{2}$$

where $\alpha > 0$, creating a positively sloped Phillips curve. This is based on the assumption that the growth rate of nominal wage rate responds positively to output gap. (Carlin & Soskice, 2015, p.69)

The third and final part of the 3-equation model is the monetary policy rule. This rule depicts how a central bank determines their policy rate. A prominently used rule is the Taylor rule proposed by Taylor (1993). Using the Taylor rule, a central bank sets the policy rate in response to changes in the output gap as well as to deviations of inflation rate from target (Carlin & Soskice, 2015, p.477). One formulation (used by Carlin & Soskice (2015, p.482)) of the Taylor rule is

$$i_t = \bar{i} + \gamma(\pi_t - \pi^T) + \gamma_2(y_t - y_e), \tag{3}$$

where $\bar{i}$ is the nominal interest rate when inflation is at target and output is at equilibrium, γ_1 and γ_2 vary based on the central bank's weights.

4.3 Adverse Supply Shocks in the 3-Equation Model

These three equations can now be used to analyze the theoretical effects of the adverse supply shocks of the pandemic times. When examining these shocks theoretically, it is useful to introduce the wage and price setting curves to the framework. The Phillips curve is derived from the labor market model, more specifically the wage setting (WS) and price setting (PS) curves. The WS-PS framework lays out a labor market equilibrium at the intersection of the two curves where both wage and price setters have no incentive to change their behaviour. The Phillips curve is then used to analyze how the labor markets adjust when the economy is hit with shocks. (Carlin & Soskice, 2015)

The wage setting curve defines the wage for a given rate of unemployment. As in Carlin & Soskice (2015, p.65), this subsection will utilize the linear WS curve, expressed as follows

$$w^{WS}(y_t) = B + \alpha(y_t - y_e) - z_w, \tag{4}$$

where B is a constant, denoting the unemployment benefit, z_w is the wage-push factors.

The PS curve on the other hand shows that prices are set as a markup on costs of labor and it is expressed as follows according to Carlin & Soskice (2015, p.61)

$$w^{PS} = \frac{W}{P} = \frac{\lambda}{1+\mu} \tag{5}$$

where W is is the nominal wage rate, P is the profit maximizing price, λ is labor productivity, μ is the fixed percentage mark up of labor costs.

Now the negative productivity shock as well as a negative cost-push shock can be analyzed using these equations. First, using the price-setting curve, a decrease in productivity, λ, (while holding other variables constant) can be represented by $\lambda - \Delta\lambda$. Substituting this into the price-setting curve (Equation (6)) shows that prices will increase as the denominator decreases and consequently real wage decreases.

$$w^{PS} = \frac{W}{P} = \frac{\lambda - \Delta\lambda}{1+\mu} \iff P = \frac{W(1+\mu)}{\lambda - \Delta\lambda} \tag{6}$$

Similarly, a cost-push shock can be analyzed through the same PS equation. A positive cost-push shock such as a increase in oil prices naturally causes the costs of production to go up, causing firms to increase their markup, μ (Carlin & Soskice, 2015, p.390). This can be represented by $\mu + \Delta\mu$. Substituting the increased markup into the price setting curve (Equation (7)) shows the same effects as in the productivity shock - prices increase and real wages lower.

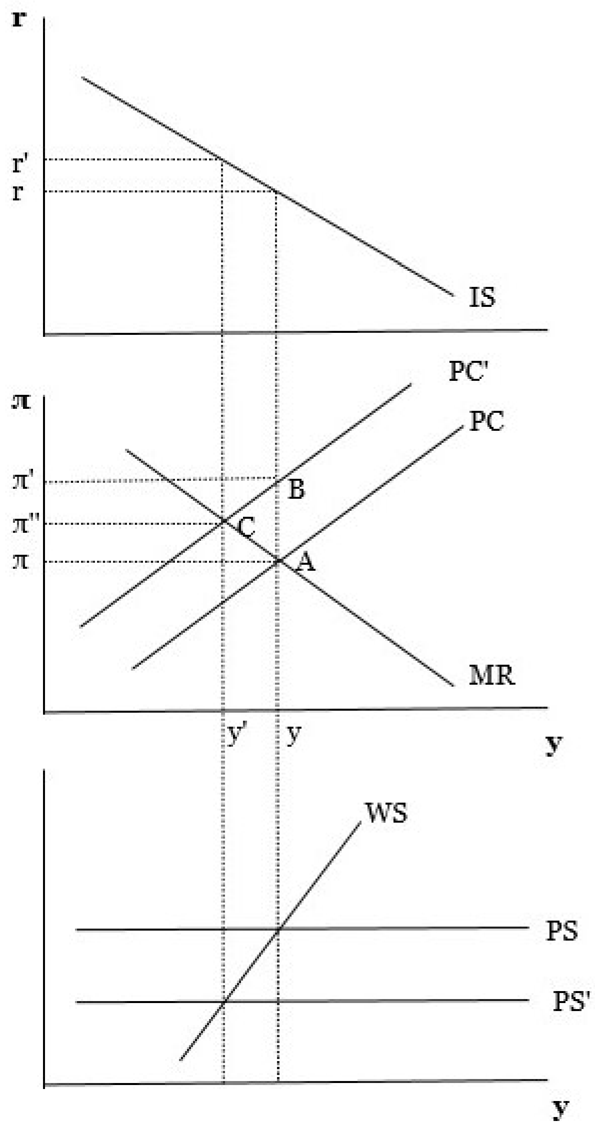
$$\frac{W}{P} = \frac{\lambda}{1 + (\mu + \Delta\mu)} \tag{7}$$

In Figure 2 these adverse supply shocks are presented graphically. This graphical representation is adapted from Carlin & Soskice (2005). As the economy is hit with a negative supply shock such as the productivity or oil shock analyzed above, causing the price setting curve to shifts downwards and consequently the Phillips curve shifts up from equilibrium (point A). As seen in the middle panel of Figure 2 this causes both inflation and output to decrease. This moves the economy to point B.

For the latter discussion on the policy implications of the findings of this thesis, it is important to theoretically understand the role that monetary policy has in combating adverse supply shocks. According to the above specified Taylor rule, an increase in inflation should move the policy rate up. The graphical analysis in Figure 2 also shows that according to this theoretical model, the optimal monetary response would be to increase interest rates to r'. This would move the economy to point C where inflation is lower and output has decreased. Hence, according to this New Keynesian framework adapted from Carlin & Soskice (2005) and Carlin & Soskice (2015), monetary policy could decrease inflation by contracting economic activity through increasing interest rates with the cost of decreasing output. This ties back to the inflation-output trade-off discussed in Section 3. Responding to supply shocks imposes a trade-off between taming inflation and avoiding a recession (Madeira et al., 2023) due to the fact outlined before that during supply shocks inflation and the output gap move in opposite directions.

This section showed how according to theory, adverse supply shocks will increase inflation. The analysis showed that both a negative productivity shock as well as a positive cost-push shock induce inflation through pushing the price setting curve down. Furthermore, this section demonstrated that, within the 3-equation framework, the appropriate monetary response to tame inflation resulting from adverse supply shocks would be to raise interest rates. This would be done at the cost of output decreasing. It is hence important to note here that the presented Taylor rule is just an approximation and the reality of setting central bank interest rates is a complex task, composing of various variables. According to the current Deputy Director General of ECB's Directorate General Monetary policy, Kamps (2024), ECB's current reaction function is based on four key aspects; 1) the outlook of inflation, 2) underlying dynamics of inflation, 3) how strong monetary policy transmission is, and 4) long-term inflation expectations. All in all, this section gave an overview of the mechanism that underpin the subsequent empirical analysis.

Figure 2: Adverse supply shock in the 3-equation model adapted from Carlin & Soskice (2005)



Notes: The figure shows a graphical representation of the 3-equation model when an adverse supply shock hits the economy. It shows how the economy moves from equilibrium, A, to point B when the shock hits and finally to point C if the interest rate is raised. The graphical representation is adapted from Carlin & Soskice (2005).

5 The Model

This section presents the model used in the empirical analysis. To study the inflationary effects of the adverse supply shocks this thesis replicates the linear model analysis of the paper "Understanding Post-Covid Inflation Dynamics" by Harding et al. (2023). Their paper uses data from the United States to examine the post-covid inflation dynamics and this thesis will use recent euro area data. The dynamic stochastic general equilibrium (DSGE) model used by Harding et al. (2023) builds on the commonly used Smets & Wouters (2007) workhorse model. As explained by Del Negro & Schorfheide (2013), DSGE models are widely used in macroeconomics to explain as well as predict the co-movement of different time series over a business cycle. They are also used to perform policy analysis. One strand of DSGE models, which this thesis' model also belongs to is the New Keynesian monetary models. In these models, economic agents' decision rules are derived by solving intertemporal optimization problems, which are based on assumptions about preferences, technologies and policy regimes. Differing from neoclassical growth models, New Keynesian DSGE models also include price and wage rigidities, consumption habit formation and investment adjustment costs. These features result in empirical models which are highly coherent with theory and hence provide a good tool for policy experiments. Therefore, estimated DSGE models have also increasingly become a tool used by central banks to conduct macroeconomic forecasting and policy analysis. (Del Negro & Schorfheide, 2013) This section will first provide an overview of the Harding et al. (2023) model after which, this section will describe in detail the different agents of the model. To explain the model, this section refers mainly to the appendix materials of Harding et al. (2023) and as support to the appendix materials of Harding et al. (2022) and Smets & Wouters (2007).

5.1 Model Overview

The Harding et al. (2023) model is based on the benchmark Smets & Wouters (2007) model. This DSGE model features seven different structural shocks. There are two intertemporal margin shocks: a risk premium shock and an investment-specific shock. There are also two intratemporal margin shocks: a wage and a price mark-up shock. Two policy shocks are also included, these are an exogenous spending shock and a monetary policy shock. Finally, the model includes a total productivity shock.(Smets & Wouters, 2007) The model features monopolistic competition in the goods market as well as the labor market. Moreover, this model features both real and nominal frictions. The real rigidities of the model are consumption habit formation, investment adjustment costs, variable capital utilization, and production fixed costs. The nominal frictions appear through sticky prices and wages but this model does allow non-optimizing firms to adjust prices and households to adjust wages based on steady-state and lagged inflation (inflation indexation). (Harding et al., 2023)

The stochastic dynamics of this model root from the aforementioned seven shocks. Both policy shocks, both intertemporal margin shocks as well as the total productivity shocks follow an AR(1) process[2]. The two intratemporal margin shocks (wages and price mark-up shocks) follow an ARMA(1,1) process[3]. (Harding et al., 2023) The key modification to the workhorse model made by Harding et al. (2023) is the introduction of the zero lower bound (ZLB) condition.

Like the three equation model utilized earlier, this model contains the supply side, demand side and the monetary policymaker. The key agents of the model are the final-goods producers, intermediate-goods producers, labor contractors, households and the monetary agent. This section will next explain each agent's optimization problems in the model following the formulation done by Harding et al. (2023).

5.2 Firms and Price Setting

In the Harding et al. (2023) model there are final-goods producers and intermediate-goods producers. Final-goods producers use intermediate goods produced by the intermediate-goods producers to produce output goods. This subsection will first describe the problem of final-goods producers and then the problem of intermediate-goods producers.

[2]The AR(1) process refers to first-order autoregressive process (Box et al., 2008, p.53)

[3]The ARMA(1,1) process refers to the mixed autoregressive-moving average process of order (1,1) (Box et al., 2008, p.54)

5.2.1 Production of Final Goods

In the Harding et al. (2023) model, firms produce a final output good, Y_t. To produce this good, they use a continuum of differentiated intermediate goods, $Y_(f)$. To introduce price rigidities in price setting, the process for turning these intermediate goods into final goods follows Kimball (1995, as cited in Harding et al. 2023) according to the following equation

$$\int_0^1 G_Y\left(\frac{Y_t(f)}{Y_t}\right) df = 1, \tag{8}$$

where $G_Y(\frac{Y_t(f)}{Y_t}$ is the Kimball aggregator[4] used in Dotsey and King (1995, as cited in Harding et al. 2023). It is expressed as follows

$$G_Y\left(\frac{Y_t(f)}{Y_t}\right) = \frac{\phi_p}{1-(\phi_p-1)\epsilon_p}\left[\left(\frac{\phi_p+(1-\phi_p)\epsilon_p}{\phi_p}\right)\frac{Y_t(f)}{Y_t} + \frac{(\phi_p-1)\epsilon}{\phi_p}\right]^{\frac{1-(\phi_p-1)\epsilon_p}{\phi_p-(\phi_p-1)\epsilon_p}} + \left[1-\frac{\phi_p}{1-(\phi_p-1)\epsilon_p}\right], \tag{9}$$

where $\phi_p \geq 1$ denotes intermediate firms' gross markup, ϵ_p is the elasticity of substitution and hence determines the shape of the firm's demand curve. In this model, $\epsilon_p > 0$, meaning elasticity is not constant and as a result price setting has more strategic complementary[5]. On the contrary, if $\epsilon_p = 0$, the firm's demand curve would have constant elasticity. This would be the case if the Dixit-Stiglitz aggregator was used instead of the the Kimball aggregator. (Harding et al., 2023)

In this model, firms are price takers for the intermediate goods, $Y_t(f)$, and hence take the given price, $P_t(f)$. They maximize the following problem subject to the technology constraint expressed in Equation (8)

$$\max_{Y_t, Y_t(f)} P_t Y_t - \int_0^1 P_t(f) Y_t(f) df, \tag{10}$$

[4]The Kimball aggregator is often used in New Keynesian models. It introduces properties that lower the price sensitivity to marginal cost for a certain price-stickiness level. This differs from the standard aggregator used, the Dixit-Stiglitz aggregator, which has constant elasticity of substitution. (Harding et al., 2023)

[5]Strategic complementary refers to a situation where one agent choosing higher strategies incentivizes other players to choose higher strategies (Cornand & Heinemann, 2022). This reduces the sensitivity of prices to changes in marginal cost and hence increases the real effects of monetary disruptions.(Levin et al., 2007)

where P_t is the price that the firm sells their final good at.

5.2.2 Production of Intermediate Goods

In the Harding et al. (2023) model, monopolistically competitive intermediate-goods producers utilize capital services and a labor index to produce a continuum of intermediate goods, $Y_t(f)$ for $f \in [0, 1]$. Intermediate producers hence face the following Cobb-Douglas production function

$$Y_t(f) = \epsilon_t^a K_t(f)^\alpha [\gamma^t L_t(f)]^{1-\alpha} - \gamma^t \Phi, \tag{11}$$

where ϵ_t^a denotes total factor productivity, $K_t(f)$ denotes capital services, $L_t(f)$ the labor index, γ^t denotes the labor-augmenting growth rate and Φ the fixed costs.

The total productivity, ϵ_t^a, is given by the following AR(1) process

$$\ln \epsilon_t^a = (1 - \rho_a) \ln \epsilon^a + \rho_a \ln \epsilon_{t-1}^a + \eta_t^a, \eta_t^a \sim N(0, \sigma_a), \tag{12}$$

where ρ_a defines the persistence of the productivity shock, η_t^a denotes the technology disturbance and σ_a the standard deviation of the shock distribution.

In this model, intermediate producers' price setting follows Calvo (1983, as cited in Harding et al. 2023) style pricing. Hence, the probability that a firm reoptimizes their price is $1 - \xi_p$. As stated by Harding et al. (2023), this probability is independent of the last time the specific firm reset its prices. The rest of the firms adjust their prices based on lagged and steady-stated rate of inflation, $P_t(f) = (1 + \pi_{t-1})^{\iota_p} (1 + \pi)^{1-\iota_p} P_{t-1}(f)$, where π_{t-1} is net inflation in period $t - 1$, π is steady state net inflation and $0 \leq \iota_p \leq 1$ is the price indexation.

Furthermore, in the Harding et al. (2023) model, firms face a perfectly competitive market for both factors of their production. The market for renting capital is perfectly competitive and they rent at price R_{Kt}. They also face a perfectly competitive market for hiring labor and hence hire labor at the price determined by the wage index W_t (see Section 5.3.1). Firms can costlessly adjust either of these factors of production (capital or labor) and hence, the marginal cost, MC, for each output unit is identical for all firms. Thus, the intermediate firms optimize profits according to the following maximization problem:

$$\max_{\tilde{P}_t(f)} E_t \sum_{j=0}^{\infty} (\beta\xi_p)^j + \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} \left[\tilde{P}_t(f)(\Pi_{s=1}^{j}(1+\pi_{t+s-1})^{\iota_p}(1+\pi^{1-\iota_p}) - MC_{t+j} \right] Y_{t+j}(f), \quad (13)$$

where $\tilde{P}_t(f)$ is the new price and $\frac{\beta \Xi_{t+j} P_t}{\Xi_t P_{t+j}}$ is the nominal discount factor. Additionally, the model introduces a price markup shock, ϵ_t^p in the first order condition of the maximization problem and assumes that the shock follows the subsequent exogenous ARMA(1,1) process

$$\ln \epsilon_t^p = (1-\rho_p)\ln \epsilon^p + \rho_p \ln \epsilon_{t-1}^p + \eta_t^p - \mu_p \eta_{t-1}^p, \eta_t^p \sim N(0, \sigma_p), \quad (14)$$

where ρ_p defines the persistence of the shock, η_t^p denotes the disturbance and σ_p the standard deviation of the shock distribution.

5.3 Households and Wage Setting

In the Harding et al. (2023) model, there is a continuum of monopolistically competitive households. Each supply labor services to the production sector. The production sector perceives that a household's labor services, $L_t(h), h \in [0,1]$ are imperfect substitutes to the other households' labor services. In the model, it is convenient to think that there are labor contractors, which aggregate labor from different households. This subsection will first introduce the labor contractors' problem followed by the households' problem and finally the wage setting.

5.3.1 Labor Contractors

In the Harding et al. (2023) model, labor contractors aggregate labor hours from households. Like on the production side, real rigidities are introduced on the demand side through the Kimball aggregator. The aggregated labor index, L_t hence takes the following form:

$$L_t = \int_0^1 G_L\left(\frac{L_t(h)}{L_t}\right) dh = 1, \quad (15)$$

where $G_L\left(\frac{L_t(h)}{L_t}\right)$ is the Kimball aggregator and has the same functional form as the Kimabll aggregator of the production side (Equation (9)) but the curvature of the demand curve is determined instead by ϵ_w and instead of gross price markup includes the gross wage markup parameter, ϕ_w. Subject to this constraint, the contractors minimize their production costs for given the aggregate labor index, L_t. The households' wage rate, $W_t(h)$ is given and the aggregators sell units of the labor index at unit cost W_t to the intermediate-goods producers. (Harding et al., 2023)

5.3.2 Households

In the Harding et al. (2023) model, the three components of the utility function of a representative household member are current consumption, lagged aggregate per capita consumption and their hours worked. The utility function of household, h is

$$E_t \sum_{j=0}^{\infty} \beta^j \left[\frac{1}{1-\sigma_c} (C_{t+j}(h) - \kappa C_{t+j-1} \right]^{1-\sigma_c} exp \left(\frac{\sigma_c - 1}{1+\sigma_l} L_{t+j}(h)^{1+\sigma_l} \right), \tag{16}$$

where $0 < \beta < 1$ is the discount factor. $C_t(h)$ denotes household $h's$ current consumption, κ denotes external habit persistence, C_{t+j-1} is the lagged aggregate per capita consumption and $L_t(h)$ denotes hours worked.

A household, h, has a budget constraint that limit's its period utility:

$$\begin{aligned} P_t C_t(h) + P_t I_t + \frac{B_{t+1(h)}}{\epsilon_t^b R_t} + \int \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h) \\ = B_t(h) + W_t(h) L_t(h) + R_t^k Z_t(h) K_t^p(h) - a(Z_t(h)) K_t^p(h) + \tau_t(h) - T_t(h), \end{aligned} \tag{17}$$

where the household purchases goods at price, P_t. The household then either consumes the good, $C_t(h)$, or invests $I_t(h)$ in physical capital. This budget constraint shows that the household's spending on goods and financial assets (left hand side of the equation) has to equal it's income (right hand side of the equation). The remaining components of the budget constraint are discussed next.

As for financial assets, according to Christiano, Eichenbaum and Evans (2005, as cited in Harding et al. 2023) investment increases household's end of period physical capital stock, $K_{t+1}^p(h)$, as follows

$$K_{t+1}^p(h) = (1-\delta) K_t^p(h) + \epsilon_t^i \left[1 - S\left(\frac{I_t(h)}{I_{t-1}(h)} \right) \right] I_t(h), \tag{18}$$

where ϵ_t^i is an exogenous investment shock, which determines how the investment by household, h, turns into physical capital. The shock follows the subsequent AR(1) process

$$\ln \epsilon_t^i = \rho_i \ln \epsilon_{t-1}^i + \eta_t^i, \eta_t^i \sim N(0, \sigma_i), \tag{19}$$

where ρ_i defines the persistence of the shock, η_t^i denotes the disturbance and σ_i the standard deviation of the shock distribution.

As seen in Equation (18), the change in a household's rate of investment is on the other hand determined by the function $S\left(\frac{I_t(h)}{I_{t-1}(h)}\right)$, which takes the following form

$$S\left(\frac{I_t(h)}{I_{t-1}(h)}\right) = \frac{\varphi}{2}\left(\frac{I_t(h)}{I_{t-1}(h)} - \gamma\right)^2, \tag{20}$$

where φ denotes the investment adjustment cost and γ is a deterministic trend variable.

In addition to physical capital, in the Harding et al. (2023) model, households can also obtain government nominal bond holdings, B_{t+1}. Holding these bonds earns households an interest rate, R_t and this return has a risk shock, ϵ_t^b. The risk shock takes the following form:

$$\ln \epsilon_t^b = \rho_b \ln \epsilon_{t-1}^b + \eta_t^b, \eta_t^b \sim N(0, \sigma_b), \tag{21}$$

where ρ_b defines the persistence of the shock, η_t^b denotes the disturbance and σ_b the standard deviation of the shock distribution.

To decrease idiosyncratic risk, in the model, agents can participate in trading of contingent claim bonds. In the budget constraint, the term $\int \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h)$ denotes the net purchases of these bonds. Here $\xi_{t,t+1}$ denotes the price and $B_{D,t+1}(h)$ the quantity purchased at time t.

Turning to the income side of the budget constraint, the Harding et al. (2023) model specifies that each member of household h earns income. They earn after-tax labor income, $W_t(h)L_t(h)$, a share of firm profits, $\tau_t(h)$, and after-tax capital rental income, $R_t^k Z_t(h) K_t^p(h)$. Here R_t^k denotes the rental rate for capital that households can rent to firms. The amount of physical capital that households can rent is given by $K_t(h) = Z_t(h)K_t^p(h)$. Household members have to pay a utilization cost for this physical capital, $a(Z_t(h))K_t^p(h)$. Here $Z_t(h)$ is the capital utilization rate and $a(Z_t(h))$ is the capital utilization adjustment function. The capital utilization adjustment function is expressed as follows

$$a(Z_t(h)) = \frac{r^k}{\tilde{z}_1}[exp(\tilde{z}_1(Z_t(h) - 1)) - 1], \tag{22}$$

where r^k denotes net real interest rate in the steady state of the model. In addition to paying the above specified utilization cost, each household member also pays a lump sum tax, $T_t(h)$.

In summary, in the (Harding et al., 2023) model, each household, h, representative member maximizes utility (Equation (16)) in each period t with respect to six aspects: 1) consumption, 2) investment, 3) physical capital stock, 4) capital utilization rate, 5) bond holdings and, 6) contingent claim holdings. Utility is maximized subject to three constraints: 1) its labor demand function (derived from the optimization of the labor contractor's problem), 2) the budget constraint (Equation (17)), and, 3) the capital transition equation (18).

5.3.3 Wage Setting

In the Harding et al. (2023) model, households face a standard monopoly problem of setting wages in order to maximize utility. Households set nominal wages according to Calvo (1983, as cited in Harding et al. (2023)). These are staggered contracts, similar to those in price-setting described for the production side, where the probability that a household re-optimizes its wage contract in a certain period is given by $1 - \xi_w$. For households that cannot re-optimize, their wages adjust according to the following indexation scheme for wage adjustment: $W_t(h) = \gamma(1 + \pi_{t-1})^{\iota_w}(1 + \pi)^{1-\iota_w} W_{t-1}(h)$.

This leads to the household wage-setting optimization problem, which takes the following form:

$$\max_{\tilde{W}_t(h)} E_t \sum_{j=0}^{\infty} (\beta\xi_w)^j + \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} [\tilde{W}_t(h)(\Pi_{s=1}^{j} \gamma(1 + \pi_{t+s-1})^{\iota_w}(1 + \pi^{1-\iota_w}) - W_{t+j}] L_{t+j}(h), \quad (23)$$

where $\tilde{W}_t(h)$ is the new wage and $\frac{\beta \Xi_{t+j} P_t}{\Xi_t P_{t+j}}$ is the nominal discount factor.

A wage markup shock, ϵ_t^w, is introduced in the first-order condition of the household maximization problem. It follows the subsequent exogenous ARMA(1,1) process

$$\ln \epsilon_t^w = (1 - \rho_w) \ln \epsilon^w + \rho_w \ln \epsilon_{t-1}^w + \eta_t^w - \mu_w \eta_{t-1}^w, \eta_t^w \sim N(0, \sigma_w), \quad (24)$$

where ρ_w defines the persistence of the shock, η_t^w denotes the disturbance and σ_w the standard deviation of the shock distribution.

5.4 Monetary Policy

In the Harding et al. (2023) model, the monetary authority adjusts the interest rate according to the Taylor rule (Taylor, 1993). In this model, the policy rule takes the ZLB into account and is expressed as follows

$$R_t = \max\left[1+\bar{b}, R_{t-1}^{\rho_R}\overline{R}^{(1-\rho_R)}\left(\frac{\pi_t}{\overline{\pi}}\right)^{(r_\pi)(1-\rho_R)}\left(\frac{y_t}{y_t^{pot}}\right)^{(r_y)(1-\rho_R)}\left(\frac{y_t/y_t^{pot}}{y_{t-1}/y_{t-1}^{pot}}\right)^{r_{\Delta y}}\epsilon_{r,t}\right], \quad (25)$$

where R is the interest rate, $\bar{b} > 0$ reflects the effective lower bound (ELB). This value is set as a constant to reflect the economic area's ELB (see Section 6 for ELB value set for the euro area). Variable ρ_R denotes the degree of interest rate smoothing, and y_t^{pot} denotes the output that would exist without the inefficient monetary policy and markup shocks. Variable ϵ_r represents a monetary shock and it follows an AR(1) process.

5.5 Market Clearing Conditions

The final aspect of the Harding et al. (2023) model is the market clearing condition on the total output of the goods market, which is as follows:

$$Y_t = C_t + I_t + G_t + a(Z_t)\bar{K}_t, \quad (26)$$

where, $a(Z_t)\bar{K}_t$ denotes the capital utilization adjustment cost defined above and G_t denotes government purchases. In this model, government purchases, G_t are exogenous. The exogenous process for government spending follows the subsequent AR(1) process

$$\ln g_t = (1-\rho_g)\ln g + \rho_g(\ln g_{t-1} - \rho_{ga}\ln \epsilon_{t-1}^a) + \epsilon_t^g, \epsilon_t^g \sim N(0,\sigma_g), \quad (27)$$

where ρ_g defines the persistence of a government spending shock, η_t^g denotes the disturbance, σ_g the standard deviation of the shock distribution, and as defined by Smets et al. (2014), ρ_{ga} denotes the effect of total factor productivity on exogenous spending. In this model, the government uses lump-sum taxes to balance its budget. As Ricardian equivalence[6] holds in this model, the lump-sum taxes are irrelevant and hence the government budget and fiscal rule for lump-sum taxes are not further explained. (Harding et al., 2023)

[6]Ricardian Equivalence assumes that consumers adjust their behaviour with the understanding that the government balances their budget overtime and hence government fiscal policy through taxes/increased borrowing does not affect total demand in the economy (Bernheim, 1987).

6 Calibration

This section explains the calibration of the model to represent the euro area in the beginning of 2021. The model is partly calibrated based on prior literature and partly estimated using seven macroeconomic time series using Harding et al. (2022) replication package, which uses the MATLAB programming tool and the Dynare extension. Dynare contains a collection of MATLAB routines which are used to solve linearized dynamic models (Harding et al., 2023). This section will first explain the data used and then the calibration and estimation of the model.

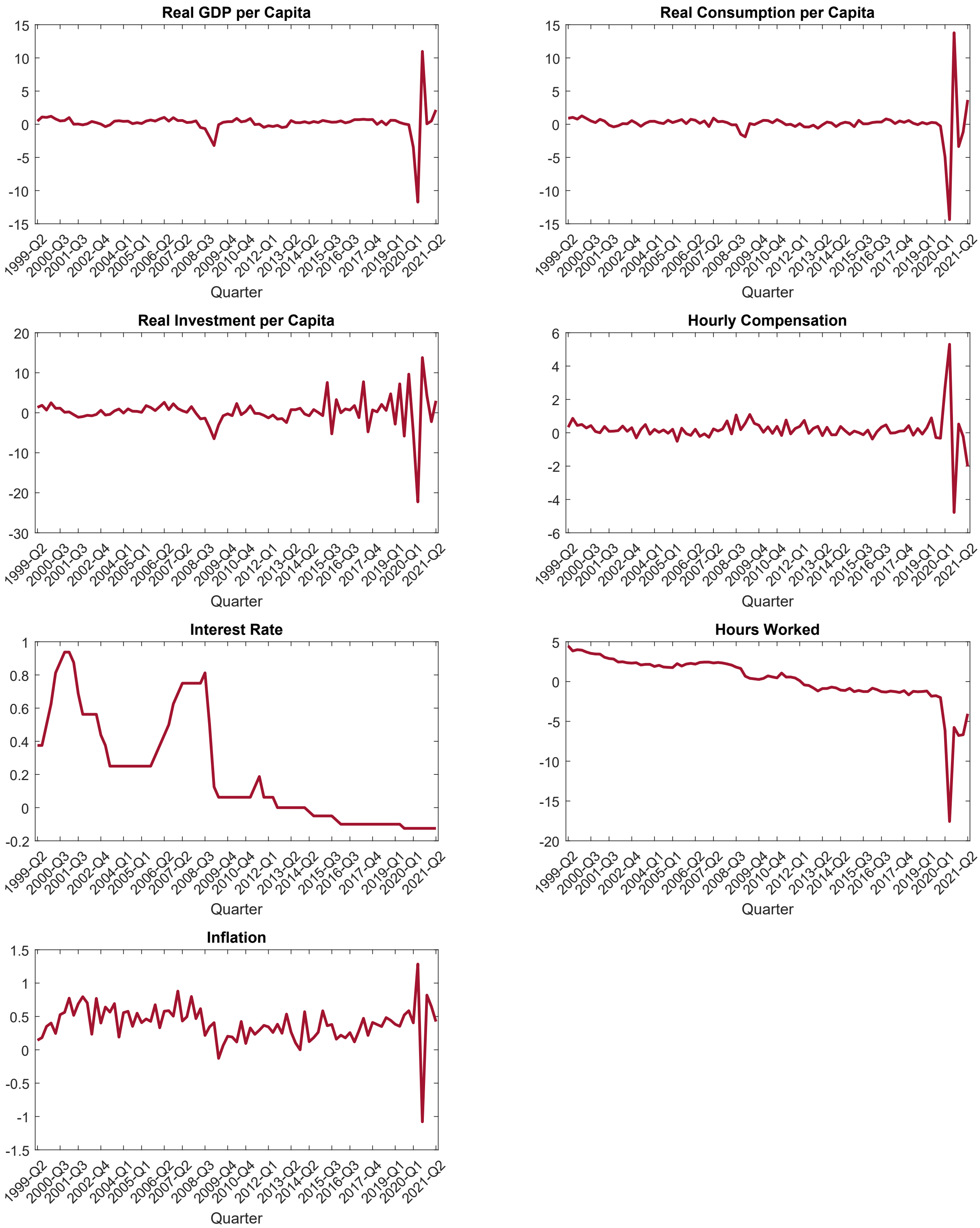
6.1 Data

In order to run the simulations, the DSGE model is first calibrated and estimated to characterise the euro area as accurately as possible. Following Harding et al. (2023), the model is estimated using the following seven macroeconomic quarterly time series: GDP, consumption, investment, worked hours, unit labor costs, GDP deflator inflation, interest rate. These timeseries are retrieved from ECB's database except the population data[7] is retrieved from OECD. The population data is used to express the real data in per capita terms. GDP, consumption, investment and wage data are deflated using the GDP deflator to achieve real values. All real variables are then transformed to log-differences. Worked hours are transformed to the log difference of the mean. Moreover, employment data from the ECB database is used to divide hours worked into hours worked per person[8]. See the Appendix Table 1 for the specifics of the data. Figure 3 shows the log-differentiated seven time series. This figure highlights the economic shocks induced by the pandemic; there are sharp drops in the growth rates of GDP, consumption and real investment per capita in 2020 and the fast recovery of GDP and consumption in the beginning of 2021.

[7]Population data covers the whole euro area population since quarterly population labor force population in the euro area could not be found from before 2005.

[8]For full data processing, see the code file dataedit.m in the code zip-folder.

Figure 3: Macroeconomic variable timeseries expressed in growth rates



Notes: The figure shows the seven key euro area macroeconomic variables used to solve the DSGE model. The variables are expressed in growth rates. The data is from the ECB Database and OECD. The computations are done by the author of this thesis.

6.2 Calibration

The parameters of this DSGE model are partly calibrated and partly parameterized. Calibration means setting values for the model parameters based on previous results and theory. The parameterization is done using the same estimation procedure as Harding et al. (2023). Harding et al. (2023) adopt the same Bayesian estimation procedure as the workhorse Smets & Wouters (2007) model. Bayesian estimation begins with a prior distribution for parameters that depicts the available information of the parameters before observing the data (Harding et al., 2023).

This paper will use the same priors as Harding et al. (2023). Using the same priors for the euro area and the U.S. is a standard procedure when there are many parameters to estimate as argued by Smets et al. (2014). As the estimation is a re-estimation of the workhorse Smets & Wouters (2007) model, the priors are taken from the workhorse model with a few modifications to three pricing parameters $(\phi_p, \epsilon_p, \xi_p)$, following Harding et al. (2023). To have a lower gross markup in the model, the steady-state price markup prior is altered to have a lower mean and standard deviation $\phi_p \sim N(1.2, 0.05)$. This is done as Harding et al. (2023) argue that recent literature has found that markups are significantly lower than the estimated 61% by Smets & Wouters (2007). Additionally, the Kimball curvature parameter's prior is altered to $\epsilon_p \sim N(75, 25)$. Finally, Calvo probability prices are altered to $\xi_p = 0.667$, which means that on average prices change every three quarters. See table 1 for a full list all priors.

Like in Smets & Wouters (2007) and following Harding et al. (2023), the depreciation rate, δ, is also calibrated to a fixed value of 0.025. This implies the annual depreciation rate of capital is 10 percent. Furthermore, according to Harding et al. (2023), gross wage markup, ϕ_w, is calibrated to 1.50, government G/Y ratio, g_y, is calibrated to 0.18 and the Kimball Elasticity of wages, ϵ_w, is calibrated to 10. These are aligned with euro area calibrations of the model as well (see e.g. Smets et al. (2014)).

The rest of the parameters, which are not calibrated are estimated based on data via Bayes' theorem to achieve a posterior distribution from their priors. To update these priors, a script from Harding et al. (2022) is used. Harding et al. (2023) use this script to estimate their parameters. Using this script, this thesis re-estimates the Smets & Wouters (2007)

Table 1: Prior values as in Harding et al. (2023)

Parameter	Distribution	Mean	St. Dev.
φ	Normal	4.00	1.50
σ_c	Normal	1.50	0.375
κ	Beta	0.70	0.10
ξ	Beta	0.50	0.10
σ_l	Normal	2.00	0.75
ϵ_p	Normal	75.00	25.00
ι_w	Beta	0.50	0.15
ι_p	Beta	0.50	0.15
α	Normal	0.30	0.05
ψ	Beta	0.50	0.15
Φ_p	Normal	1.25	0.125
γ	Normal	0.40	0.10
π	Gamma	0.625	0.10
β	Gamma	0.25	0.10
ρ_R	Beta	0.75	0.10
$r_{\Delta y}$	Normal	0.125	0.05
r_y	Normal	0.125	0.05
r_π	Normal	1.50	0.25
ρ_a	Beta	0.50	0.20
ρ_b	Beta	0.50	0.20
ρ_g	Beta	0.50	0.20
ρ_i	Beta	0.50	0.20
ρ_p	Beta	0.50	0.20
ρ_w	Beta	0.50	0.20
ρ_r	Beta	0.50	0.20
ρ_{ga}	Normal	0.50	0.25
μ_p	Beta	0.50	0.20
μ_w	Beta	0.50	0.20
σ_a	Inv. Gamma	0.10	2.00
σ_b	Inv. Gamma	0.10	2.00
σ_g	Inv. Gamma	0.10	2.00
σ_i	Inv. Gamma	0.10	2.00
σ_p	Inv. Gamma	0.10	2.00
σ_w	Inv. Gamma	0.10	2.00
σ_r	Inv. Gamma	0.10	2.00

Note: The table shows the prior values of the structural parameters. These values are those used by Harding et al. (2023). The use of same priors for the euro area and the U.S. is a standard procedure when there are many parameters to estimate as argued by Smets et al. (2014)

model with euro area data from 1999Q2-2007Q4 with the above mentioned modified priors. To ensure correct parameterization, the obtained posterior parameter estimates are then compared to those obtained in Smets et al. (2014) and Smets & Wouters (2002), which are both variations of the workhorse model estimated on euro area data. Parameters that differ greatly are adjusted based on the values of Smets et al. (2014) and Smets & Wouters (2002). This is done as the sample used for the estimation is relatively constrained (only 8 years) and hence the estimates might not represent the euro area completely accurately.

The investment adjustment cost, φ is estimated to be 5.65. The inverse of the intertemporal substitution elasticity, σ_c is estimated to be 0.39. The degree of external habit formation, κ, is set as 0.65. The Calvo probability wages, ξ_w is set as 0.74. This is slightly higher than the Calvo parameter for prices, which means that wages are relatively rigid compared to prices. The labor supply elasticity, σ_l is estimated to be 2.39. Using the adjusted prior distribution for Kimball elasticity of prices it is estimated to be 73.3, which is slightly higher than estimated by Harding et al. (2023) for the US. The price indexation, ι_p and wage indexation, ι_w, are both set as 0.22. The capital production share, α, is estimated to be 0.21. The capital utilization cost, ψ is set to be 0.46. The gross price markup, ϕ_p is estimated as 1.34. The steady-state gross growth, γ, is set as 0.14 and the steady-state net inflation rate as 0.55. The discount factor, β is set as 0.24. The Taylor rule interest rate smoothing parameter, ρ_R is estimated to be 0.82. The Taylor rule coefficient for change in output gap, $r_{\Delta y}$ is estimated to be 0.18 and the Taylor rule coefficient for the output gap, r_y is set as 0.15. The Taylor rule coefficient of inflation, r_π gets the value 1.67.

The shock process autoregressive parameters are also estimated and adjusted based on Smets et al. (2014) and Smets & Wouters (2002). The autoregressive parameter for the neutral technology shock, ρ_a, obtains the value 0.97. The risk premium shock, ρ_b, obtains the value 0.91. The government spending shock, ρ_g, obtains the value 0.99. The investments specific technology shock, ρ_i, is estimated as 0.45. The price markup shock, ρ_p, is set as 0.56 whilst the wage markup shock, ρ_w, is estimated as 0.93. The monetary policy shock, ρ_r, gets value 0.30. Finally the parameter ρ_{ga}, which shows the effect of total factor production innovations on exogenous government spending Smets et al. (2014) is set

Table 2: Posterior estimates of parameters

Parameter	Description	Value	Source
θ	Depreciation rate	0.025	Harding et al. (2023)
Φ_w	Gross wage markup	1.50	Harding et al. (2023)
g_y	Gov. G/Y steady state ratio	0.18	Harding et al. (2023)
ξ_p	Calvo probability prices	0.67	Harding et al. (2023)
ϵ_w	Kimball elasticity (labor)	10	Harding et al. (2023)
φ	Investment adjustment cost	5.65	Estimated
σ_c	Intertemporal substitution elasticity	0.39	Estimated
κ	Degree of external habit	0.65	Smets et al. (2014)
ξ	Calvo probability wages	0.74	Smets et al. (2014)
σ_l	Labor supply elasticity	2.39	Estimated
ϵ_p	Kimball elasticity (goods)	72.3	Estimated
ι_w	Ind. for non-opt. wages	0.22	Smets et al. (2014)
ι_p	Ind. for non-opt prices	0.22	Smets et al. (2014)
α	Capital production share	0.21	Estimated
ψ	Capital utilization cost	0.46	Smets et al. (2014)
Φ_p	Gross price markup	1.34	Estimated
γ	Steady-state gross growth	0.14	Smets et al. (2014)
π	Steady-state net inflation rate	0.55	Smets et al. (2014)
β	Discount factor	0.24	Smets et al. (2014)
ρ_R	Taylor rule interest rate	0.82	Estimated
$r_{\Delta y}$	Taylor rule output gap coefficient	0.18	Estimated
r_y	Taylor rule output coefficient	0.15	Smets & Wouters (2002)
r_π	Taylor rule inflation	1.67	Smets et al. (2014)
ρ_a	Technology shock	0.98	Smets et al. (2014)
ρ_b	Risk premium shock	0.91	Smets et al. (2014)
ρ_g	Government spending shock	0.99	Smets et al. (2014)
ρ_i	Investment shock	0.45	Estimated
ρ_p	Price markup shock	0.56	Smets et al. (2014)
ρ_w	Wage markup shock	0.93	Estimated
ρ_r	Monetary policy shock	0.30	Smets et al. (2014)
ρ_{ga}	TFP spending on exogenous spending	0.18	Smets et al. (2014)
μ_p	Moving average of price markup	0.44	Smets et al. (2014)
μ_w	Moving average of wage markup	0.85	Smets et al. (2014)
σ_a	Standard deviation of technology shock	0.58	Smets et al. (2014)
σ_b	Standard deviation of risk premium shock	0.24	Smets et al. (2014)
σ_g	Standard deviation of gov. spending shock	0.30	Smets et al. (2014)
σ_i	Standard deviation of investment shock	0.49	Smets et al. (2014)
σ_p	Standard deviation of price markup shock	0.35	Smets et al. (2014)
σ_w	Standard deviation of wage markup shock	0.30	Smets et al. (2014)
σ_r	Standard deviation of monetary shock	0.11	Smets et al. (2014)

Note: The table shows the posterior values of the structural parameters. These values are partially estimated using Bayesian estimation scripts adapted from Harding et al. (2022) and partially taken from prior literature. The euro area data used in the estimation is obtained from ECB and OECD.

as 0.18 and the moving average of price markup as 0.44 and the corresponding variable for wage mark up as 0.85. Table 2 summarize these values and based on which source the estimates were altered (if at all).

7 Simulation

By adapting the replication package by Harding et al. (2023), this section computes the linearized solutions for the above stylized and estimated model by employing the model into MATLAB and using the Fair and Taylor (1983, as cited in Harding et al. (2023)) solution algorithm. More practically, in this replication package, the equilibrium equations of the log-linearized model[9] are employed into Dynare and then a perfect foresight simulation algorithm developed by Fair and Taylor (1983, as cited in Harding et al. (2023))[10] is applied by using the 'simul'-command. This algorithm allows the implementation of the ZLB-constraint through the Taylor rule. For the linearized solution, the effective lower bound (ELB) prevents the interest rate from falling below it. (Harding et al., 2023) For the quarters where the ZLB is binding in the euro area (2012Q2-2022Q2) the key deposit facility rate is adjusted to the quarterly average. Hence, this model's monetary policy rule will be constrained by an ELB of -0.125% (annual interest rate of -0.5%).

Conditional on the calibrated and estimated parameters, the Fair and Taylor inversion filter is used to filter the shocks for the period 1999Q2 to 2021Q1 using euro area data. Since, the time period of interest and data differ from Harding et al. (2023), their scripts are modified to match this thesis' analysis. This filtering results in a filtered state of 2021Q1 in which the transmission of adverse supply shocks are then examined. More practically, once the model has been filtered to the state of 2021Q1, one standard deviation total productivity and cost-push shocks are added. This also differs slightly from Harding et al. (2023) approach as they only examine cost-push shocks out of these two and do not analyze negative productivity shocks at all. The main output variable of interest is inflation but output gap will also be observed to give a better overview of the economic effects of the shocks and to guide discussion on the monetary policy trade off between output and inflation, which is discussed later.

The resulting impulse response functions (IRFs) [11] of these shocks are presented in

[9]See Harding et al. (2023) supplementary materials for the summary of the log-linearized equations

[10]The Fair Taylor (1983 as cited in Harding et al. (2023)) method is generally used for non-linear models. It is used here since Harding et al. (2023) also estimate a non-linear model so their replication package uses this for the linear model IRFs as well.

[11]Impulse-response functions describe how a variable of interest, an output variable, evolves over some

the following two subsections (Section 7.1 and Section 7.2). After these, section 7.3 will conduct a sensitivity analysis to examine how the persistence of these adverse supply shocks affect the output variables. Finally, this section will present some findings on monetary policy response and the trade-off between output gap and inflation.

7.1 Productivity Shock

The results of the 1σ negative productivity shock are shown in Figure 4. The simulations show that following the 1σ shock, inflation increases by approximately 0.1% and GDP gap decreases by approximately 0.12%. These results are in accordance with the theoretical overview in Section 4 as a decrease in the economy's productivity will decrease supply, leading to increased prices. These findings also align with the general empirical findings that supply chain constraints induced inflation (e.g. Comin et al. 2023; Amiti et al. 2024; Acharya et al. 2023; Ascari, Bonomolo, et al. 2023). However, many of these studies find that these types of shocks played a larger role in the early stages of the pandemic, which could be the reason for the relatively low inflationary effects in these results for a productivity shock implemented at the start of 2021.

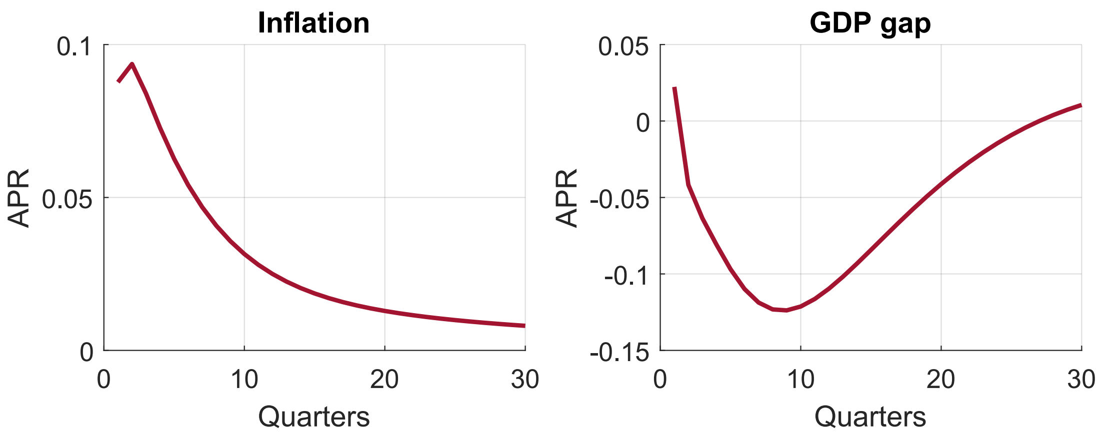
Another reason for the relatively low inflationary effects could be underestimated values. According to Harding et al. (2023) this linear model underestimates the inflationary effects. They find that a non-linear formalization of this same model is able to generate more sizable inflation surges such as the actual one experienced after Covid-19. They argue that this is due to the fact that in the non-linear model shocks propagate more strongly when inflation is high. Hence, despite showing the positive inflationary effects of the productivity shock, the linear model used in this thesis underestimates the true effect.

7.2 Cost-Push Shock

Figure 5 shows the impulse response functions (IRF) for a 1σ cost-push shock in 2021Q1. The simulations show that following the 1σ shock, inflation rises by roughly 2% and GDP gap decreases up to roughly 1.7% over a year after the shock. The positive results on inflation are expected as a cost-push shock will cause prices to increase as the costs of

time horizon after a shock is introduced to the economy (see e.g.Gali (2008))

Figure 4: Impulse response functions to a 1 σ productivity shock in 2021Q1

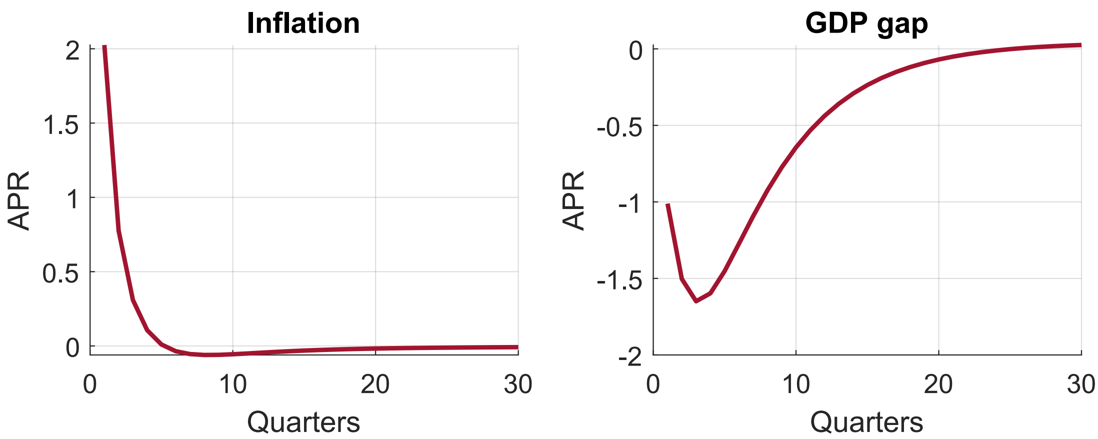


Notes: The figure depicts the IRFs to a 1σ adverse productivity shock employed in the beginning of 2021 in the euro area. The data is from the ECB Database and OECD. The computations are by the author of this thesis using a modified version of Harding et al. (2023) replication package.

production go up and firms are forced to increase their mark up as analyzed in Section 4. Relative to the above analyzed negative productivity shock, in this model cost-push shocks seem to have greater inflationary effects.

The direction of the inflation and output gap results are aligned with empirical literature, which examined cost-push shocks from both the United States (see e.g. Harding et al. 2023; Gagliardone & Gertler 2023; Ball et al. 2022 as well as the euro area (see e.g., Ascari et al. 2024; Acharya et al. 2023). However, compared to Harding et al. (2023) findings on the US (using their linear model), this inflation response to the 1σ cost push shock is twice as large. The magnitude of the inflation response is nearly the same as their results obtained from their non-linear model. This would indicate that the cost-push shock had significantly larger effects on inflation in the euro area than in the US. This result aligns with the findings of Di Giovanni et al. (2023) who find that energy shocks had a more significant role in the euro area inflation surge than the US. Again, as mentioned in the previous subsection, despite showing the inflationary effects of the cost-push shock, the true effect of the cost-push shock is likely even larger as Harding et al. (2023) claim that the linear model used in this thesis underestimates the inflationary effects.

Figure 5: Impulse response functions to a 1 σ cost-push shock in 2021Q1



Notes: The figure depicts the IRFs to a 1σ positive cost-push shock employed in the beginning of 2021 in the euro area. The data is from the ECB Database and OECD. The computations are by the author of this thesis using a modified version of Harding et al. (2023) replication package.

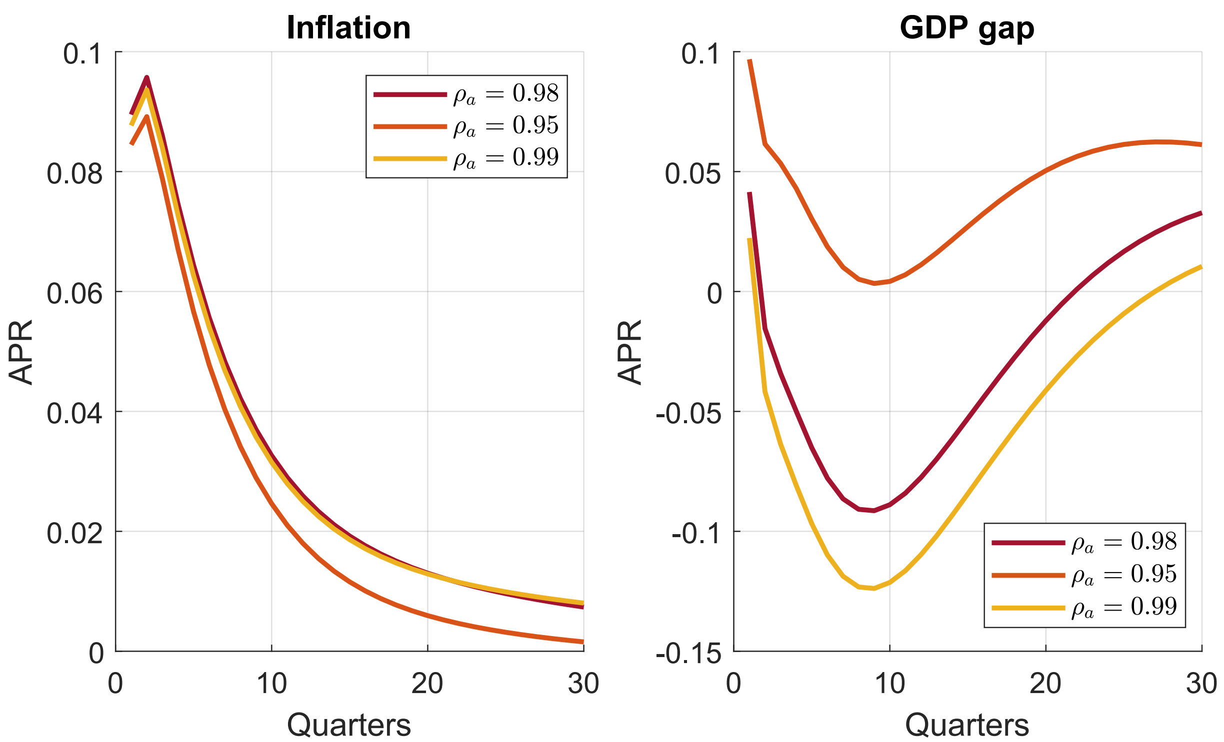
7.3 Sensitivity Analysis

Given that the persistence of both adverse supply shocks were taken from existing literature, and the true persistence of pandemic era supply shocks cannot be known for certain beforehand - as discussed in earlier sections where e.g., Reis (2022) claims the shocks were misjudged as transitionary - this subsection will conduct a sensitivity analysis to assess how the persistence of the two types of adverse supply shocks affect the results. The scenario analysis is done by altering the values of the persistence parameters of both shocks. This subsection will first perform a sensitivity analysis on the negative productivity shock followed by the cost-push shock.

7.3.1 Productivity Shock

To examine how the persistence of the productivity shock affects the results, this subsection will alter the persistence variable, ρ_a, based on values from literature while keeping all other parameters constant. Harding et al. (2023) estimate the persistence of the productivity shock to be 0.95, which is slightly below this thesis' parameter value of 0.98. Gorodnichenko & Ng (2010) perform simulations where the persistence parameter is given values 0.95, 0.99 and 1. As the supply shocks were seen as highly persistent (Ascari et al., 2024), this sensitivity analysis will focus on the higher persistence values from literature. Hence, Figure 6 shows the IRFs when the persistence parameter, ρ_a, is altered to 0.95 and 0.99 from the baseline value of 0.98.

Figure 6: IRFs to a 1 σ adverse productivity shock with varying persistence of the shock



Notes: The figure depicts the IRFs to a 1σ productivity shock employed in the beginning of 2021 in the euro area with three different variations of the persistence parameter. The data is from the ECB Database and OECD. The computations are by the author of this thesis using a modified version of Harding et al. (2023) replication package.

The impulse response functions show that the effects of a more persistent adverse productivity shock has limited effects on inflation. The initial inflation response increases only by approximately 0.005%. However, it does take longer to reach its steady state, the more persistent the adverse productivity shock is. The persistence of the adverse productivity shock appears to have a greater effect on output gap. GDP gap's initial response decreases by approximately 0.075% more with the most persistent shock than in the baseline model and over 0.1% within the next 10 quarters. The variation between the persistence values is not large and is likely the reason the differences in inflation response are not very different between each simulation. The scenario analysis does however help verify the robustness of the model as it shows expected results aligned with theory and literature as more persistent productivity shocks imply that the growth of the economy is below its steady state for a longer time (Fornaro & Wolf, 2023).

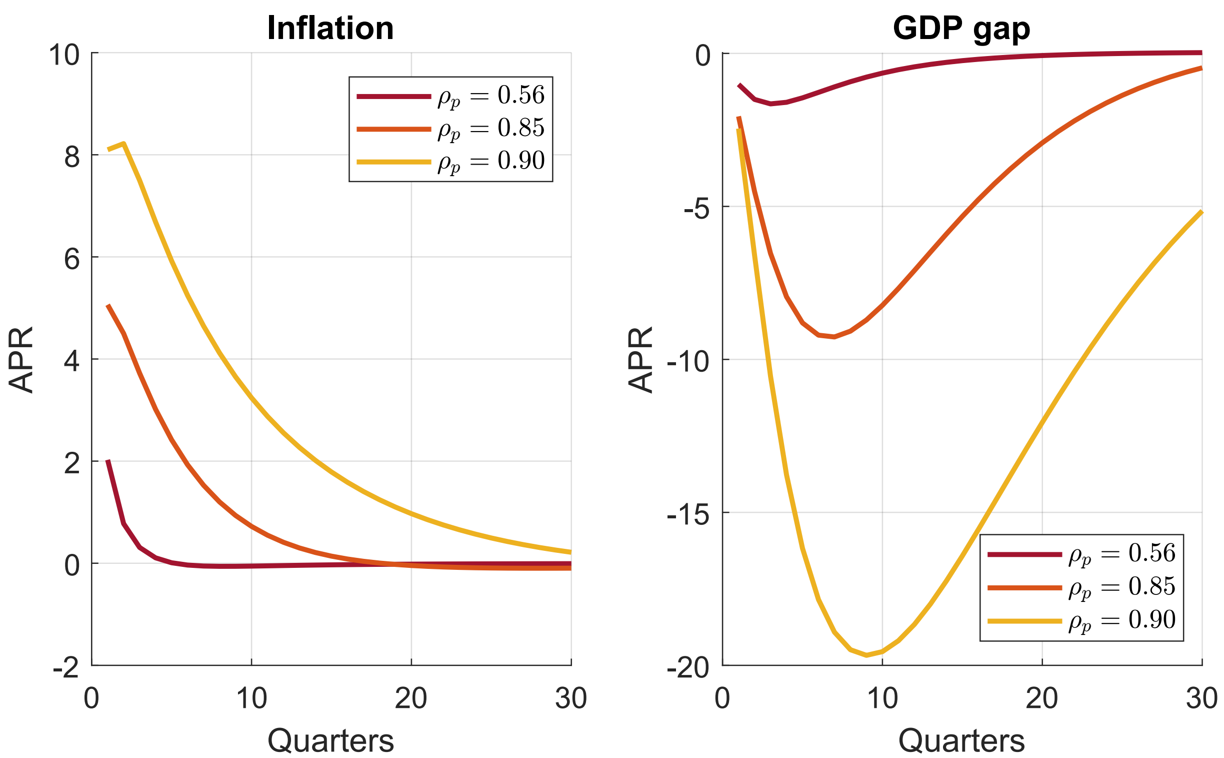
7.3.2 Cost-Push shock

To examine how the persistence of the cost-push shock affects the results, this subsection will alter the persistence variable, ρ_p, based on values from literature while keeping all other parameters constant. Harding et al. (2023) estimates the persistence of the cost-push shock to be 0.83, which is significantly higher than the parameter value used in this thesis. Hakamada & Walsh (2024) estimates the persistence of the pandemic related inflation shocks as 0.85 while Brandão-Marques et al. (2024) set the cost shock parameter as 0.92. Using these values from literature, Figure 7 shows the impulse response functions when the persistence parameter, ρ_p, is altered to 0.85 and 0.90 from the baseline value of 0.56.

The impulse response functions show that the persistence of the cost-push shock has relatively large effects on both output variables. Differing from the persistence analysis of the productivity shock, the persistence of the cost-push shock appears to significantly affect the initial inflation response. It is important to note that the range of the varied persistence is larger than for the productivity shock and hence larger reactions to the varied values is natural. When persistence is the greatest, $\rho_p = 0.90$, the initial inflation response increases by approximately 6% from the baseline simulations up to 8%. When $\rho_p = 0.85$ so the closest to the parameter used by Harding et al. (2023), the initial inflation response is nearly four fold of their linear model result. One explanation for the increase in initial inflation response to more persistent cost-push shocks could be the de-anchoring of inflation expectations. As Reis (2022) argued in his paper, persistent cost-push shocks are likely to de-anchor inflation expectations as households will notice large increases in household energy costs and hence unsettle their expectations about future inflation. There are also long term effects for inflation as the time taken to reach the steady state increases by multiple years.

Higher persistence also increases the effects on output gap. In the most persistent scenario, the output gap decreases by nearly 20%, which is a lot higher than what Harding et al. (2023) find. The increase persistence also significantly increases the time taken to return back to the steady state. The larger effects on inflation and output compared to Harding et al. (2023) results, again indicate the significance of cost-push shocks in the euro area compared to the United States, which aligns with findings in existing literature (Di Giovanni et al., 2023).

Figure 7: IRFs to a 1 σ cost-push shock with varying persistence of the shock



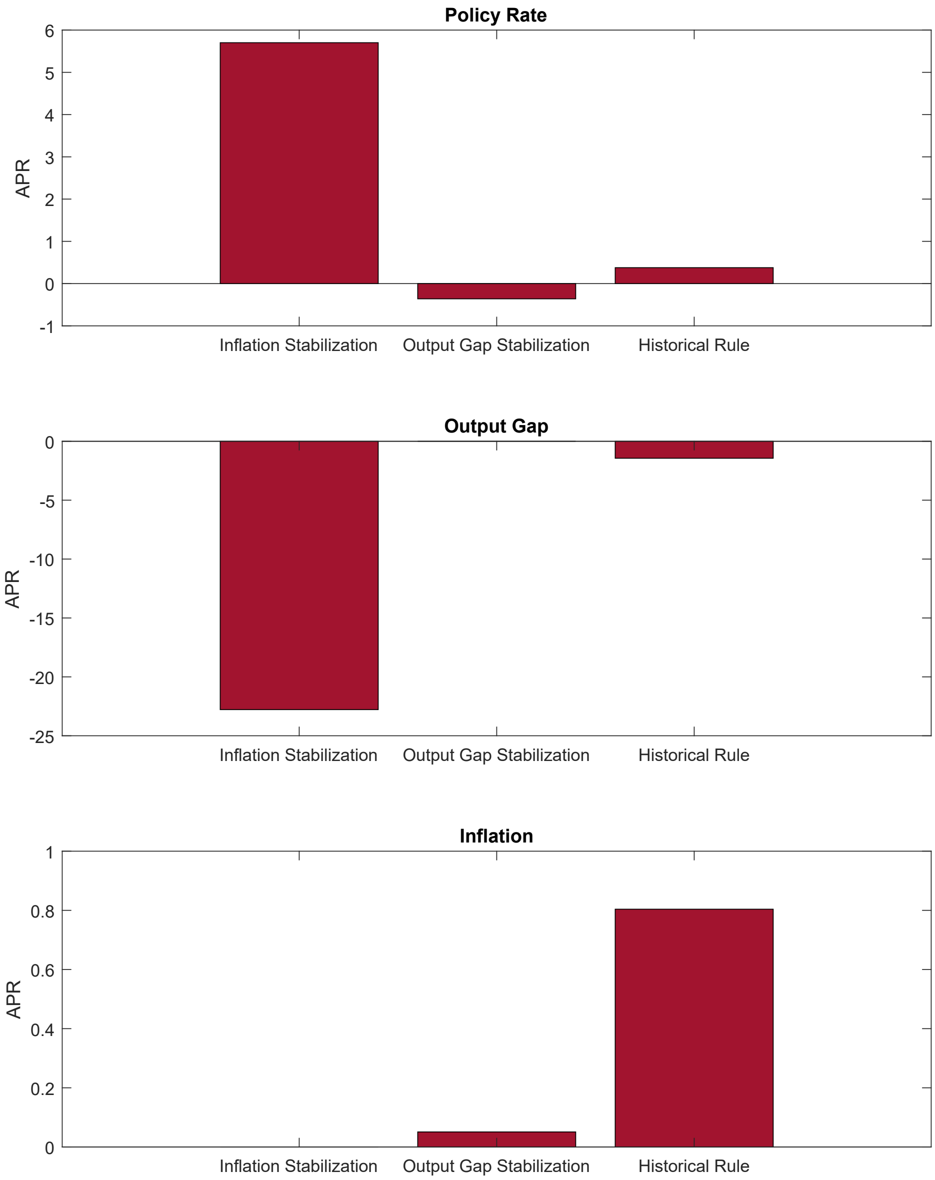
Notes: The figure depicts the IRFs to a 1σ cost-push shock employed in the beginning of 2021 in the euro area with three different variations of the persistence parameter. The data is from the ECB Database and OECD. The computations are by the author of this thesis using a modified version of Harding et al. (2023) replication package.

7.4 Trade-offs For the Monetary Policy Response

As the secondary aim of this thesis is to examine the policy implications for adverse supply shocks, this subsection will follow the analysis done by Harding et al. (2023) and present some alternative interest rate policy scenarios in response to the same 1σ cost-push shock and the resulting trade-offs between taming inflation and stabilizing the output gap. This section uses the cost-push shock instead of the productivity shock as the previous sections highlighted the relative significance of cost-push shocks in the euro area. Figure 8 shows three different interest rate scenarios and the resulting average effect on output gap and inflation in the following year. The first scenario is an inflation stabilization interest rate policy, which has the main goal of keeping inflation at target. The second scenario is full output gap stabilization with the goal of stabilizing the output gap to steady state and the final scenario is the historical policy rule of this thesis' sample, meaning a response that follows the estimated Taylor rule.

Determining what the optimal monetary policy response would have been during the pandemic era is beyond the scope of the thesis but Figure 8, highlights the output inflation trade-off faced by monetary policy. Figure 8 shows that in the inflation stabilization policy scenario, policy rate would need to be increased to nearly 6% to keep the annual percentage rate of inflation at 0. This is nearly the same as Giannone & Primiceri (2024) findings. This would cause an over 20% output gap decrease within the first year which is substantially larger than found by Giannone & Primiceri (2024). The output gap stabilization policy would need a policy rate just below zero, at the ELB, creating only a slight increase in inflation. This finding is slightly lower than the roughly 0.6% inflation increase that Harding et al. (2023) find for the United States using the linear model and the 1.5% increase they find using the nonlinear model. According to the model and data used in this thesis, the historical rule on the other hand would cause a larger increase in inflation compared to the other three scenarios and a slight decrease in output gap. However, despite showing a larger increase in inflation compared to the other scenarios, this is still well below the true observed post-pandemic inflation. Similar to Harding et al. (2023), the historical policy seems to have an emphasis on output stabilization. The direction of the output variables in the historical rule are aligned with Giannone &

Figure 8: Output-inflation trade-off under different interest rate policy scenarios.



Notes: The figure shows the trade-offs for monetary policy. It depicts the required interest rate tightening and resulting output gap and inflation under three different monetary response scenarios. The data is from the ECB Database and OECD. The computations are by the author of this thesis using a modified version of Harding et al. (2023) replication package.

Primiceri (2024) but the magnitude of the effects differ.

Overall, the general direction of these results are aligned with Giannone & Primiceri (2024) but magnitudes differ. Giannone & Primiceri (2024) however conduct this analysis with a set of various shocks and not just for one shock like in this thesis. Hence, their analysis shows a more holistic view of these policy scenarios. Another probable reason for the differences between findings of this monetary response scenario analysis and those of existing literature, is the fact that according to Harding et al. (2023) this linear model does not completely accurately represent the dynamics of the economy. Furthermore, this linear model is not able to account for the positive correlation between initial inflation level and the shock's inflationary effects that Harding et al. (2023) find in their paper. Harding et al. (2023) find using their non-linear model that the shocks propagate stronger as initial inflation levels rise and hence policy should act vigorously to counteract the cost-push shock. Due to these limitations, the main contribution of this monetary scenario analysis is not the magnitude of the output variables but to highlight that there exists a difficult trade-off for monetary policymakers between stabilizing inflation and stabilizing the output gap.

8 Conclusion

To examine the inflationary effects of adverse supply shocks of the pandemic era, this thesis used two theoretical frameworks as well as a linear DSGE model by Harding et al. (2023). More specifically, this thesis used the DSGE model to simulate two different negative supply shocks that occurred during the pandemic, a negative productivity shock and a positive cost-push shock. These shocks were imposed in the model in the beginning of 2021 to simulate what happened in the euro economy after the initial pandemic shock and during a time when demand had rebounded but supply constraints remained. To mitigate uncertainty on the persistence of the shock and to evaluate the robustness of the model, this thesis conducted a sensitivity analysis by varying the persistence of the productivity and cost-push shocks. Furthermore this thesis shed some light on the monetary policy response to such adverse supply shocks and the trade-offs policymakers face when economies are hit with such shocks.

The theoretical analysis showed the mechanisms through which these adverse supply shocks increase inflation. The empirical analysis was consistent with the theory as the simulations showed that in the euro area both types of negative supply shocks imposed to the economy in the beginning of the year 2021 had positive effects on inflation. The simulations showed that a negative productivity shock increased inflation by nearly 0.1% and a positive cost-push shock by around 2%. In the simulations, cost-push shocks have larger inflationary effects, which highlights the role of energy prices in the euro area. As the persistence of both shocks was taken from literature and it is difficult to know the true persistence of the adverse supply shocks, this thesis conducted a sensitivity analysis with varying persistence. The role of cost-push shocks was also highlighted in the sensitivity analysis as a persistent cost-push shock caused a four-fold inflation response in the simulations.

These inflationary findings from the beginning of year 2021 raise questions on whether the loose monetary policy stance by the ECB was justified until mid 2022. Answering this is beyond the scope of this thesis but in order to answer the secondary research question on the policy implications, this thesis examined the trade-offs faced by monetary policy during a cost-push shock. The results showed that choosing the monetary response scheme has large implications for either keeping inflation at target or avoiding large output losses. This highlights the difficulty of determining the optimal monetary policy response to such adverse supply shocks. The general findings of this thesis are consistent with findings from prior literature, which have used different empirical methods, models and/or different data to examine the role of shocks during the pandemic.

Despite finding positive inflationary effects, the linear model used in this thesis has been found to underestimate the effects of the inflation response (Harding et al., 2023). Hence the results of this thesis' simulations should be viewed as indicative estimates of the magnitude of the inflationary effects caused by these shocks. The primary focus, however, should be on the direction of the results - a positive inflation effect. Therefore, the main contribution is an enhanced understanding of how pandemic- and war- induced supply shocks played a role in driving inflation in the euro area, aimed at helping better navigate similar economic situations in the future.

To gain a better understanding of the true magnitude of the inflationary effects of these shocks and the output-inflation trade-off faced by monetary policies, it would be beneficial to simulate the same shocks using Harding et al. (2023) non-linear model, which was out of the scope of this thesis. Furthermore, as mentioned by Harding et al. (2023), it would be interesting to expand the model to include endogenous cost-push shocks (ie. monetary policy could influence the drivers of inflation) as well as how the de-anchoring of expectations (as discussed in the literature review) would affect the inflation dynamics. Moreover, it would be interesting to include demand shocks to this analysis. As the focus of this thesis was on the supply side, positive demand shocks were only explored indirectly since simulated demand led to some of the explored supply chain issues as well as through the brief examination of monetary implications. Hence, in order to gain a more holistic view of the economic environment and to better understand the appropriate monetary response, future research could expand the analysis to simultaneous positive demand and negative supply shocks.

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A Description of Data

Table 1: Description of the data used in this thesis

Variable	Details	Series Key
GDP*	Euro area 20, seasonally and calendar adjusted, measured in millions in current prices	MNA.Q.N.I9.W2.S1.S1.B. B1GQ._Z._Z._Z.EUR.V.N
Private final consumption*	Euro area 20, seasonally and calendar adjusted, measured in millions in current prices	MNA.W.Y.I9.W0.S1M.S1.D. P31._Z._Z._T.EUR.V.N
Gross fixed capital formation*	Euro area 20, seasonally and calendar adjusted, measured in millions in current prices	MNA.Q.Y.I9.W0.S1.S1.D.P51G. N11G._T._Z.EUR.V.N
Hourly compensation*	Euro area 20, seasonally and calendar adjusted, index	MNA.Q.Y.I9.W2.S1.S1._Z.COM _HW._Z._T._Z.IX.V.N
Hours worked*	Euro area 20, seasonally and calendar adjusted, measured in thousands of hours	Q.THSHW.TOTAL.SCA.EMPDC.EA20
Deposit facility rate*	Euro area, date of changes (raw data)	FM.D.U2.EUR.4F.KR.DFR.LEV
Deflator*	Euro area 20, seasonally and calendar adjusted, GDP at market prices	MNA.Q.Y.I9.W2.S1.S1.B. B1GQ._Z._Z._Z.IX.D.N
Population**	Euro area 20, working age population	-
Employment*	Euro area 20, seasonally and calendar adjusted, measured in thousands	ENA.Q.Y.I9.W2.S1.S1._Z. EMP._Z._T._Z.PS._Z.N

Notes: This table describes the time series used in this data and provides the series key for them. The specifics of the data processing can be seen from the dataedits.m script found in the codes zip file. * Data retrieved from ECB database, ** Data retrieved from OECD