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Applications in Dynamic Stochastic General Equilibrium Macroeconomics

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by

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DOCTORAL JURY

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A lovely Sunday evening in May. With a cold beer in my hand and an Enya song in the background I reflect on the progress of my PhD. It was a pretty eventful period to say the least. The course I followed was full of bends, pits and detours. Not exactly the most efficient route, but quite recognisable, I think, for anyone who embarked on a doctorate. Today, with the end in sight, I look back and wonder how I ever got to where I am. I would not have been able to do it without the support of several fantastic people.

My adventure started in the autumn of 2006. During my Master studies at the 'Université Catholique de Louvain' I met Raf Wouters of the National Bank of Belgium for the first time. Somewhat like a confused host professor at the UCL Raf introduced his students to the wondrous world of 'DSGE models'. For me it was the Holy Grail! No more Adam Smith's invisible hand. I wanted and had to understand the macroeconomic relationships and the DSGE methodology would help me in this. The plan became clear: first a PhD where I could study this methodology, then a job with a policy institution to apply my knowledge in practice.

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Nederlandstalige Samenvatting

Dit doctoraal proefschrift behandelt twee macro-economische thema's uiteengezet in vijf aparte hoofdstukken. Het eerste thema bestudeert de onderliggende oorzaken van olieprijswijzigingen, de macro-economische effecten van olieschokken en de gevolgen hiervan voor het monetair beleid. Het tweede thema analyseert het belang van competitiviteit voor de inflatie en het economisch beleid. De rode draad in de thesis wordt gevormd door de gemeenschappelijke onderzoeksmethodologie. In het bijzonder worden beide onderzoeksonderwerpen geanalyseerd met behulp van 'Dynamic Stochastic General Equilibrium' (DSGE) modellen en Bayesiaanse schattingstechnieken voor de empirische implementatie van dergelijke modellen. In wat volgt geef ik een bondige uiteenzetting van de twee onderzoeksthema's van mijn doctoraatsverhandeling.

Sinds de exponentiële stijging van de olieprijzen tussen 2003 en 2008 is er een vernieuwde interesse ontstaan voor de macro-economische effecten van olieprijsstijgingen, dit zowel onder beleidsmakers als in de academische wereld. Een belangrijke bevinding van recent onderzoek naar de transmissiekanalen van olieschokken is dat de gevolgen van olieprijswijzigingen voor de economie sterk verschillen naargelang deze fluctuaties aanbod of vraag gedreven zijn, bv., Kilian (AER, 2009). Dit resultaat impliceert dat beleidsmakers bij hun reactie op een waargenomen olieprijsstijging de dieperliggende oorzaken moeten bekijken. Doet men dit niet dan dreigt elke fluctuatie in de oliemarkt over dezelfde kam geschoren te worden met mogelijks foutieve beleidskeuzes tot gevolg.

Ondanks dit inzicht is het tot op heden voor monetaire beleidsmakers onduidelijk in welke mate en in welke richting het rentebeleid dient afgestemd te worden op de onderliggende oorzaken van olieprijsschommelingen. Twee problemen in de huidige academische literatuur verhinderen een eenduidig antwoord op deze vraag. Ten eerste, bestaande normatieve monetaire beleidsanalyses modelleren de olieprijs als een exogene variabele die gedreven wordt door een enkele aanbodschok; deze studies maken dus geen onderscheid tussen vraag- en aanbodgedreven olieprijswijzigingen. Ten tweede, onder de positieve analyses die de olieprijs wel beschouwen als een endogene variabele (gedreven door zowel vraag- als aanbodfactoren) bestaat er geen eensgezindheid of vraag- dan wel aanbodfactoren de voornaamste drijvers zijn van de waargenomen fluctuaties in olieprijzen. De eerste twee hoofdstukken van mijn thesis behandelen deze twee probleemstellingen.

In de eerste paper onderzoek ik samen met Gert Peersman welke factoren aan de grond liggen van de verschillende bevindingen in de literatuur betreffende de historische drijvers van olieprijzen. We ontwikkelen en schatten een open-economie DSGE model van de Verenigde Staten en olieproducerende landen waarin olieprijzen endogeen worden bepaald en waarbij olie naast een inputfactor in productie en consumptie ook als een investeringsgoed wordt gemodelleerd. Door middel van robuustheidtesten onderzoeken we in welke mate het al dan niet erkennen van enkele kerneigenschappen van de oliemarkt de analyse betreffende het relatieve belang van vraag- en aanbodschokken voor olieprijsfluctuaties beïnvloedt. Als belangrijkste resultaat van deze paper tonen we aan dat aanbodschokken niet te verwaarloosbare determinanten zijn van olieprijzen, van zodra we erkennen dat de olie-aanbodcurve niet perfect inelastisch is en olie naast een verbruiksgoed ook een investeringsgoed is.

Op basis van het geschatte model ontwikkeld in de eerste paper onderzoekt de tweede paper of het optimaal monetair beleid van een olie-importerend land na een olieprijswijziging afhankelijk is van de schok die de olieprijs drijft. Ik analyseer de transmissiekanalen van verschillende olieschoktypes en bepaal de verschillen in de optimale beleidsreacties. De centrale boodschap van deze paper is dat oliespecifieke vraag- en aanbodschokken gelijkaardige beleidsreacties vereisen. Bijgevolg is het niet noodzakelijk voor monetaire beleidsmakers om te onderscheiden met welk type schok we geconfronteerd worden. Dit komt voornamelijk omdat olie verhandeld wordt in een internationale omgeving gekenmerkt door '*incomplete markets*'. Onafhankelijk van de onderliggende schok leidt een olieprijsstijging dan tot een verschuiving van welvaart van de olie-importerende naar de olie-exporterende landen. Om deze verschuiving in welvaart tegen te gaan, dient het optimaal monetaire beleid de interestvoet te verhogen om de economische activiteit en dus olievraag en -prijs te verlagen.

Recent theoretisch onderzoek heeft aangetoond dat bij het maken van conjunctuuranalyses het belangrijk is de effecten van productintroducties en bedrijfsdynamieken in rekening te brengen, bv., Bilbiie et al. (JPE, 2012). Heel specifiek beklemtoont deze '*endogenous-entry*' literatuur het belang van het zogenaamde 'competitie-effect'. Via dit transmissiekanaal leidt een stijging van de competitiviteit tot een daling van de beoogde '*markup*' van prijzen op marginale kosten die bedrijven onderhandelen. Op zijn beurt drukt de dalende prijs-'*markup*' de inflatie naar beneden, terwijl het de economische activiteit een duw in de rug geeft. Het tweede gedeelte van mijn proefschrift analyseert de relaties en interacties tussen dit competitie-effect en de inflatie. Mijn onderzoek betreffende dit onderwerp levert drie belangrijke bijdragen tot de literatuur.

De eerste bijdrage is theoretisch van aard. Daar de graad van competitiviteit zich procyclisch neigt te gedragen, versterkt het hierboven beschreven competitie-effect de transmissie van productiviteitsschokken. Met behulp van een '*real business cycle*' (RBC) model kwantificeren

Floetotto en Jaimovich (JME, 2008) dit versterkend effect. Ze vinden dat het competitie-effect de volatiliteit van productiviteitsschokken met ongeveer 50% doet dalen. Echter, een belangrijke tekortkoming van Floetotto en Jaimovichs analyse is dat zij mogelijke nominale rigiditeiten in de prijszetting van bedrijven buiten beschouwing laten. In het conventioneel nieuw-Keynesiaans model, gekenmerkt door rigide prijzen, leidt een exogene stijging in de productiviteit tot een grotere daling van marginale kosten dan van prijzen, waardoor de prijs-'*markup*' stijgt. Dit effect verzwakt de dynamische effecten van technologieschokken in plaats van deze te versterken. In de derde paper van het doctoraat analyseer ik het relatieve belang van het competitie-effect en rigide prijzen voor de transmissie van productiviteitsschokken. Hiertoe breid ik de analyse van Floetotto en Jaimovich uit door te beschouwen dat de prijszetting gekenmerkt wordt door nominale rigiditeiten. Ik toon aan dat deze nominale prijsrigiditeiten de versterkende effecten van het competitie-effect op de transmissiekanalen van productiviteitsschokken significant doen dalen. In het bijzonder, de versterkende effecten op de output- en consumptiereacties worden meer dan gehalveerd.

De tweede bijdrage is empirisch van aard. Terwijl een groeiende theoretische literatuur het belang van het competitie-effect in conjunctuuranalyses belicht, bestond er tot voor kort geen grondige empirische analyse die dit transmissiekanaal kwantificeert. In gezamenlijk werk met Vivien Lewis overbruggen we deze tekortkoming. Gebruikmakend van Bayesiaanse technieken schatten we het competitie-effect in een '*endogenous-entry*' DSGE model van de Verenigde Staten. Het geschatte competitie-effect bedraagt 0.15; dus, een stijging van het aantal concurrenten in de economie met 1% doet de beoogde prijs-'*markups*' van bedrijven met 0.15% dalen. Hoewel het competitie-effect niet groot is, tonen we aan dat de bijdrage van dit effect tot de Amerikaanse inflatiefluctuaties niet onbelangrijk is. Daar inflatiewijzigingen die gedreven worden door competitiviteitswijzigingen als efficiënt beschouwd worden, betekent deze bevinding dat een monetair beleid gericht op inflatiestabilisatie niet steeds optimaal is.

Ten slotte, in de laatste paper, analyseer ik de impact van competitiviteitsstijgingen op de relatie tussen de hoogte van inflatie en de hoogte van de economische activiteit, i.e., de helling van de zogenaamde Phillips-curve. Sinds het midden van de jaren ´80 is the Phillips curve in de meeste industriële landen significant vlakker geworden. Dit fenomeen wordt dikwijls toegeschreven aan de stijgende competitiviteit die werd waargenomen over deze periode en welke werd gedreven door zowel deregulering als globalisering van de markten. Empirisch onderzoek naar deze mogelijke verklaring levert echter geen eenduidig antwoord. Welke inzichten kan de microgefundeerde nieuw-Keynesiaanse Phillips-curve (NKPC) ons brengen? In deze paper toon ik aan dat we deze vraag niet kunnen beantwoorden onder de traditionele assumpties van monopolistische concurrentie. Monopolistisch concurrerende markten worden gekenmerkt door een groot aantal kleine bedrijven. Onder deze marktvoorwaarden bedient elke bedrijf slechts een fractie van het globale marktaanbod, zodat elke competitiviteitsstijging slechts een verwaarloosbaar markteffect kan genereren. Vandaar, als alternatieve marktvorm, beschouw ik oligopolistische concurrentie, waarbij elk bedrijf een significante portie van de markt bedient. Vervolgens toon ik aan dat een stijging in de competitiviteitsgraad ontegensprekelijk leidt tot een stijging van de helling van de Phillips curve. De gangbare NKPC ondersteunt dus niet het idee dat stijgende competitiviteit heeft geleid tot een dalende output-inflatie '*trade-off*'.

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Chapter 0

General Introduction

1 Introduction

This doctoral dissertation comprises five essays on two broad macroeconomic themes. The first theme analyzes the sources of oil price fluctuations, their effects on key macroeconomic aggregates and the optimal policy response to such movements. The second theme investigates the effects of changes in product market competition on inflation dynamics and the propagation of business cycle shocks more generally. Initially, these two research topics may appear to be fairly distinct from one another; however, they are unified by a common new-Keynesian perspective. In particular, all of the research questions posed in this dissertation are addressed through the framework of dynamic stochastic general equilibrium (DSGE) models. It is fair to state that the DSGE methodology has become the modern method of conducting macroeconomics. The success of this methodology lies in its modeling principles. First, DSGE models are derived from optimizing behavior by rational economic agents. This microfounded approach overcomes the Lucas Critique Problem from which more traditional non-structural macroeconomic models suffer. Second, through the modeling of intertemporal linkages, the DSGE framework is dynamic and offers a tool for studying business cycle movements in macroeconomic prices and quantities. Third, DSGE models are stochastic in that business cycles within these frameworks are generated by random disturbances affecting the economy. Finally, the general equilibrium characteristics of DSGE models enable us to analyze the macroeconomy in its entirety. This modeling principle is important because interesting economic actions most often lie in the spill-over effects from one market to another. In the remainder of this introductory chapter, I provide an outline of two research themes of this dissertation and briefly discuss the application of DSGE methodology in addressing both of these themes.

2 Outline

2.1 Oil Price Shocks, Business Cycles and Monetary Policy

The recent volatility in the oil market has created renewed interest among academics in understanding the evolution of the real oil price. One important finding of this line of research is that different origins of oil price shocks, which include both demand and supply, trigger distinct macroeconomic effects (e.g., Kilian 2009). This result has important implications for monetary policymakers, as it suggests that distinguishing between the causes of oil price shocks may be important in determining the appropriate policy responses to address them.

However, until now, the extent to which the design of optimal monetary policy should depend on the different origins of oil price fluctuations has been unclear, primarily because academic research has not yet provided much constructive advice on this topic. Specifically, two main issues hinder policymakers from deriving unambiguous conclusions from the extant literature. First, existing normative contributions on optimal policy behavior typically ascribe all variations in oil prices to a unique supply shock and hence do not account for the deeper sources of these fluctuations. Second, recent positive analyses of the oil market that treat oil prices as endogenous are highly inconclusive with respect to the relative importance of supply and demand factors in determining oil prices. For instance, Hamilton (2009) and Nakov and Pescatori (2010) argue that historical oil price changes have primarily been caused by oil supply disruptions, whereas Kilian and Murphy (2010), Balke et al. (2010) and Bodenstein and Guerrieri (2011) find that shocks to oil demand have historically driven oil prices. The first two chapters of this PhD dissertation attempt to overcome these issues.

Chapter 1 *'Analyzing Oil Demand and Supply Shocks in an Estimated DSGE Model'*

The essay that is presented in Chapter 1, which was coauthored with Gert Peersman, seeks to determine what factors explain the diversity of findings with respect to the historical drivers of oil prices. More specifically, we examine which features of the oil market are important traits to consider in assessments of the relative contribution of shocks to oil price volatility. We address this issue in two steps. First, we develop a benchmark DSGE model of the US and the Oil-Producing Countries that regards oil prices as endogenous, estimate this model with Bayesian techniques and perform a variance decomposition exercise to identify the source of oil price fluctuations. Subsequently, we evaluate the robustness of the main findings by subjecting the baseline model to alternative specifications of the oil market. The perturbations that we investigate in these robustness assessments are designed to capture the different model approaches that are considered in the extant oil literature. For instance, we analyze the implications of endogenizing the supply side of the oil market and treating oil as a storable commodity in addition to serving as a production and consumption input.

This first chapter reports two main results. First, we find that oil inventory behavior and an elastic oil supply curve are important traits to consider in assessments of the historical drivers of oil price fluctuations. More specifically, we demonstrate that the presence of oil storage and an elastic oil supply render real oil prices relatively more sensitive to oil supply shocks. Intuitively, following demand shocks, arbitrage induces trading in oil inventories, which acts to mitigate the resulting fluctuations in oil prices. Moreover, a shallow oil supply curve causes oil prices to be less sensitive to demand-side disturbances. Second, we show that neglecting disturbances in precautionary or speculative holdings of oil inventories causes an upward bias in the estimated contribution of oil efficiency shocks to oil price fluctuations. Given the evidence that oil is a storable commodity and that oil supply elasticity is non-zero, our results indicate that oil supply shocks are non-negligible drivers of real oil prices. This result contrasts with the findings of many recent studies that exclude the possibility of oil storage or utilize a perfectly inelastic oil supply curve. In particular, these studies find that demand factors are of primary importance in the determination of oil prices, whereas supply factors play a negligible role in explaining oil price variability.

Chapter 2 *'Optimal Monetary Policy Response to Endogenous Oil Price Fluctuations'*

Based on the estimated model developed in the first chapter, Chapter 2 derives the Ramsey-optimal conduct of monetary policy and assesses differences in the policy responses to various oil shocks.

The central result of this chapter is that the types of shock that are identified in the literature as the main drivers of oil price fluctuations (i.e., oil supply and oil-specific demand shocks) call for similar policy responses once we acknowledge that oil is difficult to substitute in production and that international asset markets are incomplete. This approach suggests that monetary policy that fails to identify the causes of oil price fluctuations is not significantly misguided. Intuitively, in a case with low substitutability of oil and incomplete markets, oil-specific demand and supply shocks induce similar welfare effects that call for similar policy responses. More specifically, if oil is a gross complement of domestic factors of production, then real marginal costs are a convex function of the real oil price. Independent of their underlying cause, oil price hikes then induce a negative wedge between the natural and efficient levels of output. By aiming to close this gap, the Ramsey policy aligns the recessionary consequences of the various oil supply and oil-specific demand shocks. If, additionally, international financial markets are incomplete, then both unfavorable oil supply and oil-specific demand shocks induce a shift in wealth from oil-importing to oil-producing countries. To curb this wealth-shifting effect, optimal policy calls for a large but short-lived increase in the real interest rate, as this increase reduces oil demand and mitigates the oil price increase. A second key finding is that actual policy behavior, as captured by an empirical Taylor-type rule, is significantly different from the optimal conduct of monetary policy. However, whether actual monetary policy amplifies or dampens the recessionary effects of oil price hikes depends on the type of oil shock that occurs, the degree of oil substitutability and the degree of international risk sharing.

2.2 Product Market Competition, Markups and Inflation Dynamics

Recent theoretical research highlights the role of firm and product entry in business cycles, including the work of Bilbiie et al. (2012). Specifically, the endogenous-entry literature proposes a novel transmission channel, namely, the 'competition effect'. Through the competition effect, desired markups decline as the number of competitors increases, which in turn lowers inflation and boosts economic activity. The second part of my dissertation analyzes this competition effect in relation to inflation dynamics. My research on this topic produces three important contributions to the literature.

Chapter 3 *'Competition, Price Stickiness and the Propagation of Technology Shocks'*

The first contribution that is presented in Chapter 3 is theoretical. Because competitive pressures tend to be procyclical, the competition effect magnifies the propagation of productivity shocks. Within a flexible real business cycle model, Floetotto and Jaimovich (2008) quantify this internal magnification mechanism and find that it causes a decline in the volatility of technology shocks by approximately 50%. However, the analysis of Floetotto and Jaimovich has an important shortcoming, in that it ignores nominal rigidities in price setting. In the canonical new-Keynesian model, neglecting firm entry and featuring price stickiness, an exogenous increase in technology lowers marginal production costs more than prices, such that markups increase. This effect weakens rather than amplifies the propagation of technology shocks. To analyze the relative importance of sticky prices and competition effects for the propagation of technology shocks, I extend the analysis conducted by Floetotto and Jaimovich (2008) by relaxing their assumption of perfectly flexible prices. I show that increasing price stickiness considerably weakens the internal magnification mechanism that is delivered by the competition effect. Overall, when nominal prices are sluggish in adjusting, the countercyclical movement that the technology shock induces in the markup is milder, and the magnification effects on output and consumption are nearly halved.

Chapter 4 *'The Competition Effect in Business Cycles'*

Second, although an emerging body of theoretical literature highlights the role of the competition effect in business cycle analysis, a rigorous empirical evaluation of this effect has not yet been conducted. In joint work with Vivien Lewis, we estimate the competition effect in an endogenous-entry DSGE model employing US data and Bayesian methods.

Specifically, we investigate how this transmission channel affects (conditional and unconditional) markup dynamics and whether it is important for US inflation fluctuations.

Three results emerge. First, the estimated competition effect equals 0.15. Thus, a one percent increase in the number of competitors decreases desired markups by 0.15 percent. Second, the influence of the competition effect on business cycle transmission is shock-dependent. Demand shocks result in procyclical desired markups and amplify inflation through the competition effect because they crowd out entry. The opposite is true for monetary shocks and supply shocks. Overall, the model-implied markup is countercyclical. We show that this result stems from the combination of the competition effect and shocks to desired price markups (typically referred to as 'cost-push shocks'). This part of our work contributes to the long-standing debate on the cyclicality of markups, with seminal papers by Rotemberg and Woodford (1999) and Nekarda and Ramey (2010). Third, using a counterfactual decomposition, we demonstrate that the competition effect contributes to US inflation dynamics at the business cycle frequency. Importantly, inflation changes resulting from the competition effect are regarded as efficient. Therefore, our results indicate that some risk is incurred when monetary policy mistakenly reacts to inflation fluctuations that originate from market structure changes rather than from price-setting distortions.

Chapter 5 *'Can Stronger Competition Explain the Flattening of the Phillips Curve?'*

Finally, in Chapter 5, I analyze the effect of increased product market competition on the response of inflation to output (i.e., the slope of the Phillips curve). There is widespread evidence that the slope of the Phillips curve has declined in recent years. Since the mid-1980s, nearly all advanced countries have experienced a flattening of the Phillips curve, as noted by researchers such as Borio and Filardo (2007) and Ihrig et al. (2007). Many observers suggest that this decline in the Phillips curve slope is explained by the stronger competition that is generated by deregulation and globalization. However, the empirical literature is highly inconclusive with respect to this topic. In this essay, I investigate what insights we can gain from the microfounded new-Keynesian Phillips curve (NKPC). First, I argue that to identify the effects of increased competition on the NKPC slope, we must relax the standard Dixit-Stiglitz monopolistic competition assumption regarding market structure. Monopolistic markets are characterized by a continuum of many small firms. Within this framework, each firm supplies only a small portion of aggregate output, and each firm's actions produce a negligible effect on the market. Given these assumptions, increases in competition do not generate any significant effect on the overall economy. Therefore, in this essay, rather than examining monopolistic markets, I consider an oligopolistic market in which each firm in the market possesses increased relative importance. Subsequently, I demonstrate that a structural increase in the degree of oligopolistic competition unambiguously increases the slope of the Phillips curve. Therefore, the standard NKPC does not support the argument that the observed increases in competition that have been induced by deregulation and globalization have reduced the slope of the Phillips curve.

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Chapter 1

Analyzing Oil Demand and Supply Shocks in an Estimated DSGE Model

Analyzing Oil Demand and Supply Shocks in an Estimated DSGE Model*

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Abstract

Which features of the oil market are the most important traits to consider in assessments of the relative importance of supply and demand factors in determining oil prices? In this study, we develop and estimate a DSGE model for the US and Oil-Producing Countries in which oil prices are endogenously determined and oil is treated as a storable commodity. By subjecting the model to different perturbations, we find that the presence of oil storage and an elastic oil supply render oil prices less sensitive to demand shocks. Furthermore, neglecting speculative oil demand shocks causes an upward bias in the estimated contribution of oil efficiency shocks to oil price fluctuations.

JEL classification: C11, E32, Q43.
Keywords: Oil Prices, Oil Storage, DSGE Modeling, Bayesian Estimation.

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1 Introduction

In a seminal work, Kilian (2009) demonstrates that oil price shocks with different origins, including both supply and demand, trigger distinct types of macroeconomic effects. This phenomenon has fostered the development of structural models of the oil market to identify the sources of oil price shocks and to analyze their economic effects. Specifically, one strand of the literature, which includes studies by Peersman and Van Robays (2009) and Kilian and Murphy (2010), proposes a decomposition of the oil price based on structural vector autoregressive (VAR) models that are identified by either sign or exclusion restrictions. Alternatively, a second strand of the literature extends the standard dynamic stochastic general equilibrium (DSGE) models with a well-specified oil market that regards oil prices as endogenous. Recent examples of studies in this line of research include investigations by Nakov and Pescatori (2010a), Balke et al. (2010) and Bodenstein and Guerrieri (2011) addressing the macroeconomic effects of oil shocks on the US economy as well as research by Forni et al. (2012), who examine the transmission of oil price shocks in the euro area.

Although recent studies in the oil literature generally treat oil prices as endogenous, considerable disagreement remains with respect to the relative importance of oil supply and demand factors in determining oil prices. For instance, Hamilton (2009) and Nakov and Pescatori (2010a) argue that historical oil price changes have primarily been caused by oil supply disruptions. However, Kilian and Murphy (2010), Balke et al. (2010) and Bodenstein and Guerrieri (2011) find that shocks to oil demand have historically driven oil prices, whereas oil supply shocks play a negligible role in explaining oil price variability. Finally, Peersman and Van Robays (2009) report that oil supply and demand shocks provide equal contributions to oil price volatility.

This paper seeks to determine the factors that explain the diversity of findings with respect to the historical drivers of oil prices. More specifically, we examine which features of the oil market are important traits to consider in assessments of the relative contribution of shocks to oil price volatility. We address this issue in two steps. First, we develop a benchmark DSGE model of the US and the Oil-Producing Countries. We estimate this model using Bayesian techniques for the period following the structural break that occurred in the oil market in 1986 and perform a variance decomposition analysis to identify the sources of oil price fluctuations. Subsequently, we evaluate the robustness of the main findings by subjecting the baseline model to alternative specifications of the oil market. The perturbations that we investigate in these robustness assessments are designed to capture the different model approaches that are considered in the extant oil literature.

Importantly, in contrast to VAR-based analyses, existing DSGE-based analyses of the sources of oil price fluctuations generally neglect two important features of the oil market. First, none of the recent general equilibrium models that have endogenized oil prices view oil as a storable commodity. Oil storage creates an intertemporal channel through which shifts in expectations regarding future oil prices directly affect current oil prices. Kilian and Murphy (2010) demonstrate that demand shocks driven by expectations have historically been important determinants of oil price fluctuations. Therefore, an appropriate account of the sources of oil price fluctuations should regard oil as both an asset and an input factor for production and consumption. Second, most structural analyses of the oil market focus on the demand side of the market and simplify the supply side by assuming that oil supply is determined by an exogenous endowment (e.g., Bodenstein and Guerrieri 2011 and Forni et al. 2012). This assumption may be overly simple because it involves a perfectly inelastic oil supply curve and therefore favors demand shocks in driving oil price fluctuations.[1] Given these issues, as the primary objective of the paper, we wish to evaluate the importance of oil inventory behavior and an elastic oil supply curve in assessments of the relative contribution of shocks to oil price volatility. To this end, we propose a novel method of incorporating oil storage and endogenizing the supply side of the oil market in an estimable DSGE model.

Recent structural investigations of the sources of oil price fluctuations often differ with respect to the stochastic structures that they consider. This dissimilarity may provide another explanation as to why the literature is inconclusive with respect to the relative importance of oil supply and demand shocks in driving oil prices. To analyze this argument, we match the rich structural setup of our model to an equally rich set of observable variables; this approach allows us to identify a wide variety of shocks and to evaluate their relevance to oil price fluctuations. With respect to the supply side of the oil market, we distinguish among three different types of shocks. Building on the work of Balke et al. (2010) and using data pertaining to active drilling rigs, we first identify shocks to investments in oil-bearing reservoirs. These shocks include changes in either the likelihood of striking oil or the efficiency of oil drilling. Employing data on spare oil production capacity, we further differentiate between oil markup shocks, which capture exogenous

[1] One notable exception is the model of Nakov and Pescatori (2010a, 2010b), which is further refined by Nakov and Nuño (2011). This model treats the oil market as consisting of a single dominant firm with a competitive fringe where, à la Stackelberg, the dominant firm internalizes the behavioral responses of both fringe producers and oil consumers. Although conceptually appealing, this modeling approach renders estimation a daunting task because each iteration from the posterior distribution requires a recalculation of the dominant oil producer's policy functions. As discussed below, the current paper proposes a simpler means of endogenizing the supply side of the oil market, thus ensuring that the model remains tractable for estimation purposes.

shifts in market power, and oil capacity shocks, which refer to exogenous alternations in the productive capacity of the oil-producing sector. To address the demand side of the oil market, we follow the approach of Kilian and Murphy (2010) and distinguish between oil demand shocks that are driven by economic activity and oil demand shocks that are driven by expectations. The latter type of shocks results from speculative or precautionary motives and can be identified with the assistance of data on crude oil inventories. Finally, as part of our robustness assessments, we also model a shock to the relative efficiency of oil usage, as in the work of Bodenstein and Guerrieri (2011).

There are a few notable features of our model. First, the model includes real and nominal frictions that are standard aspects of the recent generation of new-Keynesian models as proposed by Christiano et al. (2005) and Smets and Wouters (2007). Previous estimates of DSGE models that endogenize the oil market have often disregarded many of these frictions. For instance, Balke et al. (2010) employ a real business cycle (RBC) setup in which inflation rates are zero and monetary policy plays no role in the oil market. By contrast, Nakov and Pescatori (2010a) build a new-Keynesian model, but ignore real frictions, such as habit formation in consumption.

Second, oil storage takes the form of above-ground oil inventory holdings.[2] Thus, in addition to being an input factor for both consumption and production, oil is treated as an asset that is part of a household's investment portfolio. Within this framework, arbitrage not only links an expected oil price increase to an expected rate of return on other assets but also acts to mitigate fluctuations in oil prices. Speculative or precautionary oil demand shocks are identified by exogenous deviations of oil inventories from this arbitrage condition. Hamilton (2009) argues that speculation could also take the form of oil producers withholding production because of expectations of rising oil prices. In this case, oil producers use below-ground oil as inventories. We do not model this below-ground oil inventory behavior.[3] In our model, therefore, speculation on the part of oil producers is captured by the oil markup shock, representing shifts in the market power of oil producers.

Third, the US is treated as a relatively closed economy that engages in trade only with oil-producing countries. This assumption may be too simplifying because it ignores open economy aspects of the transmission of oil price shocks, such as changes in the nominal exchange rate and shifts in the terms of trade. Moreover, this assumption implies that

[2] Recently, and independently of our work, Unalmis et al. (2012) also model and analyze above-ground oil inventory behavior within a DSGE model of the oil market.

[3] As noted by Kilian and Murphy (2010), unlike above-ground oil inventories, oil below the ground is inaccessible in the short term. Moreover, there exists no reliable time series data on the quantity of below-ground oil.

positive demand shocks in the Rest of the World produce no positive spillover effects in the US economy. However, given the evidence in the new open-economy macroeconomics literature (e.g., Jacob and Peersman 2013) that economic fluctuations in the US largely result from domestic shocks, this assumption must produce relatively small errors.

Our analysis of the relative contribution of shocks to oil price volatility yields two important results. First, we find that oil inventory behavior and an elastic oil supply curve are important traits to consider in assessments of the relative contribution of shocks to oil price volatility. More specifically, we demonstrate that the presence of oil storage and an elastic oil supply render real oil prices relatively more sensitive to oil supply shocks. Intuitively, following demand shocks, arbitrage induces trading in oil inventories, which acts to mitigate the resulting fluctuations in oil prices. Moreover, a shallow oil supply curve causes oil prices to be less sensitive to demand-side disturbances. Second, we show that neglecting disturbances in precautionary or speculative holdings of oil inventories causes an upward bias in the estimated contribution of oil efficiency shocks to oil price fluctuations. In contrast to the findings of many recent studies that neglect oil storage or utilize a perfectly inelastic oil supply curve, the results of the current study suggest that supply shocks play a non-negligible role in explaining oil price variability. Specifically, we find that shifts in the market power of oil producers explain at least one-fourth of the observed oil price fluctuations if we acknowledge that oil is a storable commodity, allow for speculative oil demand shocks and treat oil supply as an endogenous variable. A particularly notable observation is that speculative oil demand shocks explain approximately one-third of the sustained oil price surge that has occurred since 2002. Turning to an examination of the transmission channels of various types of oil shocks, our findings corroborate Kilian's conclusion that '*not all oil price shocks are alike*' (Kilian 2009, p.16). In addition to differences between the dynamic effects of oil supply and oil demand shocks, various types of oil supply shocks present different macroeconomic repercussions.

The paper proceeds as follows. In Section 2, we present an outline of the baseline model. Section 3 provides details regarding our estimation method, data and choice of priors. Section 4 presents the baseline estimation results. Specifically, we assess the relative importance of each type of shock in explaining fluctuations in the oil market and variability in US economic activity. In Section 5, we carefully evaluate the robustness of the baseline result to alternative model specifications and examine the sources of differences relative to the existing literature. Section 6 performs a historical shock decomposition of the real oil price. In Section 7, we characterize the transmission channels of various types of oil shocks. Finally, Section 8 concludes the paper.

2 A Baseline Model of the US and Oil-Producing Countries

In this section, we develop an open economy model of the US (the domestic economy) and Oil-Producing Countries (the foreign economy). The model includes a well-specified oil market in which both oil price and oil quantities are endogenously determined. Trade between these two economies is carried out in dollars, which are assumed to be the common currency in both economies.[4] The Rest of the World (RoW) is assumed to be divided into small economies, each of which has a negligible effect on the US economy. The setup of the aggregate RoW economy is highly stylized. In particular, the US is assumed to be the world's leading economy, and aggregate oil demand in the RoW is therefore modeled as a function of US oil demand and an exogenous AR(1) process.[5]

The modeled structure of the domestic (US) economy is closely related to the closed economy models described in Christiano et al. (2005) and Smets and Wouters (2003, 2007). The main difference between these models and the model of the current study is the introduction of oil to the economy. Oil is imported from the oil-producing country to be used for three different purposes. First, intermediate goods producers use oil as an intermediate input for the production of non-oil manufactured goods, which are known as core goods. Second, households consume oil in addition to their consumption of core goods. Finally, oil is a storable commodity. There are two reasons why economic agents may decide to store oil. First, oil inventories provide a service to consumers by supporting liquidity in the oil market. Second, similar to any other commodity, oil can be regarded as an asset in the investment portfolio.

The foreign oil-producing countries are assumed to produce only oil. Core goods for consumption and investments are completely imported from the US and the RoW. In accordance with the model of Balke et al. (2010), the production of crude oil occurs in two steps. At the upstream of oil manufacturing, a competitive drilling firm constructs exploitable oil fields. In the downstream step of oil manufacturing, the oil production sector rents these fields and extracts oil from the ground. In contrast to Balke et al. (2010), it is assumed that both the oil drilling and oil extraction sectors only require

[4] We assume that oil-producing countries maintain a currency peg against the dollar; this assumption is valid for most of the oil-exporting countries in the world. As a result, these economies need to adopt the US monetary policy.

[5] Although simplifying, the assumption of the US being the main driving source of fluctuations in global oil demand can be justified by two observations over the course of the prior four decades. First, US oil consumption has remained at a relatively stable 23% of total world oil production throughout these decades. Second, the linearly detrended series of world oil production and US oil consumption have a correlation of 85%.

capital as the single factor of production and do not demand labor. Instead, we allow for a variable utilization rate of capital stock in these two sectors.

The remainder of this section outlines the model's equilibrium conditions. We present the log-linearized model equations.[6] Variables that are presented as deviations from the deterministic steady state are denoted by the superscript '^'. Variables without a hat or time subscript refer to the steady-state level. Unless otherwise noted, foreign region parameters and variables are denoted by the superscript '*'. Given that the dollar is the common currency, we use the US CPI as the numeraire price index for each region.

2.1 The Oil-Importing Domestic Economy (the US)

Domestic Firms There exists a continuum of intermediate monopolistic firms, each of which produces a differentiated type of core good that can be either consumed or invested. Production is modeled in the spirit of Rotemberg and Woodford (1996). First, the value added output $\widehat{VA}_t$ (i.e., GDP) is produced under a Cobb-Douglas production function with capital services $\hat{K}_t^S$ and labor $\hat{L}_t$, weighted by θ and $1-\theta$, respectively; thus., $\widehat{VA}_t = \theta \hat{K}_t^S + (1-\theta)\,\hat{L}_t + \hat{\eta}_t^Z$. Total factor productivity (TFP) $\hat{\eta}_t^Z$ is assumed to follow an exogenous process. Second, value added is aggregated with oil $\hat{O}_t^G$, using a constant elasticity of substitution (CES) technology, to produce gross output $\hat{Y}_t$; thus, $\hat{Y}_t = \phi\left(\eta \widehat{VA}_t + (1-\eta)\,\hat{O}_t^G\right)$, where η is the share of GDP in gross output and $\phi \geqslant 1$ is equal to one plus the share of fixed costs in production.

Real marginal costs $\widehat{mc}_t$ for producing core goods are a weighted average of the real wage rate $\hat{w}_t$, the rental rate of capital $\hat{r}_t^k$ and the real oil price $\hat{p}_t^o$, corrected for TFP,

$$\widehat{mc}_t = \eta \hat{s}_t + (1-\eta)\,\hat{p}_t^o, \text{ where } \hat{s}_t \equiv \theta \hat{r}_t^k + (1-\theta)\,\hat{w}_t - \hat{\eta}_t^Z. \tag{1}$$

Cost minimization by firms implies the following demand curves for labor and oil:

$$\hat{L}_t = -\left(\hat{w}_t - \hat{r}_t^k\right) + \hat{K}_t^S \text{ and} \tag{2}$$

$$\hat{O}_t^G = -\alpha\,(\hat{p}_t^o - \hat{s}_t) + \widehat{VA}_t, \tag{3}$$

where $\alpha > 0$ defines the elasticity of substitution between value added and oil.

Price decisions are subject to Calvo (1983)-staggering. Non-adjusted prices are indexed to lagged core inflation rates. The new-Keynesian Phillips curve (NKPC) for core goods relates the change in core prices $\hat{\pi}_t^y$ to its lagged and expected future value, and to the

[6] For a full derivation of the model, please see the appendix at http://users.ugent.be/~ansteven.

price markup $\hat{p}_t^y - \widehat{mc}_t$,

$$\hat{\pi}_t^y - \gamma_p \hat{\pi}_{t-1}^y = \beta \left(E_t \hat{\pi}_{t+1}^y - \gamma_p \hat{\pi}_t^y \right) - \frac{\left(1 - \beta \xi_p\right)\left(1 - \xi_p\right)}{\xi_p} \left(\hat{p}_t^y - \widehat{mc}_t\right) + \hat{\eta}_t^P, \tag{4}$$

where $\xi_p \in (0,1)$ is the Calvo price stickiness parameter, $\gamma_p \in (0,1)$ is the rate of indexation, $\beta \in (0,1)$ is the representative agent's subjective discount factor and E_t denotes the expectations operator conditional on the information set at the beginning of period t. The term $\hat{\eta}_t^P$ captures a shock to the markup of core prices $\hat{p}_t^y$ over marginal costs $\widehat{mc}_t$ (which is henceforth referred to as a 'price markup shock').

Domestic Households Households derive utility from consuming $\hat{C}_t$ and oil inventory holdings $\widehat{OS}_t$ and derive disutility from working $\hat{L}_t$. Specifically, in non-linearized form, period utility is given by $U_t = \left(\frac{1}{1-\sigma_c} \left(C_t - hC_{t-1}\right)^{1-\sigma_c} - \frac{1}{1+\sigma_l} \left(L_t\right)^{1+\sigma_l} + \eta_t^{OS} \ln(OS_{t-1}) \right)$, where $\sigma_c > 0$ is the degree of risk aversion, $h \in (0,1)$ captures external habit formation in consumption and $\sigma_l > 0$ is the inverse Frisch wage elasticity of labor supply. We comment on the term η_t^{OS} and the role of oil stocks in utility in the next subsection, in which we discuss our approach for modeling oil storage behavior. The marginal utilities of consumption and labor are given by

$$\hat{U}_{C,t} = -\frac{\sigma_c}{1-h} \left(\hat{C}_t - h\hat{C}_{t-1} \right) \quad \text{and} \quad \hat{U}_{L,t} = \sigma_l \hat{L}_t. \tag{5}$$

The consumption basket $\hat{C}_t$ is produced by a competitive retailer and is constructed by combining imported oil $\hat{O}_t^C$ and domestically produced core consumption goods $\hat{Y}_t^C$ via a Dixit-Stiglitz aggregator. Oil consumption and core consumption demand are specified by

$$\hat{O}_t^C = -\psi \hat{p}_t^o + \hat{C}_t \text{ and} \tag{6}$$

$$\hat{Y}_t^C = -\psi \hat{p}_t^y + \hat{C}_t, \tag{7}$$

respectively, where $\psi > 0$ is the elasticity of substitution between oil and core consumption. CPI inflation $\hat{\pi}_t$, which is also known as headline inflation, is a weighted sum of the oil and core inflation rates. In particular, $\hat{\pi}_t = \delta \hat{\pi}_t^o + (1-\delta)\hat{\pi}_t^y$, where δ denotes the expenditure share of oil in the consumption basket.

Households have access to several types of assets to facilitate the inter-temporal transfer of wealth. First, they can purchase domestic risk-free bonds, with a gross nominal interest rate of $\hat{R}_t$. The optimal choice of bonds yields the usual consumption Euler equation,

$$\hat{U}_{C,t} = \left(\hat{R}_t - E_t \hat{\pi}_{t+1} \right) + E_t \hat{U}_{C,t+1} + \hat{\eta}_t^T. \tag{8}$$

The 'time preference shock' $\hat{\eta}_t^T$ is derived from a disturbance to the subjective discount factor β. Second, households can hold international securities. The optimal arbitrage condition for domestic and foreign bonds is given by

$$\hat{R}_t^*{=}\hat{R}_t + \kappa\widehat{NFA}_t. \tag{9}$$

The international bond pays interest $\hat{R}_t^*$, which equals the domestic rate $\hat{R}_t$, corrected for a default risk premium. This risk premium is positively depend on the net foreign asset position $\widehat{NFA}_t$ with elasticity $\kappa > 0$, and acts as a stationarity-inducing device.[7]

In addition to accumulating financial wealth, households can invest $\hat{I}_t$ in the physical capital stock $\hat{K}_t$. Accumulation of physical capital takes the form

$$\hat{K}_t = (1-\tau_K)\hat{K}_{t-1} + \tau_K\hat{I}_t + \tau_K\left(1+\beta\right)\varphi_K\hat{\eta}_t^I, \tag{10}$$

where $\tau_K \in (0,1)$ represents the depreciation rate of capital. The term $\hat{\eta}_t^I$ represents an exogenous shock to investment specific technology. The optimal choice of physical capital gives rise to the typical Tobin's Q equation,

$$\hat{Q}_t{=}-\left(\hat{R}_t - E_t\hat{\pi}_{t+1}\right) + \left(1-\beta\left(1-\tau_K\right)\right)E_t\hat{r}_{t+1}^k{+}\beta\left(1-\tau_K\right)E_t\hat{Q}_{t+1}, \tag{11}$$

which equates the real return on bond holdings with the real return on capital accumulation. Investment is subject to flow adjustment costs of the type introduced by Christiano et al. (2005). As a result, the market value of capital $\hat{Q}_t$ can differ from the replacement cost $\hat{p}_t^y$ for this capital. The difference between $\hat{Q}_t$ and $\hat{p}_t^y$ drives investments,

$$\hat{I}_t = \frac{1}{(1+\beta)}\hat{I}_{t-1} + \frac{\beta}{(1+\beta)}E_t\hat{I}_{t+1} + \frac{1}{(1+\beta)\,\varphi_K}\left(\hat{Q}_t - \hat{p}_t^y\right) + \hat{\eta}_t^I, \tag{12}$$

where $\varphi_K > 0$ governs the size of the (capital) investment adjustment cost.

Capital services are equal to the sum of the capital stock $\hat{K}_{t-1}$ and its utilization $\hat{z}_t$; in other words, $\hat{K}_t^S = \hat{z}_t + \hat{K}_{t-1}$. Variations in the capital utilization rate incur a cost in units of core consumption. The optimal condition for the utilization rate equates the rental price of capital with the marginal cost of higher capital utilization; thus,

$$\hat{r}_t^k = \hat{p}_t^y + \chi\hat{z}_t, \tag{13}$$

where $\chi^{-1} = \frac{1-\tilde{\chi}}{\tilde{\chi}}$ and $\tilde{\chi} \in (0,1)$ measures utilization adjustment costs.

[7] See Boileau and Normandin (2008) for details regarding the non-stationarity problem in open-economy models with incomplete financial markets, and how to resolve it.

We assume monopolistic wage setters and sticky wages as in Erceg et al. (2000). In addition, we stipulate that non-adjusted wages are indexed to lagged CPI inflation with coefficient $\gamma_w \in (0,1)$. Wage inflation $\hat{\pi}_t^w$ is thus determined as follows:

$$\hat{\pi}_t^w - \gamma_w \hat{\pi}_{t-1} = \beta \left(E_t \hat{\pi}_{t+1}^w - \gamma_w \hat{\pi}_t \right) + \frac{(1-\beta\xi_w)(1-\xi_w)}{\xi_w \left(1 + \sigma_l \frac{(1+\eta^W)}{\eta^W} \right)} \left[\left(\hat{U}_{L,t} - \hat{U}_{C,t} \right) - \hat{w}_t \right] + \hat{\eta}_t^W, \quad (14)$$

where $\xi_w \in (0,1)$ is the Calvo parameter for nominal wage stickiness and $\hat{\eta}_t^W$ is a shock to the markup of the real wage $\hat{w}_t$ over the marginal rate of substitution between consumption and leisure $\hat{U}_{L,t} - \hat{U}_{C,t}$.

Oil Storage Oil storage takes the form of above-ground oil inventory holdings. In addition to serving as an input factor for both consumption and production, oil is also an asset in which households can invest. If $\hat{I}_t^O$ denotes oil inventory investments, the total stock of oil inventories $\widehat{OS}_t$ evolves according to the following law of motion:

$$\widehat{OS}_t = (1-\tau_O)\,\widehat{OS}_{t-1} + \tau_O \hat{I}_t^O. \quad (15)$$

The depreciation cost that related to holding oil inventories, which is measured by $\tau_O > 0$, acts as a mechanism to ensure stationarity.[8] Oil storage involves storage costs. Similar to investments in the physical capital stock of firms, storage costs are modeled in terms of changes in oil inventories rather than in terms of stock levels. As a result, the value of oil inventories $\hat{Q}_t^O$ can differ from the real oil price $\hat{p}_t^o$. Oil inventory investment depends positively on the difference between $\hat{Q}_t^O$ and $\hat{p}_t^o$,

$$\hat{I}_t^O = \frac{1}{(1+\beta)} \hat{I}_{t-1}^O + \frac{\beta}{(1+\beta)} E_t \hat{I}_{t+1}^O + \frac{1}{(1+\beta)\,\varphi_O} \left(\hat{Q}_t^O - \hat{p}_t^o \right), \quad (16)$$

where φ_O captures flow adjustment costs in oil inventories.

As suggested by Hamilton (2009), in addition to involving costs, oil storage also produces benefits, which are commonly referred to as 'convenience yields'.[9] These benefits include the ability of households and firms to sustain their consumption patterns and keep their production processes running, respectively. In accordance with the approach of Kahn et al. (2002), we model the convenience yield by treating inventories as an extra source

[8] In the absence of oil inventory depreciation, i.e., if $\tau_O = 0$ in (15), the stock of oil inventories is a non-stationary variable, which, in turn, would imply indeterminacy of the model solution.

[9] From a theoretical perspective, the existence of a convenience yield ensures that the steady-state level of oil storage is positive. If the deviations of oil inventories from steady state are sufficiently small, this approach imposes a non-negativity constraint on aggregate storage and thereby ensures the absence of non-linearities in inventory behavior.

of household utility. Our motivation for this modeling approach for oil inventories is that these stocks support liquidity in the oil market. Inventories that are built up during a previous period can be used to bridge any lead time in oil delivery from distant oil-producing countries during the current period. The convenience yield $\hat{C}_t^y$ is therefore determined by the marginal rate of substitution of oil inventories for consumption,

$$\hat{C}_t^y \equiv \widehat{U_{OS_{t-1}}} - \widehat{U_{C_t}} = \left(-\widehat{OS}_{t-1} + \hat{\eta}_t^{OS}\right) + \left(\frac{\sigma_c}{1-h}\left(\hat{C}_t - h\hat{C}_{t-1}\right)\right). \tag{17}$$

The convenience yield $\hat{C}_t^y$ depends negatively on lagged oil inventory levels and, through consumption, positively on economic activity. The term $\hat{\eta}_t^{OS}$ represents an oil-specific demand shock to the desired level of oil inventories and captures exogenous shifts in precautionary or speculative holdings of oil inventories (this type of shock is henceforth referred to as an 'oil inventory shock').[10] Arbitrage equates the real return on bond holdings with the real return on oil inventory holdings,

$$\hat{Q}_t^O = -\left(\hat{R}_t - E_t\hat{\pi}_{t+1}\right) + \left(1-\beta\left(1-\tau_O\right)\right)E_t\hat{C}_{t+1}^y + \beta\left(1-\tau_O\right)E_t\hat{Q}_{t+1}^O, \tag{18}$$

where the return on oil stocks depends positively on both expected oil price increases and expected future convenience yields.

2.2 The Oil-Producing Foreign Economy

Oil Producers Analogously to the core goods producers in the oil-importing country, crude oil producers operate in a regime of monopolistic competition. Because oil-producing firms are located throughout the world, each firm produces a type of oil that is differentiated from the other oil producers' outputs in terms of geographical distance.[11] Oil production is described by an AK technology, $\hat{O}_t^* = \hat{\eta}_t^{OC} + \hat{D}_t^S$, where $\hat{D}_t^S$ represents capital services and $\hat{\eta}_t^{OC}$ refers to the exogenous oil production technology. The physical capital stock $\hat{D}_{t-1}$ is predetermined and should be interpreted as a combination of exploitable oil

[10] Note that the certainty equivalence property holds because our model is linearized to first order. This phenomenon implies that the oil inventory dynamics in our model only react endogenously to the expected mean oil price but not to the expected volatility of oil prices. Therefore, the oil inventory shock captures both shifts in expectations about future oil demand and supply (i.e., 'speculative oil demand shocks', as discussed by Kilian and Murphy (2010)) and shifts in uncertainty regarding future oil demand and supply (i.e., 'precautionary oil demand shocks', as discussed by Alquist and Kilian (2010)).

[11] In the literature, there is no clear consensus regarding the structure of the oil market. OPEC is often considered to be a powerful cartel that behaves as a monopolistic price setter. However, others have claimed that OPEC has no market power and that the oil market is perfectly competitive. An overview of these different viewpoints may be found in the work of Crémer and Salehi-Isfahani (1991).

fields and the machinery that is installed in these fields. Short-term fluctuations in capital services are captured by the variable utilization rate $\hat{u}_t$; thus, $\hat{D}_t^S = \hat{u}_t + \hat{D}_{t-1}$. Oil production occurs at normal capacity, denoted $\widehat{OCAP}_t^*$, if $\hat{u}_t = 0$; therefore, $\widehat{OCAP}_t^* = \hat{\eta}_t^{OC} + \hat{D}_{t-1}$. Accordingly, we refer to exogenous disturbances of the oil sector's TFP $\hat{\eta}_t^{OC}$ as 'oil capacity shocks'. Military conflicts or natural disasters that destroy a region's oil productive capacity are examples of these types of exogenous oil supply disturbances.

Real marginal costs of oil producers $\widehat{mc}_t^*$ equal the rental rate $\hat{r}_t^d$ of capital services (i.e., oil fields) less TFP,

$$\widehat{mc}_t^* = \hat{r}_t^d - \hat{\eta}_t^{OC}. \tag{19}$$

Given the monopolistic competitive market structure, oil prices $\hat{p}_t^o$ are set as a markup $\hat{\eta}_t^O$ over marginal costs $\widehat{mc}_t^*$,

$$\hat{p}_t^o = \widehat{mc}_t^* + \hat{\eta}_t^O. \tag{20}$$

In contrast to domestic core prices, oil prices are perfectly flexible. Therefore, variations in the oil markup $\hat{\eta}_t^O$ are ascribed entirely to exogenous sources. This 'oil markup shock' represent an exogenous shifts in the market power of oil producers.[12] Note that because we do not consider below-ground oil inventory behavior in our model, oil markup shocks also capture speculative supply decisions by oil producers, by which oil production is hold back in anticipation of higher oil prices.

Drilling Firm Exploitable oil fields $\hat{D}_{t-1}$ are owned by competitive drilling firms that produce new fields $\widehat{DN}$ according to an AK technology: $\widehat{DN}_t = \hat{\eta}_t^{OI} + \hat{K}_t^{S,*}$. The variable $\hat{K}_t^{S,*}$ denotes drilling rigs that are rented from foreign households at the rental rate $\hat{r}_t^{k,*}$. The 'oil investment shock' $\hat{\eta}_t^{OI}$ represents a disturbance in the productivity of oil drilling. This type of disturbance could result from technological changes or from shifts in the likelihood of discovering oil. Given the extraction of oil from existing fields, the total amount of utilizable oil fields evolves according to

$$\hat{D}_t = \hat{D}_{t-1} + \mu\widehat{DN}_t - \mu\hat{O}_t^*, \tag{21}$$

where μ denotes the steady-state depletion rate of oil fields. Drilling firms rent exploitable oil fields D_{t-1} to oil producers and select the utilization rate $\hat{u}_t$ of the oil capital stock. Profit maximization implies

$$\hat{r}_t^d = \hat{p}_t^y + \vartheta\hat{u}_t, \text{ and} \tag{22}$$

$$\hat{Q}_t^D = -\left(\hat{R}_t^* - E_t\hat{\pi}_{t+1}\right) + (1-\beta)\,E_t\hat{r}_{t+1}^d + \beta E_t\hat{Q}_{t+1}^D, \text{ where } \hat{Q}_t^D = \hat{r}_t^{k,*} - \hat{\eta}_t^{OI}. \tag{23}$$

[12] Modeling OPEC as a cartel would induce behavioral equations for oil producers that, up to the first order, are observationally equivalent to those obtained in our model. In that case, we could interpret oil markup shocks as shifts in the degree to which cartel agreements are observed by OPEC members.

Variations in the utilization rate of oil fields incur costs in units of core consumption. Therefore, in equation (22), the utilization rate $\hat{u}_t$ is positively dependent on the difference between the rental rate of oil fields and the real core price with elasticity $\vartheta^{-1} \geqslant 0$. Equation (23) constitutes an intertemporal condition between the real rental price $\hat{r}_t^d$ of oil fields and the real rental price $\hat{r}_t^{k,*}$ of drilling rigs.

Oil Supply Curve By combining the aggregate oil production function of $\hat{O}_t^* = \hat{\eta}_t^{OC} + \hat{u}_t + \hat{D}_{t-1}$ with equations (19), (20) and (22), we obtain the oil supply curve,

$$\hat{O}_t^* = \hat{\eta}_t^{OC} + \vartheta^{-1}\left(\hat{p}_t^o\right) - \vartheta^{-1}\left(\hat{\eta}_t^O + \hat{p}_t^y - \hat{\eta}_t^{OC}\right) + \hat{D}_{t-1}. \tag{24}$$

Note that the price-elasticity of oil production is equal to the inverse of the elasticity of the rental rate of oil fields with respect to the utilization rate, i.e., $\frac{dO_t^*/O_t^*}{dp_t^o/p_t^o} = \vartheta^{-1}$. Remarkably, both unfavorable oil capacity and oil markup shocks cause an increase in oil prices for a particular given level of output; however, the resulting oil price increases operate through different transmission channels. Therefore, both categories of oil supply shock produce different effects on the oil capacity utilization rate. Specifically, as detailed in the impulse response analysis in Section 7, the utilization rate falls in response to adverse shocks in oil markups, whereas the rate increases following exogenous declines in oil productive capacity. Given these differing dynamic responses, oil capacity and oil markup shocks can be identified through the use of data on spare oil production capacity.

Foreign Households In contrast to domestic households, the utility of foreign households depends only on the consumption of core goods $\hat{Y}_t^{C,*}$. Households are endowed with a fixed amount of oil and do not invest in above-ground oil inventories. Note that consumption goods $\hat{Y}_t^{C,*}$ are entirely imported from the domestic economy and the RoW. The optimal consumption path is determined by the familiar Euler equation,

$$\hat{Y}_t^{C,*} = \frac{h^*}{1+h^*}\hat{Y}_{t-1}^{C,*} + \frac{1}{1+h^*}E_t\hat{Y}_{t-1}^{C,*} - \frac{(1-h^*)}{(1+h^*)\,\sigma_c^*}\left(\hat{R}_t^* - E_t\hat{\pi}_{t+1}^y\right), \tag{25}$$

where $\sigma_c^* > 0$ is the degree of risk aversion and $h^* \in (0,1)$ is the degree of external habit formation.

The number of active drilling rigs that are used by the drilling firms are the sum of the stock of drilling rigs $\hat{K}_{t-1}^*$ and the utilization of these rigs $\hat{z}_t^*$, i.e., $\hat{K}_t^{S,*} = \hat{z}_t^* + \hat{K}_{t-1}^*$. Variations in the capital utilization rate entail a cost in units of core consumption. In the optimal condition for the utilization rate, the rental rate of the drilling rigs will be equal to the marginal cost of higher capital utilization,

$$\hat{r}_t^{k,*} = \hat{p}_t^y + \chi^* \hat{z}_t^*, \tag{26}$$

where $(\chi^*)^{-1} = \frac{1-\tilde{\chi}^*}{\tilde{\chi}^*}$ and $\tilde{\chi}^* \in (0,1)$ measures utilization adjustment costs. The law of accumulation of the stock of drilling rigs, the Q equation for the market value of drilling rigs and the investment Euler equation for the drilling rigs are, respectively, given by

$$\hat{K}_t^* = (1-\tau_K^*)\hat{K}_{t-1} + \tau_K^* \hat{I}_t, \quad (27)$$

$$\hat{Q}_t^* = -\left(\hat{R}_t^* - E_t\hat{\pi}_{t+1}\right) + \left(1-\beta\left(1-\tau_K^*\right)\right) E_t \hat{r}_{t+1}^{k*} + \beta\left(1-\tau_K^*\right) E_t \hat{Q}_{t+1}^*, \text{ and} \quad (28)$$

$$\hat{I}_t^* = \frac{1}{(1+\beta)}\hat{I}_{t-1}^* + \frac{\beta}{(1+\beta)} E_t \hat{I}_{t+1}^* + \frac{1}{(1+\beta)\, S_K^*}\left(\hat{Q}_t^* - \hat{p}_t^y\right). \quad (29)$$

2.3 The RoW, Market Clearing and Monetary Policy

RoW Oil Demand and Oil Market Clearing The Rest of the World (RoW) is assumed to be divided into many small economies, and each of these economies is presumed to exert a negligible effect on the US economy. The setup of this RoW economy is highly stylized. Assuming that the US is the world's leading economy, the RoW demand for oil $\hat{O}_t^{d,RW}$ is a function of US oil demand $\hat{O}_t^{d,US}$ and an exogenous disturbance $\hat{\eta}_t^{RW}$, producing

$$\hat{O}_t^{d,RW} = \hat{\eta}_t^{RW} + \hat{O}_t^{d,US}, \quad (30)$$

where US oil demand is given by $\hat{O}_t^{d,US} = \frac{O^G}{O^{d,US}}\hat{O}_t^G + \frac{O^C}{O^{d,US}}\hat{O}_t^C + \frac{I^o}{O^{d,US}}\hat{I}_t^O$. The 'RoW oil demand shock' $\hat{\eta}_t^{RW}$ captures all events that drive a wedge between US and RoW oil demand patterns.

The market clearing condition for oil reads $\hat{O}_t^* = \frac{O^{d,US}}{O^*}\hat{O}_t^{d,US} + \frac{O^{d,RW}}{O^*}\hat{O}_t^{d,RW}$. Using equation (30) to substitute for $\hat{O}_t^{d,RW}$, this condition simplifies to

$$\hat{O}_t^* = \hat{O}_t^{d,US} + \frac{O^{d,RW}}{O_t^*}\hat{\eta}_t^{RW}. \quad (31)$$

US oil consumption $\hat{O}_t^{cd,US}$ is equal to US oil demand net of oil inventory investments,

$$\hat{O}_t^{cd,US} = \frac{O^G}{O^{cd,US}}\hat{O}_t^G + \frac{O^C}{O^{cd,US}}\hat{O}_t^C. \quad (32)$$

National Income Accounts The national income account of the oil-importing country is given by

$$\hat{Y}_t = \frac{Y^C}{Y}\hat{Y}_t^C + \frac{I}{Y}\hat{I}_t + \frac{O^{d,US}}{Y}\left(\hat{p}_t^o + \hat{O}_t^{d,US} - \hat{p}_t^y\right) + \frac{K\chi'(1)}{Y}\hat{z}_t + \left(\widehat{NFA}_t - \frac{1}{\beta}\widehat{NFA}_{t-1}\right) + \hat{\eta}_t^G, \quad (33)$$

where $\hat{\eta}_t^G$ represents exogenous spending, including shifts in government consumption and shifts in the non-oil trade balance.

With respect to the foreign income account, we assume that foreign agents pay the same dollar price $\hat{P}_t^y$ for each import good, irrespective of the country of origin.[13] As a result, imports from the US $\hat{M}_t^{*,US}$ and the RoW $\hat{M}_t^{*,RW}$ evolve equally,

$$\hat{M}_t^{*,US} = \hat{M}_t^{*,RW} = \frac{Y^{c,*}}{M^*}\hat{Y}_t^{C,*} + \frac{I^*}{M^*}\hat{I}_t^* + \frac{D\vartheta'(1)}{M^*}\hat{u}_t + \frac{K^*\chi^{*\prime}(1)}{M^*}\hat{z}_t^*. \tag{34}$$

Balance of payments equilibrium of the US requires that $\hat{p}_t^o + \hat{O}_t^{d,US} = \hat{p}_t^y + \hat{M}_t^{*,US} - \frac{Y}{M^{*,US}}\left(\widehat{NFA}_t - \frac{1}{\beta}\widehat{NFA}_{t-1}\right)$. After using this expression to replace $\hat{O}_t^{d,US}$ in the oil market equilibrium condition (31), and accounting for the condition specified in equation (34), we obtain the national income account of the oil-producing economy,

$$\begin{aligned}\hat{O}_t^* &= (\hat{p}_t^y - \hat{p}_t^o) + \frac{Y^{c,*}}{O^*}\hat{Y}_t^{C,*} + \frac{I^*}{O^*}\hat{I}_t^* + \frac{D\vartheta'(1)}{O^*}\hat{u}_t + \frac{K^*\chi^{*\prime}(1)}{O^*}\hat{z}_t^* \\ &\quad -\frac{Y}{O^{d,US}}\left(\widehat{NFA}_t - \frac{1}{\beta}\widehat{NFA}_{t-1}\right) + \frac{O^{d,RW}}{O_t^*}\hat{\eta}_t^{RW}.\end{aligned} \tag{35}$$

Monetary Policy To close the model, we assume that monetary policy follows a Taylor-type rule with interest rate smoothing. The interest rate is adjusted to the level and the growth rate of the output gap, to CPI inflation and to the lagged interest rate,

$$\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)\left\{r_\pi\hat{\pi}_t + r_y\widehat{VA}_t^{gap}\right\} + r_{dy}\Delta\widehat{VA}_t^{gap} + \hat{\eta}_t^R, \tag{36}$$

where Δ is the first difference operator and $\widehat{VA}_t^{gap}$ is the output gap defined as actual GDP $\widehat{VA}_t$ less the potential level of GDP that would prevail under flexible prices and wages in the absence of markup shocks. The term $\hat{\eta}_t^R$ represents an exogenous monetary policy shock.

Exogenous Shock Processes Table 1 summarizes the functional forms assumed for the 12 structural innovations. We group these shocks in terms of oil demand- and supply-side disturbances. Specifically, we distinguish the following three types of oil supply shocks: oil capacity shocks $\hat{\eta}_t^{OC}$, oil markup shocks $\hat{\eta}_t^{O}$ and oil investment shocks $\hat{\eta}_t^{OI}$. On the demand side of the oil market, the model identifies oil inventory shocks $\hat{\eta}_t^{OS}$ and RoW oil demand shocks $\hat{\eta}_t^{RW}$. The remaining shocks are classified as 'US macroeconomic driven (ME) oil demand shocks', which affect oil demand indirectly by altering US economic activity.

[insert Table 1 here]

[13] This assumption requires the absence of a home bias in trade between the US and the RoW; furthermore, this assumption also implies that firms do not follow a local-currency pricing strategy. Under these two conditions, the law of one price will be valid.

With the exception of the exogenous spending, price markup and wage markup shocks, all disturbances follow $AR(1)$ processes in logarithmic terms. In accordance with Smets and Wouters (2007), disturbances to core price and wage markups follow $ARMA(1,1)$ processes; the moving average terms detect high-frequency movements in inflation.[14] Exogenous spending is also affected by the innovation in the TFP process. This specification is designed to capture unmodeled variations in net exports to non-oil-producing countries, which may be affected by domestic productivity developments.

3 Estimation

We apply Bayesian estimation techniques as in Fernandez-Villaverde and Rubio-Ramirez (2004) and Smets and Wouters (2003, 2007). For a detailed description, we refer to the original papers. Briefly, using the Bayesian paradigm, prior information is combined with the data to obtain posterior distributions for the parameters.[15] In the following subsections, we describe our data and our choice of priors.

3.1 Data

In our baseline specification, we estimate the model using 13 quarterly series of US and global oil data. The US data include real GDP, consumption, investment, hours worked, real wages, headline inflation, the federal funds rate, US oil inventories and US oil consumption. The observed global oil data series are global oil production, world real oil prices, global active drilling rigs and the global oil capacity utilization rate. Series for US real GDP, US consumption and US investments are obtained from the US Department of Commerce, Bureau of Economic Analysis (BEA). Data for US hours and wages are obtained from the US Department of Labor, Bureau of Labor Statistics (BLS). The interest rate is the Effective Federal Funds Rate from the Board of Governors of the Federal Reserve System. US consumer price or headline inflation is measured as the difference of the log implicit price deflator of the personal consumption expenditures (PCE) (from the BEA). Series for US crude oil refinery inputs (i.e., oil consumption), US crude oil stocks

[14] Our first estimation attempt involved specifying all markup shocks as $ARMA(1,1)$ processes. However, in doing so, the MA term in the process of the oil markup shock chafed against the lower bound of the unit circle. Therefore, we assume that the oil markup shock follows an $AR(1)$ process.

[15] We use 400,000 iterations of the random walk Metropolis-Hastings algorithm to simulate posterior distributions, and we achieve acceptance rates of approximately 30% in all of our specifications. We discard the initial 4% of drawings to compute the posterior moments in each case. We monitor the convergence of the marginal posterior distributions using CUMSUM statistics as defined by Bauwens et al. (1999).

and world oil production are retrieved from the US Department of Energy (DoE), Energy Information Administration. Oil prices are measured in terms of the US refiner acquisition cost of imported crude oil, which is obtained from the DoE-database. The rig count database of the oil-field services company Baker Hughes offers a monthly worldwide census of active drilling rigs that explore for oil and develop new oil fields (the Worldwide Rig Count). Global oil capacity utilization rates are calculated as the percentage use of total potential world oil production, which is measured by the sum of available OPEC spare capacity and actual world oil production. Data on OPEC spare capacity for the 1986-2008 period are obtained from the IMF World Economic Outlook (August 2006) and are updated with the DoE's Short-Term Energy Outlook (January 2009). This series is available only at an annual frequency. Annual data were interpolated to quarterly frequency using quadratic average-matching techniques.

All nominal variables are deflated with the PCE deflator. The log of the real oil price and the oil capacity utilization rate are demeaned.[16] The aggregate real variables are expressed in per capita terms by dividing by the civilian non-institutional population over 16 (from the BLS) and are linearly detrended in logarithmic terms. Finally, the inflation rate and the nominal interest rate are demeaned by subtracting their respective sample averages. Other particulars about data sources and filtering are detailed in the Appendix.

In terms of our model variables, the vector of observables reads as follows:

$$\mathbf{Y}_t = \left(\widehat{VA}_t,\, \widehat{C}_t,\, \widehat{\widetilde{I}}_t,\, \widehat{L}_t,\, \widehat{w}_t,\, \widehat{\pi}_t,\, \widehat{R}_t,\, \widehat{\widetilde{OS}}_t,\, \widehat{\widetilde{O}}_t^{cd,US},\, \widehat{O}_t^{*},\, \widehat{p}_t^{o},\, \widehat{K}_t^{S,*},\, \widehat{\widetilde{u}}_t\right),$$

where $\widehat{\widetilde{I}}_t$, $\widehat{\widetilde{OS}}_t$, $\widehat{\widetilde{O}}_t^{cd,US}$ and $\widehat{\widetilde{u}}_t$ are defined below. Two remarks are merited. First, we deflate all observable nominal variables by the US consumer price index P_t. However, in the model, the price of investment goods corresponds to the core- or producer price index P_t^y. Therefore, to link the model with the data, we multiply real investments I_t by P_t^y and divide the resulting product by P_t. The corresponding linearized data-consistent counterpart then reads $\widehat{\widetilde{I}}_t = \widehat{I}_t + \widehat{p}_t^y$. Second, in the estimation process, we use 13 time series, although our model contains only 12 structural innovations (see Table 1). To avoid stochastic singularity—a problem that arises if there are more variables than shocks—we include an exogenous *iid* normal error term $\hat{\varepsilon}_t^{mes,OD}$ in the measurement equation for

[16] In the Appendix, we test the sensitivity of the parameter estimates to another commonly used specification of the filtering of the oil price series. Specifically, we re-estimate the model using the alternative data set in which the log real oil prices are linearly detrended. We find that the parameter estimates in this alternative environment are similar to the baseline case in which oil prices are simply demeaned; all confidence intervals overlap. Given that real oil prices do not feature a clear upward or downward trend over the considered sample period, this result is not-surprising.

US oil consumption $\hat{O}_t^{cd,US}$, such that the data-consistent counterpart of $\hat{O}_t^{cd,US}$ becomes $\widehat{\hat{O}}_t^{cd,US} = \hat{O}_t^{cd,US} + \hat{\varepsilon}_t^{mes,OD}$. We also include an error term, $\hat{\varepsilon}_t^{mes,OS}$, to account for measurement errors in US oil inventories. This shock allows us to correct for the '*crude oil adjustments*' that are reported in the oil accounting tables; these adjustments are often large in magnitude. Finally, an error term for the oil capacity utilization rate, $\hat{\varepsilon}_t^{mes,u}$, is introduced to account for measurement errors that are produced by interpolating annual data to quarterly frequencies. Therefore, the measurement equations for oil inventories and the oil capacity utilization rate are $\widehat{\widehat{OS}}_t = \widehat{OS}_t + \hat{\varepsilon}_t^{mes,OS}$ and $\widehat{\widehat{u}}_t = \widehat{u}_t + \hat{\varepsilon}_t^{mes,u}$, respectively.

The data span the period 1986Q1-2008Q4. The relationship between oil prices and US macroeconomic performance has markedly changed since the mid-1980s. More specifically, several studies have noted a substantial decline over the past several decades in the macroeconomic consequences of oil price shocks.[17] The traditional line of reasoning in the literature ascribes this weakened relationship to structural changes, such as improved monetary policy (Bernanke et al. 1997) and more flexible labor markets (Blanchard and Gali 2007). By contrast, more recent studies argue that changes in the relative importance of oil demand and supply shocks in driving oil prices help explain changes in the oil-macroeconomy relationship (see, e.g., Barsky and Kilian 2004 and Kilian 2009). However, Baumeister and Peersman (2012) find that even after distinguishing between oil demand and supply shocks, the oil market underwent a considerable structural change in the first quarter of 1986. In particular, the price-elasticity of oil demand has substantially decreased since the mid-1980s. Given these findings, we choose to begin our sample in 1986. We end our sample in the fall of 2008. This end date eliminates the non-linearities that are associated with the zero lower that was established on the federal funds rate during the recent economic crisis.

3.2 Priors

An overview of our priors can be found in Table 2. Twelve parameters are fixed. The subjective discount factor is set to $\beta = 0.99$, implying a steady-state annualized real interest rate of 4%. Physical capital depreciates at an annual rate of 10%, i.e., $\tau_K = \tau_K^* = 0.025$. We set $\theta = 0.24$, which implies that on average, labor accounts for approximately three quarters of GDP. The steady-state consumption share in GDP is set to $\frac{PC}{sVA} = 0.62$.

[17] Mork (1989) and Hooker (1996) first identify a breakpoint in the oil-macroeconomy relationship. More recent evidence has been provided by Hooker (2002), Jiménez-Rodriguez and Sánchez (2005), Blanchard and Gali (2007), Edelstein and Kilian (2007) and Herrera and Pesavento (2009).

Following Smets and Wouters (2007), the long-run wage markup is fixed at $\eta^W = 0.5$. In accordance with the approach of Jacob and Peersman (2013), we assume that the elasticity of the cost of accumulating foreign debt is low at $\kappa = 0.001$. Based on data from the DoE regarding US energy consumption by different sectors, the relative share of oil use in consumption to oil use in production is calibrated to $\frac{O^C}{O^G} = 0.84$. We assume that a small percentage of oil inventory investment is wasted during the storage process and, therefore, conjecture that $\tau_O = 0.001$. Taking the calibration of τ_O into account and using data about the level of and changes in US crude oil stocks, the share of oil inventory investments in total US oil demand is set to $\frac{I^O}{O_t^{d,US}} = 0.002$. Finally, following Balke et al. (2010), the oil depletion rate is set to $\mu = 0.0065$.

[insert Table 2 here]

The prior distributions of the shock parameters are quite diffuse. In particular, the beta distributions for the autoregressive and moving average coefficients feature a mean of 0.5 and a standard deviation of 0.15, whereas the inverse gamma distributions for the standard errors of the innovations demonstrate a mean of 0.1 and a standard deviation of 2. For most of the structural parameters, we use priors as imposed by Smets and Wouters (2007). The monetary policy parameters, however, are given gamma distributions instead of normal distributions, to impose a lower bound of zero. In lieu of defining a prior on the Calvo probabilities of price and wage adjustment, we follow Rabanal and Rubio-Ramirez (2005) and impose our prior beliefs directly on the duration of price and wage contracts. Specifically, the average durations of US price and wage contracts, which are represented by $\frac{1}{1-\xi_p}$ and $\frac{1}{1-\xi_w}$, respectively, are assumed to be normally distributed with a mean of 3 quarters and a standard deviation of 1 quarter.

To describe the elasticities of substitution between oil and non-oil goods in consumption ψ and between oil and non-oil inputs in production α, we impose diffuse gamma distributions with a mean of 0.5 and a standard deviation of 0.25. Note that the substitution elasticity coefficients α and ψ equal the short-term price-elasticities of oil demand in consumption and production, respectively. Therefore, these prior means are comparable to recent estimates of the price-elasticity of demand reported in various studies, such as, Baumeister and Peersman (2011), Kilian and Murphy (2010) and Bodenstein and Guerrieri (2011); in particular, all of these studies report estimates of the price-elasticity that are centered around 0.5. The literature provides little guidance on the size of the price-elasticity of oil supply. Structural analyses of the oil market (e.g., Bodenstein and Guerrieri 2011) typically consider a perfectly inelastic oil supply curve. However, recent empirical studies by Krichene (2002) and Baumeister and Peersman (2011) suggest the existence of a small but significantly positive oil supply elasticity. Given this evidence, the elasticity of the utilization cost of capital in the oil sector ϑ is assigned a normal distribution with a mean of 15 and a standard deviation of 3. This specification implies that on average, the price-elasticity of oil supply $1/\vartheta$ falls between 0.05 and 0.1 in the 90% confidence interval. We impose a beta distribution on the oil share in consumption δ. The parameterization of this distribution is selected to obtain a mode for δ of 0.04, which is consistent with the mean oil share of consumption observed in the US National Income and Product Accounts (NIPA). Finally, flow adjustment costs in oil inventories φ_O are assumed to be low and gamma distributed with a mean of 0.5 and a standard deviation of 0.25.

4 Baseline Results

We now analyze the relative importance of each shock in driving real oil prices. The current section focuses on the results of this analysis obtained under the baseline specification of the model. More specifically, we first discuss the posterior estimates of the model parameters and then conduct a variance decomposition exercise to evaluate the role of each type of oil shock in explaining fluctuations in the oil market. In the next section (Section 5), we assess the robustness of the baseline results to alternative model specifications that have previously been discussed in the literature. Our aim in this sensitivity analysis is to determine which features of the oil market are important traits to consider in assessments of the relative contribution of shocks to oil price volatility.

4.1 Posterior Estimates

Our baseline estimation results are reported in Table 2, which summarizes the modes, means and the 5^{th} and 95^{th} percentiles of the posterior distributions. We first discuss the mean estimates of the standard parameters and then examine the parameters that are related to the oil market.

Our estimates of the standard parameters are in line with the literature; however, several observations are worth making. Relative to business cycle models that exclude oil (e.g., Christiano et al. 2005 and Smets and Wouters 2007), our model demonstrates a somewhat lower estimate of approximately $h = 0.50$ for consumption habit formation.[18] As noted by Medina and Soto (2005), this difference may reflect the explicit inclusion

[18] Using a sample that is comparable to the sample of the current study, Smets and Wouters (2007) report a habit formation parameter of $h = 0.68$.

of oil in the consumption basket. Through oil consumption demand, the persistence of oil shocks alone will inherently generate persistence in aggregate consumption without requiring a reliance on habit formation. We obtain a mean value of $\sigma_l = 2.88$ for the inverse Frisch elasticity of labor supply. This estimate lies at the high end of those reported in the macro literature but is consistent with values suggested in labor-related studies that utilize micro data (e.g., Altonji 1986). In accordance with the DSGE literature, we find an average contract duration of approximately 1.5 years for US prices and 1 year for US wages. Finally, our estimate of the capital utilization cost $\tilde{\chi} = 0.84$ is somewhat higher than the value of 0.54 reported in Smets and Wouters (2007).

The posterior means of the oil substitution elasticity coefficients in consumption and production are $\psi = 0.04$ and $\alpha = 0.03$, respectively. Although these results are similar to many reduced-form estimates of the price-elasticity of oil demand (e.g., Cooper 2003, Krichene 2002, and Ryan and Plourde 2002), they are significantly lower than more recent estimates that are derived from alternative structural models and on which our prior beliefs are based. Specifically, the 90% confidence intervals of the posterior distributions of ψ and α fall entirely below the corresponding 90% prior confidence intervals of $[0.17, 0.97]$.[19] We find a mean estimate of $\vartheta = 7.52$, which implies that the price-elasticity of oil supply fluctuates around 0.13. Importantly, this value is significantly higher than our prior beliefs, as it lies outside of the prior's 90% confidence interval of $[0.05, 0.10]$. The empirical short-term effect of oil inflation on US headline inflation suggests an average oil share in consumption of 1% (i.e., $\delta = 0.01$). Although this estimate is significantly lower than the value of $\delta = 0.04$ indicated by the NIPA tables, it is consistent with estimates of the oil share in consumption that are reported in other structural analyses of the oil market (e.g., Balke et al. 2010). Together with the calibrated value for $\frac{O^C}{O^G}$, the posterior distribution of δ implies a mean oil share in gross output of approximately 1% or, more specifically, $1 - \eta = 0.008$. Finally, oil inventory adjustment costs are estimated at $\varphi_O = 0.79$.

[19] In an additional robustness exercise that is available upon request, we adopt a looser prior on the oil substitution elasticity coefficients ψ and α to investigate whether our prior choices are driving the differences between our substitution elasticity estimates and those reported in the literature. More specifically, we increase the mean and standard deviation of the prior distributions of both elasticity coefficients to 1 and 0.5, respectively. We find that none of our parameter estimates change significantly in this alternative estimation relative to our baseline model. Therefore, the use of a higher prior mean for the price-elasticity of oil demand will not alter our conclusions regarding the variance decomposition of oil prices.

4.2 Determinants of Oil Market Fluctuations

To evaluate the relative importance of the shocks embedded in the baseline model, Table 3 displays the forecast error variance decomposition of oil market variables at different horizons. For all shocks, we report the mean of the posterior distribution of variance decompositions. For ease of exposition, we present the combined contribution of the US ME oil demand shocks rather than the individual contributions of these shocks. The table also reports the variance decompositions of certain key US macroeconomic variables, including real GDP, headline inflation and the federal funds rate.

[insert Table 3 here]

The relative contributions of domestic shocks to variability in US GDP, headline inflation and the federal funds rate are comparable to Smets and Wouters (2007).[20] Of special interest is the role of oil shocks in the overall US business cycle. We find that oil shocks play a negligible role in explaining US GDP variability. In total, these shocks contribute no more than 5% over all horizons. The oil inventory shock accounts for the bulk of this contribution. By affecting the energy component of the CPI, oil shocks play a larger role for US headline inflation and the federal funds rate. In particular, for forecast horizons below one year, the contributions of oil shocks to headline inflation and the federal funds rate are approximately 33% and 15%, respectively. Over longer horizons, oil shocks account for 28% of the variance in inflation and 8% of the variation in the nominal interest rate. Among the oil shocks, disturbances caused by oil markups are by far the most important source of inflation and interest rate fluctuations (in the short run, 23% and 7%, respectively).

The variance decomposition of the real oil price indicates that oil markup shocks play a dominant role in fluctuations in this price. In particular, their contribution amounts to 65% in the short run and a no less than 40% in the long run. By contrast, with less than 7% over all horizons, oil capacity shocks have relatively low importance with respect to oil price volatility. Due to the low oil depletion rate, the role of oil investment shocks in the forecast error variance of oil prices is essentially negligible. Therefore, supply driven oil price hikes are mainly accounted for by increasing market power of oil producers rather than by shortfalls in oil productive capacity. Oil inventory shocks are the second most important drivers of oil price fluctuations. Over short horizons (i.e., within a year), oil inventory shocks account for approximately 10 to 18% of the forecast error variance of oil

[20] Relative to Smets and Wouters (2007), we find a less important role for wage markup shocks in explaining long-run macroeconomic volatility. This is due to our lower estimate of the persistence ρ_W in the wage markup process. In particular, we obtain a mean estimate of $\rho_W = 0.54$, whereas, for a comparable sample, Smets and Wouters (2007) report a posterior mode of $\rho_W = 0.82$.

prices. In the medium to long run their importance increases to more than 20%. US ME oil demand shocks are of minor importance in explaining oil price volatility; in particular, these shocks explain only 4 to 6% of this volatility at the business cycle frequency (i.e., 4 to 10 quarters). Consequently, our results strongly support the idea that oil price fluctuations are exogenous to US macroeconomic developments. Finally, RoW oil demand shocks account for a stable 17% of oil price volatility across the forecast horizons.

In accordance with the forecast error variance of the real oil price, oil markup and oil inventory shocks account for a sizable portion of volatility in both global oil production and US oil consumption. More specifically, over all horizons, these two shocks together explain approximately 50% of the population variance of oil production and 20% of the forecast error variance of US oil consumption. However, oil markup and oil inventory shocks play a less dominant role in driving oil quantities than in affecting oil prices. Concerning oil production volatility, oil markup shocks lose significance in favor of RoW oil demand shocks in the short term and in favor of shocks that affect oil productive capacity (i.e., oil capacity and oil investment shocks) in the long run. Turning to US oil consumption, we initially notice the poor performance of the model in explaining this variable. In particular, at the business cycle frequency, approximately 50% of the forecast error variance of US oil consumption is explained by the error term in the corresponding oil consumption measurement equation. Furthermore, an important part of US oil consumption variability is accounted for by US ME oil demand shocks: approximately 10% and 54% in the short and long term, respectively. In Section 5, we investigate the sensitivity of our results to a model variant in which the oil consumption measurement error is supplanted with an additional structural stock within the model.

[insert Figure 1 here]

The question arises as to why US ME and RoW oil demand shocks are important drivers of US oil consumption and world oil production, respectively, if these types of shocks contribute significantly neither to the real oil price nor to world oil production and US oil consumption, respectively. The key to understanding these results is that arbitrage elicits trading in oil inventories that in turn counteracts disturbances in the oil market. To illustrate this explanation, in Figure 1, we plot the dynamic effects of RoW oil demand shocks and one form of US ME oil demand shocks (i.e., the US TFP shock) on selected oil variables. In the case of a positive US ME oil demand shock, higher US oil consumption levels exert upward pressure on both world oil production and the real oil price. The subsequent gradual return of oil prices to the lower steady state renders investments in oil inventory unprofitable. Therefore, oil storage declines, which increases oil supply for a given oil production level (as reflected by the negative wedge between oil production and US oil consumption). This occurrence, in turn, dampens any increase in oil production and oil prices and stimulates US oil consumption. By contrast, a positive oil demand shock in the RoW increases world oil production and the real oil price on impact, crowding out US oil consumption. The oil price increase induces investors to reduce their inventory positions; thus, oil storage declines. As a result, the supply of oil increases, mitigating both the initial oil price increase and the negative crowding-out effect on US oil consumption.

Finally, we examine the variance decomposition of oil investments (i.e., active drilling rigs) and oil inventories. Most of the variability in both of these variables is explained by their own respective shocks (i.e., $\hat{\eta}_t^{OI}$ and $\hat{\eta}_t^{OS}$). This result indicates that the model performs poorly with respect to endogenously generating oil investment and oil inventory dynamics. Indeed, even at the two-year horizon, oil investment and oil inventory shocks account for more than 85% of the variation in oil drilling and oil storage, respectively. In the long term (i.e., at quarter 40), the relevance of both disturbances declines. In particular, US ME oil demand shocks account for approximately 50% of oil drilling volatility, whereas the contribution of oil inventory shocks to oil storage volatility declines to approximately 60%. Note that for oil inventories, the corresponding measurement error shock explains between 5% and 30% of the population variance for forecast horizons below one year. Over longer horizons, the oil inventory measurement error plays a negligible role. This result indicates the short-term significance of the '*crude oil adjustments*' that are reported in the oil accounting tables.

5 Alternative Model Specifications

Although the recent oil literature treats oil prices as endogenous, there remains considerable disagreement regarding the relative importance of oil supply and demand shocks in driving oil prices. For instance, Hamilton (2009) and Nakov and Pescatori (2010a) argue that historical oil price changes have primarily been caused by oil supply disruptions. This result is consistent with our baseline conclusion that oil prices are predominantly driven by oil markup shocks. By contrast, Kilian (2009), Kilian and Murphy (2010), Balke et al. (2010) and Bodenstein and Guerrieri (2011) find that shocks to oil demand have historically driven oil prices, whereas oil supply shocks play a negligible role in explaining oil price variability. However, despite their consensus that demand-side disturbances dominate the forecast volatility of oil prices, these studies ascribe the relevant shifts in oil demand to different sources. For instance, Balke et al. (2010) and Bodenstein and Guerrieri (2011) find that oil demand shocks are mainly driven by changes in the relative efficiency of oil usage, whereas Kilian (2009) and Kilian and Murphy (2010) claim that shifts in oil demand primarily stem from precautionary or speculative motives. Finally, Peersman and Van Robays (2009) report an equal contribution of oil supply and demand shocks to oil price volatility.

Why do our baseline results support the notion that oil prices are primarily supply-driven? More generally, which features of the oil market are crucial to explain the ambiguous results in the literature regarding the historical drivers of oil prices? To answer these questions, this section analyzes the robustness of our baseline results for certain alternative model specifications that have been discussed in the literature. First, we impose an inelastic oil supply curve by altering our prior beliefs regarding the price-elasticity of oil supply. Second, we replace the oil consumption measurement error with a structural shock to the relative efficiency of oil usage, as in Bodenstein and Guerrieri (2011). Third, we exclude inventory behavior from the model economy.

[insert Tables 4 and 5 here]

The outcomes of these robustness exercises are summarized in Table 4, which displays the variance decomposition of the real oil price at the two- and four-quarter forecast horizons. In Table 5, we report the posterior estimates for each model specification.[21] We discuss each of the different aforementioned robustness checks in turn.

Inelastic Oil Supply Structural analyses of the oil market traditionally focus on the demand side of the market and simplify the supply side of the market by assuming that the price-elasticity of oil supply lies close to zero (e.g., Kilian and Murphy 2010) or by adopting a perfectly inelastic oil supply curve (e.g., Bodenstein and Guerrieri 2011). Therefore, as an initial robustness assessment, it is instructive to compare our baseline model that features elastic oil supply with a model variant that imposes an inelastic oil supply curve. More specifically, rather than estimating the utilization adjustment cost parameter in the oil sector, we fix the value of this parameter at $\vartheta = 40$, which implies that oil supply elasticity is low at $\vartheta^{-1} = 0.025$. This calibrated value is based on the work of Kilian and Murphy (2010), who impose an upper bound of approximately 0.025 on the impact oil supply elasticity.

[21] In accordance with the baseline results, we also consistently find a dominant role for oil markup shocks in other specifications that we do not present here. For example, the results hold when we allow for nominal rigidities in the pricing decisions of oil producers and when we adopt a looser prior on the oil substitution elasticity coefficients ψ and α. Details pertaining to these additional specifications are available upon request.

The 'Supply-Elas' column in Table 4 presents the variance decomposition of the real oil price for this alternative model specification. As indicated by this column, the variance decomposition changes dramatically in this alternative model relative to our baseline model. The oil markup shock now contributes no more than 6% of the forecast variances in real oil prices, whereas the oil inventory shock accounts for the majority (approximately 80%) of oil price fluctuations. This result is un-surprising because a steeper oil supply curve increases the sensitivity of oil prices to demand-side disturbances. Turning to the 'Supply-Elas' column of Table 5, we note that the use of an inelastic oil supply curve significantly lowers oil inventory adjustment costs φ_O. This robustness check suggests that an appropriate analysis of the relative importance of shocks in driving oil prices should jointly identify the price-elasticity of both oil demand and oil supply. The structural analyses of Kilian and Murphy (2010) and Bodenstein and Guerrieri (2011) report that oil demand shocks are a primary driver of real oil prices. This result is most likely partially explained by these studies' restrictive assumption that oil supply is inelastic.

Oil Efficiency Shocks The variance decomposition analysis of our baseline model indicates that approximately 50% of the volatility in US oil consumption is explained by the error term $\hat{\varepsilon}_t^{mes,OD}$ in its corresponding measurement equation. This result suggests that the baseline model is misspecified in that it does not sufficiently describe the dynamics of oil consumption that are observed in the data. In a second exercise, we aim to correct for this possible misspecification. To this end, we omit the oil consumption measurement error. Instead, in accordance with the approach of Bodenstein and Guerrieri (2011), we introduce a shock to the relative efficiency of oil usage. Concretely, the oil efficiency shock is modeled as a factor-augmenting technology $\hat{\eta}_t^{OE}$ that appears in both the consumption basket $\hat{C}_t$ of core and oil consumption goods and the production technology for gross output $\hat{Y}_t$, which combines oil with domestic input factors. The production functions for $\hat{Y}_t$ and $\hat{C}_t$ then read as follows:

$$\begin{aligned} \hat{Y}_t &= \phi\left(\eta\widehat{VA}_t + (1-\eta)\left(\hat{O}_t^G + \hat{\eta}_t^{OE}\right)\right), \text{ and} \\ \hat{C}_t &= \delta\hat{Y}_t^C + (1-\delta)\left(\hat{O}_t^C + \hat{\eta}_t^{OE}\right). \end{aligned}$$

For completeness, we conduct this robustness check for model variants with both elastic and inelastic oil supply.[22] The results are reported in the 'Oil-Eff' columns of Tables 4

[22] Note that in the current robustness assessment, rather than performing an estimation, we fix the oil share in consumption δ in the model variant that features inelastic oil supply because estimates of the oil share δ in this model variant exhibit a lack of convergence. To address this problem, we set δ in the model variant with inelastic oil supply equal to the estimated value obtained for this parameter in the model variant with elastic oil supply.

and 5. We find that if oil efficiency shocks are added to the model, then the contribution of oil markup shocks to oil price volatility is roughly halved. The declining relevance of oil markup shocks is primarily explained by the non-negligible contribution of oil efficiency shocks, which account for roughly 23% of oil price volatility. As a result, in contrast to our baseline specification, the model variant with oil efficiency shocks indicates that the different types of oil demand shocks in combination are of primary importance in the determination of oil prices. In total, demand shocks explain approximately 70% of the variance in oil prices. However, oil markup shocks continue to dominate the forecast volatility of oil prices in relative terms; in particular, these shocks contribute approximately 25% of this volatility at the business cycle frequency. This result differs from the findings of many recent studies that indicate that supply shocks play a negligible role in explaining oil price variability. Importantly, these recent studies, including those of Kilian and Murphy (2010) and Bodenstein and Guerrieri (2011), utilize a (nearly) perfectly inelastic oil supply curve. As indicated in Table 4, imposing an inelastic oil supply in the current robustness check further reduces the importance of supply shocks in driving oil prices. Finally, an examination of the parameter estimates in the 'Oil-Eff' column in Table 5 reveals that when we include oil efficiency shocks in the analysis, the price-elasticity of oil demand in consumption increases to about $\psi = 0.14$, while the oil supply elasticity decreases to approximately $\vartheta^{-1} = 0.07$.

Oil Efficiency Shocks and No Oil Storage With the exception of Kilian and Murphy (2010), one important difference between our work and other structural analyses of the oil market (including Balke et al. 2010 and Bodenstein and Guerrieri 2011) is that our model treats oil as a storable commodity. Therefore, our final step involves analyzing the importance of oil storage behavior in assessments of the relative contribution of shocks to oil price volatility. In particular, we extend the previous robustness test by excluding oil storage and oil inventory shocks from the model economy while including oil efficiency shocks. This simplified version of our baseline model most closely resembles the setup used by Bodenstein and Guerrieri (2011). Similar to the preceding two checks, we conduct this sensitivity analysis for both a model with elastic oil supply and a model with inelastic oil supply.[23]

The last column in Table 4 (titled 'No-OS') reports the variance decomposition of the

[23] In our initial attempt to estimate the model variant with an inelastic oil supply curve, we encountered a convergence problem for the parameter of the oil share in consumption δ. Therefore, similar to the robustness checks that consider oil efficiency shocks, we fix δ in the current robustness assessment for model variants that feature inelastic oil supply.

real oil price after we add structural oil efficiency shocks and exclude oil storage. In accordance with the results of Bodenstein and Guerrieri (2011), we find in this variant model that oil efficiency shocks play a pivotal role in explaining oil price volatility. More specifically, oil efficiency shocks account for approximately 55% of the forecast error variance of oil prices. Furthermore, relative to our baseline model, the relevance of the oil markup shock for oil price fluctuations declines to approximately 20%, whereas the importance of the RoW oil demand shock slightly increases to roughly 19%. In the 'Oil-Eff' column in Table 5, we observe that our model variant that excludes oil storage also significantly increases the price-elasticity of oil demand ψ in the consumption basket. In particular, ψ increases from $\psi = 0.04$ in our baseline case to approximately $\psi = 0.27$ in the current robustness check. Conversely, relative to the baseline model, the price-elasticity of oil supply decreases from $\vartheta^{-1} = 0.13$ to approximately $\vartheta^{-1} = 0.06$.

From these results, we derive two main conclusions. First, if oil storage is omitted from the analysis, then the contribution of oil efficiency shocks to the real oil price is upwardly biased in that these shocks capture unmodeled disturbances in the speculative holdings of oil inventories. This finding may explain the different conclusions reported by Kilian and Murphy (2010) and Bodenstein and Guerrieri (2011). Both studies find that demand shocks are the primary drivers of oil prices, but they ascribe the underlying shift in oil demand to different sources. Kilian and Murphy (2010) regard oil as a storable commodity and show that demand shocks that are driven by speculative motives have historically been important determinants of oil price fluctuations. Conversely, Balke et al. (2010) neglect to consider storage facilities and find that oil demand disturbances are primarily driven by changes in the relative efficiency of oil usage.

Second, the relative importance of oil demand and supply shocks in driving oil prices is critically dependent on assumptions regarding oil storage. To examine this finding, first note that the model variant with oil storage and oil efficiency shocks (titled 'Oil-Eff') presents the richest setup in our analysis. Subsequently, compare the 'Oil-Eff' model with our baseline model and the model variant in the current robustness check (titled 'No-OS'). The second and third models differ from the first in that each omits a certain type of oil demand shock: oil efficiency and oil inventory shocks, respectively. Relative to the 'Oil-Eff' model, in the baseline model with oil storage, the contribution of the omitted demand shock is absorbed by supply shocks (specifically, oil markup shocks). By contrast, in the model variant that excludes oil storage behavior, the contribution of the omitted demand shock is absorbed by other demand shocks (specifically, oil efficiency shocks). Therefore, we conclude that the presence of oil storage causes real oil prices to be relatively more sensitive to oil supply shocks. This result can be explained by the great volatility of oil prices relative to the volatility of oil quantities that is observed in the data.[24] Recall from the analysis presented in Figure 1 that arbitrage induces trading in oil inventories that act to mitigate the fluctuations in oil prices. As illustrated in detail in Figure 2, this phenomenon implies that the presence of oil storage mitigates the response of oil prices to demand shocks and augments the responses of oil supply and consumption to these shocks. By contrast, the presence of oil storage weakens the response of both oil prices and oil consumption levels to supply shocks. Given these results, oil demand shocks cannot easily generate the relatively high volatility of oil prices to oil quantities that is observed in the data. Oil supply shocks can generate this volatility, although this phenomenon occurs only if the oil demand curve is steep (i.e., if the price-elasticity of oil demand is small).

[insert Figure 2 here]

6 An Analysis of Important Oil Episodes Since 1986

We proceed to evaluate the role of the various oil shocks in driving real oil prices by analyzing their importance for specific episodes. To this end, we perform a historical shock decomposition of the demeaned log of the real oil price in Figure 3. The shaded-area graph illustrates the actual real oil price as a percentage deviation from its sample mean, whereas the solid lines present the cumulative effect of each shock on the real price of oil. To assess the robustness of the results, we conduct this historical decomposition exercise for the three key model environments discussed above: the baseline case with oil inventory shocks (see panel A), the model variant that includes both oil inventory and oil efficiency shocks (see panel B) and the environment that omits inventory behavior and oil inventory shocks while adding oil efficiency shocks (see panel C). If not specifically indicated, the results that we discuss are observed in all three model specifications.

[insert Figure 3 here]

Between 1986 and the beginning of the Gulf War in August 1990, the majority of oil price fluctuations can be explained by the varying degrees of success that OPEC countries experienced in setting prices. Following Iraq's invasion of Kuwait in August 1990, real oil prices rose sharply, increasing from less than 5% to approximately 60% above their average levels. About half of this oil price spike may be explained by capacity-induced supply shortfalls that were related to Iraq's scorched-earth policy, under which Kuwait's

[24] In the sample that we consider, the standard deviation of the demeaned oil price series is approximately 20 times larger than the standard deviation of the linearly detrended oil production series.

oil fields were set on fire. The upward pressure of this decline in oil productive capacity on real oil prices reached a peak in late 1991. Although the last Kuwaiti oil fire had been extinguished prior to this peak, Kuwait required more than two years to restore its productive capacity.

During the first half of the 1990s, oil prices were primarily driven by changes in both the market power of oil producers and the relative efficiency of oil usage. The US 'New Economy' boom supported oil prices during the second half of the 1990s. On average, the three model variants indicate that in 1997 and 1998, approximately two-thirds of the decline in world oil prices can be attributed to a combination of OPEC's declining market power caused by overproduction in Iraq and increasing energy efficiency in both production and consumption. As captured by the RoW oil demand shock, a portion of this decline in oil prices can also be attributed to negative demand pressures associated with the Asian financial crisis. Importantly, following these events, oil inventory shocks appeared to produce negative effects on real oil prices in our model variants that include oil storage behavior. One interpretation of this observation is that increasing oil production and declining oil demand fostered expectations of lower future oil prices and thereby reduced speculative oil demand. This phenomenon was distinctly altered in 1999, when OPEC and non-OPEC countries jointly decided to reduce production to raise oil prices. These coordinated oil supply cuts raised OPEC's perceived market power and increased speculative oil inventory holdings.

Over the course of the early millennium slowdown, both US ME and RoW oil demand shocks placed downward pressure on real oil prices. In 2003, the damaged oil production capacity in the wake of the Iraq war was largely offset by the presence of increasing restraints on the market power of oil producers. As a result, oil prices remained relatively stable during this war. Importantly, our model variants with oil storage indicate that approximately one-third of the sustained surge in oil prices that occurred after 2002 was driven by oil inventory shocks. Thus, our results provide evidence that a percentage of the recent oil price increases can be explained by speculative demand that reflects expectations for either stronger global economic growth or declining oil productive capacity in accordance with the predictions of the peak oil hypothesis. Ex post, these speculative demand pressures appear to have been unfounded with respect to the actual realizations of the shocks. Direct flow demand shocks driven by global economic activity (i.e., RoW and US ME oil demand shocks) accounted for only approximately 20% of the 2002-2008 oil price increases. Moreover, the model variants with oil storage suggest that approximately 25% to 40% of the oil price surge that occurred after 2002 can be explained by an increase in OPEC's market power rather than by capacity-induced supply shortfalls. This latter result is consistent with the work of Hamilton (2009), who argues that after 2001, OPEC may have withheld oil production in anticipation of rising oil prices. This interpretation would suggest that the 2002-2008 oil price surge was largely driven by speculation on the part of oil producers that effectively use below-ground oil as inventories. Finally, as captured by the oil efficiency shock, declining energy efficiency also played a non-negligible role in driving oil prices upward after 2001. The model variant that excludes oil storage behavior even predicts that adverse oil efficiency shocks accounted for approximately half of the recent oil price increases. However, as discussed in the previous section, if oil storage is omitted from the analysis, then the contribution of oil efficiency shocks to oil price fluctuations is upwardly biased in that these shocks capture unmodeled disturbances to oil inventory holdings. Therefore, it is fair to conclude that speculative behavior of both oil consumers and oil producers was a significant driver of the 2002-2008 oil price increases.

7 The Dynamic Effects of Various Types of Oil Shocks

This section provides an account of the most noteworthy impulse responses that are predicted by the model. We aim to assess the differences between the dynamic effects of various types of oil shocks to demonstrate that there is no such thing as a typical oil price shock. Because the variance decomposition exercise presented above indicates that both oil inventory and oil efficiency shocks are important determinants of oil price fluctuations, we conduct our impulse response analysis for the model variant that includes these two types of shocks. In the following subsections, we first discuss the propagation of the three oil supply shocks (i.e., oil capacity, oil markup and oil investment shocks), and we then examine the dynamic effects of the two key oil demand shocks (i.e., oil inventory and oil efficiency shocks). To ensure completeness, we also briefly assess the dynamics triggered by one form of US ME oil demand shock, the US TFP shock.[25] Note that all shocks have been normalized to produce an increase in the real price of oil.

Oil Supply Shocks Figure 4a depicts the impulse responses of selected oil variables to the three types of oil supply shocks. Among these types of oil supply shocks, we can distinguish between shocks that affect oil productive capacity (i.e., oil capacity or oil investment shocks) and shocks that involve shifts in the market power of oil producers (i.e., oil markup shocks). Unfavorable movements in both types of shocks cause oil prices to increase; however, the resulting oil price increases operate through different transmission

[25] Information regarding impulse responses to other US ME oil demand shocks are available upon request.

channels. Therefore, both categories of oil supply shocks produce different effects on drilling activity. After an exogenous decline in oil productive capacity, oil fields must be utilized more intensively to maintain production at pre-shock levels. This effect generates upward pressure on the rental rate for these oil fields, which drives up marginal costs and oil prices, stimulating the development of additional exploitable oil fields.[26] Conversely, unfavorable oil markup shocks dampen drilling activity. If oil producers increase their market power, they will impose a higher price for a particular given productive capacity. The resulting decline in oil demand mitigates the oil capacity utilization rate. Therefore, the rental rate of oil fields declines, slowing the development of oil reserves.

[insert Figure 4a here]

As illustrated in Figure 4b, an examination of the consequences of oil supply shocks for the US economy reveals that all three types of oil supply shocks induce a decline in GDP, consumption, investments, real wages and hours worked. Despite these similar overall consequences, the reactions to different varieties of oil supply shocks cannot be conflated into a single typical oil supply shock response. In particular, the three oil supply shocks cause different inflation and output gap effects, and differ with respect to their implied persistence of the dynamics. Before analyzing these differences in greater detail, we first briefly discuss the key transmission channels triggered by these three types of oil supply shocks. The rise in real oil prices generates a negative income effect on both US consumption and GDP. However, the oil price increase also induces a substitution effect from oil into core consumption. Similarly, as oil becomes more expensive, intermediate goods producers acquire more domestic input factors to substitute for oil. Given the low estimated degrees of oil substitutability in both consumption and production, the income effect prevails over the substitution effects, causing oil demand, GDP, consumption, investments and labor demand to decline. Because consumption levels drop, the decline in labor demand is accompanied by an increase in labor supply. This effect further depresses real wages. Employment declines on net. Finally, the real oil price increase observed on impact and the subsequent expected decline in future oil prices causes investments in oil inventories to be unprofitable. Therefore, investors reduce their oil inventory positions and shift their portfolios to more lucrative investment opportunities. At a given oil production level, the resulting decline in oil storage results in an increase in oil supply, which mitigates the aforementioned negative supply effects.

[insert Figure 4b here]

[26] Note that following a negative disturbance for oil investments, the direct effect of the shock on drilling activity exceeds the positive effects that are induced by the increased utilization rate. Therefore, following a negative oil investment shock, drilling activity decreases on net.

Although the three types of oil supply shocks produce similar dynamic effects on the real side of the economy, their implied persistence of the dynamics is considerably different. In particular, two observations stand out. First, because the oil capacity process is more persistent than the oil markup process, the former generates longer lasting effects. Second, because of the low oil depletion rate, real oil prices increase sluggishly in response to a negative oil investment shock. While domestic consumption and investment expenditures adjust accordingly, the oil producers' lower investment needs significantly push down domestic exports, output and hours worked on impact.

An exogenous increase in the oil markup does not affect the natural level of output and therefore produces a negative output gap. After unfavorable shocks to oil productive capacity (i.e., oil capacity and oil investment shocks), nominal rigidities in price and wage setting engender two opposing effects on the output gap. First, due to nominal price rigidities, price markups decline in response to an implied oil price increase. This effect mitigates the recessionary consequences of a rise in oil prices and contributes to a positive output gap. Second, as a result of both staggered price and wage contracts, the declines in consumption and real wages that occur after contractionary shocks to oil productive capacity increase wage and price markups. These effects reinforce the negative output effects of the oil price increase. In the very short run (two quarters or less), the first effect dominates the second effect in the dynamic responses to an oil capacity shock, leading to a positive output gap. Over the course of the subsequent transition period, the output gap is negative. Because of the sluggish effects of the oil investment shock on oil price dynamics, the negative output gap effect of this type of shock is dominant over all horizons.

The most striking difference between the various types of oil supply shocks relates to their impact on inflation. Following an adverse oil capacity shock, headline (or CPI) inflation increases on impact and then gradually returns to steady state after four quarters. This inflation effect is primarily explained by the direct effects of oil prices on the CPI, although oil capacity shocks cause core inflation rates to increase as well (not shown). The resulting trade-off between output gap and inflation stabilization causes the central bank to raise the real interest rate after approximately three quarters. Similarly, positive oil markup shocks raise headline inflation on impact. However, due to the short-lived nature of the resulting rise in oil prices, oil inflation quickly recedes, reducing headline inflation to below its target level in the third quarter after the shock. Finally, due to a decline in both real wages and the rental rate of capital, negative disturbances in oil investments trigger decreasing core inflation rates. This effect completely offsets the direct upward pressure of the oil price increase on headline inflation. Therefore, given the negative output gap that is triggered by the oil investment shock, the central banker faces no trade-off between stabilizing output and inflation, and the real interest rate therefore declines.

Oil Demand Shocks The analyses of the variance decomposition presented above demonstrates that in addition to oil markup shocks, oil price fluctuations are primarily driven by oil inventory and oil efficiency shocks. Therefore, we next examine the impulse responses of the these two types of oil-specific demand shocks (as displayed in Figures 4c and 4d) and contrast them with the dynamic effects of the oil markup shock. We also briefly discuss the propagation of one type of US ME oil demand shock, namely, the US TFP shock.

[insert Figures 4c and 4d here]

The first two panels of Figure 4d indicate that the dynamic responses of the US economy to positive oil inventory and negative oil efficiency shocks are rather similar to the dynamics induced by unfavorable oil supply shocks. An exogenous adverse shift in the oil stock or in the relative efficiency of oil usage increases global oil demand, oil production and oil prices. Because of the dominance of the income effect in consumption and production, this oil price increase in turn generates downward pressure on US oil consumption, GDP, consumption, investments and hours worked. Thus far, the impulse response analysis indicates that US economic activity does not expand following increases in oil prices. However, the third panel of Figure 4d reveals that higher oil prices do not necessarily lower US GDP. In fact, in the case of expansionary ME oil demand shocks (e.g., positive TFP shocks), the direct positive effects on economic activity compensate for the negative effects of the oil price increase that accompanies the oil demand shock.

Although oil-specific demand and oil markup shocks produce similar dynamic effects on US GDP and its components, it is instructive to note the differences in the dynamics that these two categories of shocks trigger. The only noteworthy differences between the dynamic responses to unfavorable oil efficiency and oil markup shocks are that the former type of shock increases oil production, oil capacity utilization and drilling activity, whereas the latter type of shock generates downward pressure on these variables.

Comparing the impulse responses of oil inventory shocks to those of oil markup shocks, three main differences are prominent. First, in contrast to oil markup shocks, an exogenous increase in oil inventory holdings increases oil storage and oil production. Second, relative to oil markup shocks, unfavorable oil inventory shocks induce a less severe (and almost insignificant) negative output gap and a more sluggish increase in inflation. As a result, for a similar oil price increase, oil inventory shocks generate stronger, more persistent increases in the federal funds rate than oil markup shocks; accordingly, the former type of shocks produces a stronger, more persistent decline in investments than the latter type of shocks. The third difference between the dynamic effects of oil inventory and oil markup shocks relates to their impact on drilling activity. As noted above, unfavorable oil markup shocks dampen the development of exploitable oil fields. Conversely, oil inventory shocks cause two opposing effects on drilling activity. These inventory shocks increase the rental rate of exploitable oil fields, stimulating investments in these fields; however, these shocks also induce the Federal Reserve to stem inflation by raising interest rates. This monetary policy induces an increase in the real interest rate after approximately five quarters, curbing investments in both domestic and foreign economies. On impact, the stimulatory effect prevails over the interest-related effect, and oil investments increase. However, after approximately one year, the strain of the higher real interest rate dominates this stimulatory effect, causing oil investments to fall.

8 Conclusions

This paper provides a close examination of the relative importance of different types of oil demand and supply shocks in driving oil prices. To this end, we develop and estimate (employing Bayesian methods) a DSGE model of the US and the Oil-Producing Countries that includes a well-specified oil market that considers oil prices to be endogenous. By subjecting this model to various perturbations, we investigate the role of certain key features of the oil market in assessments of the historical drivers of oil prices. For instance, we analyze the importance of the size of the price-elasticity of oil supply in determining the relevance of oil shocks for oil price fluctuations. Furthermore, we investigate the implications of treating oil as a storable asset in addition to serving as a production and consumption input. The presence of oil storage produces a dynamic link between expected future oil prices and the current spot price of oil. Within this framework, data on crude oil inventories can be used to identify speculative or precautionary oil demand shocks.

A key result of this paper is that oil inventory behavior and an elastic oil supply curve are important traits to consider in assessments of the relative contribution of shocks to oil price volatility. More specifically, we find that the presence of oil storage and an elastic oil supply renders real oil prices relatively more sensitive to oil supply shocks. Furthermore, we demonstrate that if oil storage is neglected, then the contribution of shocks in the relative efficiency of oil usage to oil prices is upwardly biased in that these shocks capture unmodeled disturbances in speculative holdings of oil inventories. Given the evidence that oil is a storable commodity and that oil supply elasticity is non-zero, our results indicate that oil supply shocks are non-negligible drivers of real oil prices. This result contrasts with the findings of many recent studies that exclude the possibility of oil storage or utilize a perfectly inelastic oil supply curve; in particular, these studies find that demand factors are of primary importance in the determination of oil prices, whereas supply factors play a negligible role in explaining oil price variability. Finally, our results corroborate that not all oil price shocks are alike and support the notion that different sources of oil price fluctuations generate different macroeconomic effects.

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Table 1: Exogenous Shock Processes

US ME Oil Demand Shocks	Time preference shock	$\hat{\eta}_t^T = \rho_T \hat{\eta}_{t-1}^T + \hat{\varepsilon}_t^T$
	Investment-specific technology shock	$\hat{\eta}_t^I = \rho_I \hat{\eta}_{t-1}^I + \hat{\varepsilon}_t^I$
	Exogenous spending shock	$\hat{\eta}_t^G = \rho_G \hat{\eta}_{t-1}^G + \hat{\varepsilon}_t^G + \rho_{GZ} \hat{\varepsilon}_t^Z$
	Total factor productivity shock	$\hat{\eta}_t^Z = \rho_Z \hat{\eta}_{t-1}^Z + \hat{\varepsilon}_t^Z$
	Monetary policy shock	$\hat{\eta}_t^R = \rho_R \hat{\eta}_{t-1}^R + \hat{\varepsilon}_t^R$
	Price markup shock	$\hat{\eta}_t^P = \rho_P \hat{\eta}_{t-1}^P + \hat{\varepsilon}_t^P - \mu_P \hat{\varepsilon}_{t-1}^P$
	Wage markup shock	$\hat{\eta}_t^W = \rho_W \hat{\eta}_{t-1}^W + \hat{\varepsilon}_t^W - \mu_W \hat{\varepsilon}_{t-1}^W$
Oil-Specific Demand Shocks	Oil inventory shock	$\hat{\eta}_t^{OS} = \rho_{OS} \hat{\eta}_{t-1}^{OS} + \hat{\varepsilon}_t^{OS}$
	RoW oil demand shock	$\hat{\eta}_t^{RW} = \rho_{RW} \hat{\eta}_{t-1}^{RW} + \hat{\varepsilon}_t^{RW}$
Oil Supply Shocks	Oil capacity shock	$\hat{\eta}_t^{OC} = \rho_{OC} \hat{\eta}_{t-1}^{OC} + \hat{\varepsilon}_t^{OC}$
	Oil markup shock	$\hat{\eta}_t^O = \rho_O \hat{\eta}_{t-1}^O + \hat{\varepsilon}_t^O$
	Oil investment shock	$\hat{\eta}_t^{OI} = \rho_{OI} \hat{\eta}_{t-1}^{OI} + \hat{\varepsilon}_t^{OI}$

Note: In each shock process i, the innovations $\hat{\varepsilon}_t^i$ are independently and identically distributed random variables following a normal distribution with mean zero and variance σ_i^2.

Table 2: Prior and Posterior Distributions in Baseline Estimation

ESTIMATED STRUCTURAL PARAMETERS			Posterior	
Symbol	Description	Prior (P1,P2)	Mode	Mean [5th; 95th %ile]
h	Cons habit–home & foreign	B (0.70, 0.10)	0.47	0.50 [0.39; 0.61]
σ_c	Risk aversion–home & foreign	N (1.5, 0.375)	1.82	1.80 [1.38; 2.21]
σ_l	Labor utility	N (2.00, 0.75)	2.85	2.88 [1.93; 3.82]
φ_K	Investment. adj. cost– home	N (4.00, 1.50)	6.00	6.33 [4.33; 8.34]
φ_O	Oil inventory adj. cost	G (0.50, 0.25)	0.63	0.78 [0.31; 1.23]
φ_K^*	Investment. adj. cost–foreign	N (4.00, 1.50)	4.64	4.72 [2.74; 6.60]
$\tilde{\chi}$	Cap. util. cost–goods sector	B (0.50, 0.15)	0.86	0.84 [0.74; 0.94]
$\tilde{\chi}^*$	Cap. util. cost–drilling sector	B (0.50, 0.15)	0.50	0.51 [0.41; 0.62]
ϕ	Fixed cost	N (1.25, 0.125)	1.44	1.44 [1.32; 1.57]
γ_p	Indexation core prices	B (0.50, 0.15)	0.26	0.28 [0.11; 0.43]
$1/(1-\xi_p)$	Duration core price contracts	N (3, 1.00)	5.27	5.26 [4.19; 6.28]
γ_w	Indexation wages	B (0.50, 0.15)	0.45	0.45 [0.22; 0.67]
$1/(1-\xi_w)$	Duration wage contracts	N (3, 1.00)	4.50	4.52 [3.53; 5.51]
ψ	Elasticity oil and core cons	G (0.50, 0.25)	0.04	0.04 [0.02; 0.07]
α	Elasticity oil and VA	G (0.50, 0.25)	0.03	0.04 [0.02; 0.05]
ϑ	Cap. util. cost–oil sector	N (15.0, 3.00)	7.14	7.55 [4.67; 10.46]
ρ	Interest smoothing	B (0.75, 0.10)	0.88	0.88 [0.85; 0.91]
r_π	Policy inflation	G (1.50, 0.25)	1.51	1.59 [1.30; 1.87]
r_y	Policy output	G (0.50, 0.25)	0.05	0.08 [0.02; 0.14]
r_{dy}	Policy lagged output	G (0.50, 0.25)	0.30	0.31 [0.22; 0.39]
$\delta \equiv O^C/C$	Oil share in consumption	B(0.13, 0.1)	0.01	0.01 [0.007; 0.012]

CALIBRATED STRUCTURAL PARAMETERS		
β	Discount factor	0.99
θ	Capital share in production	0.24
τ_K	Capital depreciation rate–goods sector	0.025
τ_K^*	Capital depreciation rate–drilling sector	0.025
τ_O	Oil inventory depreciation rate	0.001
κ	Cost of adjusting foreign assets	0.001
η^W	Steady state wage markup	0.5
$(PC)/(sVA)$	Consumption share in GDP	0.62
O^C/O^G	Ratio of oil used in cons. to oil used in prod.	0.84
$I^O/O^{d,US}$	Oil inventory investment share in US oil demand	0.002
μ	Oil depletion rate	0.0065

SHOCKS AR(1), MA(1)		Posterior	
Symbol	Prior (P1,P2)	Mode	Mean [5th; 95th %ile]
ρ_T	B (0.50, 0.15)	0.89	0.86 [0.80; 0.92]
ρ_I	B (0.50, 0.15)	0.82	0.80 [0.70; 0.90]
ρ_G	B (0.50, 0.15)	0.93	0.92 [0.89; 0.96]
ρ_Z	B (0.50, 0.15)	0.98	0.98 [0.97; 0.99]
ρ_R	B (0.50, 0.15)	0.34	0.35 [0.22; 0.48]
ρ_P	B (0.50, 0.15)	0.95	0.93 [0.87; 0.98]
ρ_W	B (0.50, 0.15)	0.58	0.54 [0.33; 0.76]
ρ_{OS}	B (0.50, 0.15)	0.63	0.54 [0.34; 0.73]
ρ_{OC}	B (0.50, 0.15)	0.98	0.97 [0.95; 0.99]
ρ_O	B (0.50, 0.15)	0.80	0.79 [0.72; 0.86]
ρ_{OI}	B (0.50, 0.15)	0.83	0.82 [0.76; 0.89]
ρ_{RW}	B (0.50, 0.15)	0.87	0.86 [0.79; 0.94]
ρ_{GZ}	B (0.50, 0.15)	0.77	0.76 [0.61; 0.91]
μ_p	B (0.50, 0.15)	0.76	0.68 [0.50; 0.89]
μ_w	B (0.50, 0.15)	0.47	0.41 [0.15; 0.67]
SHOCK INNOVATIONS			
σ_T	IG (0.10, 2)	0.04	0.04 [0.03; 0.06]
σ_I	IG (0.10, 2)	0.31	0.33 [0.26; 0.40]
σ_G	IG (0.10, 2)	0.43	0.44 [0.38; 0.50]
σ_Z	IG (0.10, 2)	0.48	0.49 [0.43; 0.55]
σ_R	IG (0.10, 2)	0.11	0.11 [0.09; 0.13]
σ_P	IG (0.10, 2)	0.16	0.16 [0.12; 0.19]
σ_W	IG (0.10, 2)	0.30	0.31 [0.25; 0.37]
σ_{OS}	IG (0.05, 2)	0.04	0.06 [0.02; 0.11]
σ_{OC}	IG (0.10, 2)	0.58	0.59 [0.52; 0.67]
σ_O	IG (0.10, 2)	20.42	21.17 [17.52; 24.83]
σ_{OI}	IG (0.10, 2)	6.38	6.99 [4.15; 9.77]
σ_{RW}	IG (0.10, 2)	1.48	1.48 [1.28; 1.71]
$\sigma_{mes,OD}$	IG (0.10, 2)	1.73	1.77 [1.55; 1.98]
$\sigma_{mes,OS}$	IG (0.10, 2)	0.78	0.78 [0.65; 0.92]
$\sigma_{mes,CU}$	IG (0.10, 2)	0.04	0.06 [0.02; 0.09]

Note: B = Beta, G = Gamma, IG = Inverse Gamma and N = Normal distributions. P1 = Mean and P2 = Standard deviation for all distributions. Posterior moments are computed using 384,000 draws from the distribution simulated by the Random Walk Metropolis Hastings algorithm.

Table 3: Forecast Error Variance Decomposition in Baseline Estimation

OIL VARIABLES

Horizon → / Shocks ↓	Real Oil Price 1Q	2Q	4Q	10Q	40Q	Oil Production 1Q	2Q	4Q	10Q	40Q	US Oil Consumption 1Q	2Q	4Q	10Q	40Q	Oil Investments 1Q	2Q	4Q	10Q	40Q	Oil Inventories 1Q	2Q	4Q	10Q	40Q
ME Oil Demand	2.37	3.05	4.15	6.20	8.67	5.60	6.48	7.67	10.01	20.92	7.28	11.28	18.08	31.73	54.31	2.60	2.96	3.86	8.24	53.82	0.26	0.46	0.83	2.27	12.32
Oil Inventory	9.93	13.43	18.26	22.68	21.56	22.70	27.31	31.87	32.83	26.27	3.09	5.00	7.84	9.96	6.81	0.38	0.36	0.31	0.48	3.80	60.08	79.44	88.55	86.21	60.43
RoW Oil Dem	18.72	18.34	17.70	16.67	15.48	43.28	37.86	31.53	24.93	17.75	4.89	5.71	6.25	5.79	3.93	0.29	0.30	0.32	0.46	1.22	0.87	1.34	1.97	3.50	6.91
Oil Capacity	3.97	4.19	4.58	5.46	6.77	2.40	2.85	3.83	6.86	9.28	1.15	1.47	1.88	2.34	2.29	0.22	0.24	0.30	0.59	2.00	0.25	0.42	0.70	1.68	7.83
Oil Markup	65.01	60.93	55.08	47.91	43.09	25.95	25.36	24.72	23.52	16.99	15.03	16.48	16.43	13.36	8.39	0.70	0.78	0.89	0.98	0.46	1.92	2.84	3.86	5.56	6.57
Oil Investment	0.02	0.06	0.23	1.08	4.42	0.07	0.14	0.38	1.85	8.79	0.03	0.08	0.20	0.67	1.85	95.80	95.36	94.32	89.26	38.70	0.01	0.02	0.05	0.26	5.89
Oil Cons Meas.											68.5	60	49.3	36.1	22.4										
Inventory Meas.																					36.6	15.5	4.05	0.53	0.05

KEY US MACROECONOMIC VARIABLES

Horizon → / Shocks ↓	US GDP 1Q	2Q	4Q	10Q	40Q	US Headline Inflation 1Q	2Q	4Q	10Q	40Q	Federal Funds Rate 1Q	2Q	4Q	10Q	40Q
Time Preference	5.87	5.10	3.47	1.70	1.51	3.31	4.03	4.89	5.62	5.73	36.65	37.95	37.84	36.12	32.78
Inv.-spec. Tech.	16.64	20.34	24.31	25.85	19.74	2.22	2.88	3.68	4.02	5.43	13.02	17.57	24.73	32.51	35.90
Exog. Spend.	18.50	14.01	9.40	5.11	2.88	0.62	0.72	0.86	1.02	1.10	6.15	5.77	5.36	5.32	5.40
TFP	44.30	42.78	41.20	42.01	54.14	1.74	2.09	2.26	2.22	2.49	1.88	1.71	1.51	1.38	2.91
Mon. Pol.	9.84	10.40	9.90	7.36	4.51	5.60	7.23	9.44	11.44	11.22	14.31	11.13	7.67	5.61	5.04
Price Markup	2.84	4.27	6.72	10.47	10.82	38.87	37.09	34.67	32.94	32.36	7.20	6.91	6.07	5.09	5.63
Wage Markup	0.40	0.85	1.91	4.10	3.98	10.91	12.82	13.90	13.48	13.37	3.17	3.79	4.38	4.26	3.91
Oil Inventory	0.52	0.80	1.26	1.61	1.07	5.36	5.49	5.30	5.08	5.02	3.29	3.79	4.07	3.65	3.12
RoW Oil Dem	0.23	0.36	0.50	0.50	0.31	7.04	6.25	5.63	5.37	5.17	6.34	5.21	3.96	2.87	2.44
Oil Capacity	0.11	0.17	0.25	0.33	0.31	1.51	1.37	1.24	1.17	1.14	1.07	0.91	0.73	0.55	0.52
Oil Markup	0.45	0.66	0.86	0.74	0.42	22.80	20.02	18.11	17.62	16.94	6.71	5.09	3.54	2.52	2.18
Oil Investment	0.29	0.26	0.23	0.23	0.30	0.01	0.02	0.02	0.02	0.04	0.20	0.17	0.14	0.12	0.17

Note: 'ME Oil Demand Shocks' indicates the sum of the contributions of the US structural shocks excluding the Oil inventory shock. The influence of each shock at forecast horizon k is measured by the variability generated by a unit standard deviation shock at time $t=0$, cumulated over the period $t=0$ to $t=k$, which is then divided by the aggregate variability induced by all the shocks and expressed in percentage terms. We report the mean based on 300 random draws from the posterior distribution (Each column adds to 100).

Table 4: Real Oil Price Variance Decompositions in Robustness Checks

	MODEL SPECIFICATIONS											
	Baseline		**Supply-Elas**		**Oil-Eff**				**No-OS**			
					Elastic Oil Supply		Inelastic Oil Supply		Sticky Oil Prices		Flex Oil Prices	
HORIZON →	2Q	4Q	2Q	4Q	2Q	4Q	2Q	4Q	2Q	4Q	2Q	4Q
SHOCKS ↓												
ME Oil Demand	3.05	4.15	2.29	2.45	2.71	3.79	2.59	3.58	2.86	4.24	2.44	3.53
Oil Inventory	13.43	18.26	79.01	83.50	17.04	22.37	16.56	21.46				
RoW Oil Dem	18.34	17.70	10.57	7.50	25.95	23.16	23.61	20.84	20.80	17.38	17.53	14.27
Oil Efficiency					24.25	22.53	38.91	36.99	52.69	56.12	65.12	68.42
Oil Capacity	4.19	4.58	1.78	1.60	3.34	3.73	2.77	3.02	3.16	3.68	2.47	2.79
Oil Markup	60.93	55.08	5.57	3.97	26.64	24.19	15.49	13.84	20.43	18.33	12.35	10.72
Oil Investment	0.06	0.23	0.78	0.99	0.06	0.23	0.07	0.26	0.06	0.25	0.07	0.27

Note: The table presents the 2 and 4 quarter ahead forecast error variance decompositions of real oil prices for four different model specifications. 'ME Oil Demand Shocks' indicates the sum of the contributions of the US structural shocks excluding oil inventory and oil efficiency shocks. Model variants are as follows: 'Baseline' indicates the baseline model. 'Supply-Elas' fixes the price-elasticity of oil supply at a low value of $\vartheta^{-1} = 0.025$. 'Oil-Eff' employs the oil efficiency shock as in Bodenstein and Guerrieri (2011). 'No-OS' employs the oil efficiency shock and strips the model of oil inventory investments.

Table 5: Sensitivity Analysis – Posterior Distributions of Structural Parameters

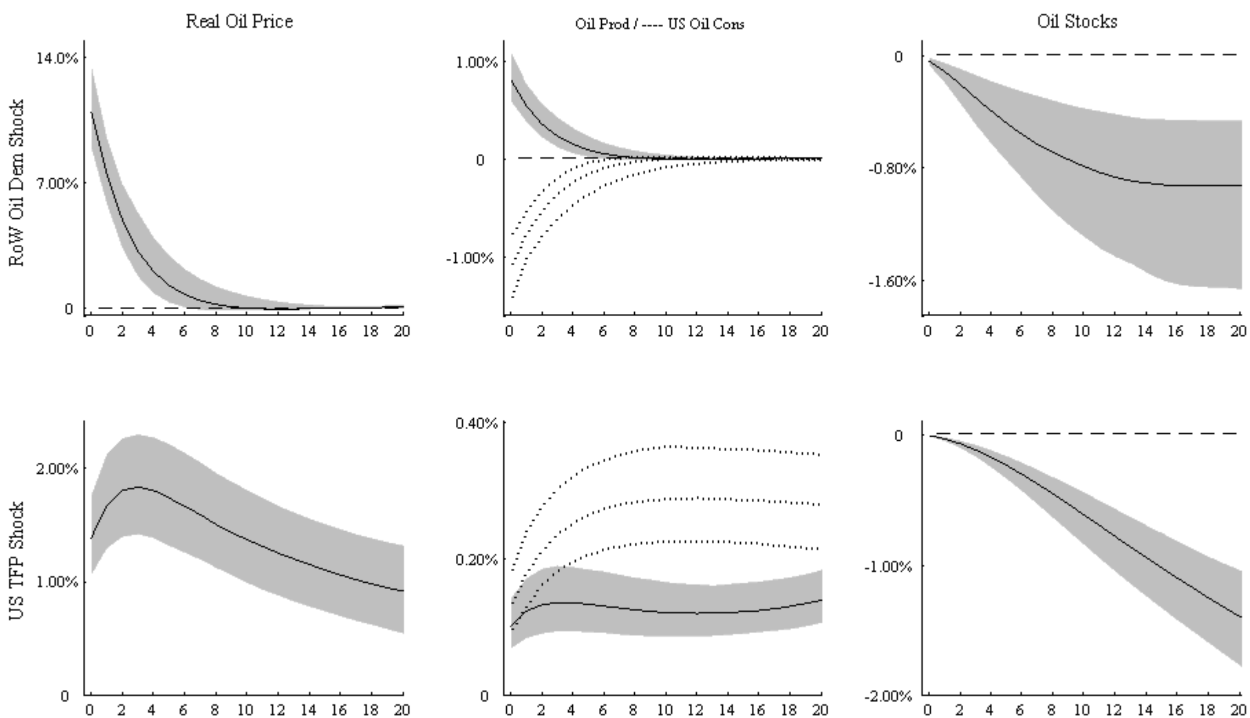
Symbol	Description	PRIOR (P1,P2)	POSTERIOR DISTRIBUTION: Mean [5th; 95th %ile] **Baseline**	**Supply-Elas**	**Oil-Eff** Elastic Oil Sup	**Oil-Eff** Inelastic Oil Sup	**No-OS** Elastic Oil Sup	**No-OS** Inelastic Oil Sup
h	Cons habit–home & foreign	B (0.70, 0.10)	0.50 [0.39; 0.61]	0.53 [0.42; 0.64]	0.51 [0.40; 0.62]	0.53 [0.42; 0.64]	0.52 [0.41; 0.62]	0.54 [0.43; 0.64]
σ_c	Risk aversion–home & foreign	N (1.5, 0.375)	1.80 [1.38; 2.21]	1.88 [1.44; 2.31]	1.89 [1.45; 2.33]	1.91 [1.48; 2.35]	1.92 [1.48; 2.34]	1.92 [1.48; 2.35]
σ_l	Labor utility	N (2.00, 0.75)	2.88 [1.93; 3.82]	3.09 [2.13; 4.03]	3.01 [2.05; 3.98]	3.12 [2.13; 4.05]	3.03 [2.08; 3.97]	3.12 [2.18; 4.10]
φ_K	Investment. adj. cost– home	N (4.00, 1.50)	6.33 [4.33; 8.34]	6.59 [4.64; 8.49]	6.34 [4.33; 8.28]	6.51 [4.45; 8.43]	6.64 [4.59; 8.58]	6.72 [4.78; 8.63]
φ_O	Oil inventory adj. cost	G (0.50, 0.25)	0.78 [0.31; 1.23]	0.01 [0.00; 0.01]	0.59 [0.24; 0.96]	0.58 [0.22; 0.93]		
φ_K^*	Investment. adj. cost–foreign	N (4.00, 1.50)	4.72 [2.74; 6.60]	5.36 [3.46; 7.24]	4.85 [2.99; 6.72]	5.00 [3.18; 6.86]	4.82 [2.87; 6.68]	4.95 [3.10; 6.75]
$\tilde{\chi}$	Cap. util. cost–goods sector	B (0.50, 0.15)	0.84 [0.74; 0.94]	0.84 [0.74; 0.94]	0.85 [0.75; 0.94]	0.85 [0.76; 0.95]	0.85 [0.76; 0.95]	0.85 [0.76; 0.95]
$\tilde{\chi}^*$	Cap. util. cost–drilling sector	B (0.50, 0.15)	0.51 [0.41; 0.62]	0.56 [0.48; 0.65]	0.52 [0.42; 0.63]	0.58 [0.49; 0.67]	0.52 [0.42; 0.62]	0.57 [0.48; 0.67]
ϕ	Fixed cost	N (1.25, 0.125)	1.44 [1.32; 1.57]	1.45 [1.32; 1.57]	1.45 [1.33; 1.57]	1.45 [1.33; 1.57]	1.46 [1.33; 1.58]	1.46 [1.34; 1.58]
γ_p	Indexation core prices	B (0.50, 0.15)	0.28 [0.11; 0.43]	0.25 [0.10; 0.41]	0.29 [0.13; 0.46]	0.29 [0.11; 0.45]	0.28 [0.11; 0.43]	0.28 [0.11; 0.45]
$\tilde{\xi}_p$	Duration core price contracts	N (3.00, 1.00)	5.26 [4.19; 6.28]	5.26 [4.21; 6.27]	5.04 [4.02; 6.04]	5.31 [4.31; 6.30]	5.12 [4.12; 6.12]	5.28 [4.33; 6.25]
γ_w	Indexation wages	B (0.50, 0.15)	0.45 [0.22; 0.67]	0.46 [0.24; 0.69]	0.45 [0.22; 0.67]	0.43 [0.21; 0.65]	0.46 [0.23; 0.68]	0.45 [0.23; 0.67]
$\tilde{\xi}_w$	Duration wage contracts	N (3.00, 1.00)	4.52 [3.53; 5.51]	4.51 [3.52; 5.45]	4.50 [3.50; 5.46]	4.55 [3.55; 5.48]	4.53 [3.53; 5.48]	4.51 [3.54; 5.48]
ψ	Elasticity oil and core cons	G (0.50, 0.25)	0.04 [0.02; 0.07]	0.04 [0.02; 0.06]	0.14 [0.06; 0.21]	0.23 [0.14; 0.33]	0.27 [0.16; 0.37]	0.37 [0.25; 0.48]
α	Elasticity oil and VA	G (0.50, 0.25)	0.04 [0.02; 0.05]	0.03 [0.01; 0.05]	0.07 [0.03; 0.11]	0.07 [0.03; 0.12]	0.08 [0.03; 0.12]	0.08 [0.03; 0.12]
ϑ	Cap. util. cost–oil sector	N (15.0, 3.00) 40	7.55 [4.67; 10.46]	40	14.1 [9.83; 18.0]	40	16.7 [12.9; 20.5]	40
ρ	Interest smoothing	B (0.75, 0.10)	0.88 [0.85; 0.91]	0.88 [0.86; 0.91]	0.88 [0.86; 0.91]	0.89 [0.87; 0.92]	0.89 [0.86; 0.92]	0.89 [0.86; 0.92]
r_π	Policy inflation	G (1.50, 0.25)	1.59 [1.30; 1.87]	1.60 [1.32; 1.86]	1.59 [1.30; 1.86]	1.59 [1.30; 1.87]	1.61 [1.32; 1.89]	1.61 [1.32; 1.89]
r_y	Policy output	G (0.50, 0.25)	0.08 [0.02; 0.14]	0.09 [0.02; 0.17]	0.09 [0.02; 0.16]	0.10 [0.02; 0.17]	0.10 [0.02; 0.17]	0.10 [0.02; 0.18]
r_{dy}	Policy lagged output	G (0.50, 0.25)	0.31 [0.22; 0.39]	0.28 [0.20; 0.36]	0.28 [0.21; 0.36]	0.26 [0.19; 0.34]	0.28 [0.20; 0.36]	0.27 [0.19; 0.34]
δ	Oil share in consumption	B(0.13, 0.1) Fixed	0.010 [0.007; 0.012]	0.009 [0.007; 0.012]	0.008 [0.005; 0.010]	0.008	0.006 [0.004; 0.009]	0.006

Note: Whenever a parameter is not estimated, the concerned cell is left blank. 'Flex-Oil' indicates the model variant with flexible oil prices. 'Baseline' indicates the baseline model. 'Supply-Elas' fixes the price-elasticity of oil supply at a low value of $\vartheta^{-1} = 0.025$. 'Oil-Eff' employs the oil efficiency shock as in Bodenstein and Guerrieri (2011). 'No-OS' employs the oil efficiency shock and strips the model of oil inventory investments. B = Beta, G = Gamma, IG = Inverse Gamma and N = Normal distributions. P1 = Mean and P2 = Standard deviation for all distributions. Posterior moments are computed using 384,000 draws from the distribution simulated by the Random Walk Metropolis Hastings algorithm.

Table 5 (Contd): Sensitivity Analysis – Posterior Distributions of Shock Parameters

Symbol	Description	PRIOR (P1,P2)	POSTERIOR DISTRIBUTION: Mean [5th; 95th %ile] **Baseline**	**Supply-Elas**	**Oil-Eff** Elastic Oil Sup	**Oil-Eff** Inelastic Oil Sup	**No-OS** Elastic Oil Sup	**No-OS** Inelastic Oil Sup
ρ_T	AR(1) Time Impatience	B (0.50, 0.15)	0.86 [0.80; 0.92]	0.84 [0.77; 0.91]	0.87 [0.81; 0.93]	0.86 [0.80; 0.92]	0.85 [0.79; 0.92]	0.84 [0.77; 0.91]
ρ_I	AR(1) Inv. Spec. Tech.	B (0.50, 0.15)	0.80 [0.70; 0.90]	0.79 [0.69; 0.89]	0.82 [0.73; 0.91]	0.82 [0.73; 0.91]	0.79 [0.70; 0.89]	0.79 [0.69; 0.89]
ρ_G	AR(1) Gov. Spending	B (0.50, 0.15)	0.92 [0.89; 0.96]	0.92 [0.88; 0.96]	0.93 [0.89; 0.96]	0.93 [0.89; 0.96]	0.92 [0.89; 0.96]	0.92 [0.89; 0.96]
ρ_Z	AR(1) TFP	B (0.50, 0.15)	0.98 [0.97; 0.99]	0.98 [0.97; 0.99]	0.98 [0.97; 1.00]	0.98 [0.97; 1.00]	0.98 [0.97; 1.00]	0.98 [0.97; 1.00]
ρ_R	AR(1) Monetary Policy	B (0.50, 0.15)	0.35 [0.22; 0.48]	0.39 [0.26; 0.52]	0.36 [0.23; 0.49]	0.38 [0.25; 0.50]	0.38 [0.26; 0.50]	0.40 [0.27; 0.52]
ρ_P	AR(1) Core Price Markup	B (0.50, 0.15)	0.93 [0.87; 0.98]	0.95 [0.90; 0.99]	0.93 [0.88; 0.99]	0.93 [0.89; 0.99]	0.94 [0.89; 0.99]	0.94 [0.90; 0.99]
ρ_W	AR(1) Wage Markup	B (0.50, 0.15)	0.54 [0.33; 0.76]	0.54 [0.33; 0.76]	0.53 [0.32; 0.75]	0.54 [0.32; 0.75]	0.55 [0.33; 0.77]	0.55 [0.33; 0.76]
ρ_{OS}	AR(1) Oil Inventory	B (0.50, 0.15)	0.54 [0.34; 0.73]	0.96 [0.93; 0.99]	0.48 [0.23; 0.75]	0.50 [0.25; 0.74]		
ρ_{OE}	AR(1) Oil Efficiency				0.78 [0.66; 0.91]	0.85 [0.76; 0.93]	0.91 [0.85; 0.98]	0.93 [0.88; 0.98]
ρ_{OC}	AR(1) Oil Capacity	B (0.50, 0.15)	0.97 [0.95; 0.99]	0.97 [0.95; 0.99]	0.97 [0.95; 0.99]	0.97 [0.95; 0.99]	0.97 [0.95; 0.99]	0.97 [0.95; 0.99]
ρ_O	AR(1) Oil Markup	B (0.50, 0.15)	0.79 [0.72; 0.86]	0.76 [0.70; 0.82]	0.77 [0.70; 0.84]	0.77 [0.71; 0.83]	0.77 [0.70; 0.84]	0.76 [0.70; 0.82]
ρ_{OI}	AR(1) Oil Investment	B (0.50, 0.15)	0.82 [0.76; 0.89]	0.80 [0.73; 0.88]	0.82 [0.75; 0.89]	0.81 [0.73; 0.88]	0.82 [0.75; 0.89]	0.81 [0.74; 0.89]
ρ_{RW}	AR(1) RoW Oil Demand	B (0.50, 0.15)	0.86 [0.79; 0.94]	0.72 [0.58; 0.87]	0.73 [0.62; 0.85]	0.73 [0.62; 0.85]	0.66 [0.53; 0.80]	0.66 [0.53; 0.79]
ρ_{GZ}	Corr. TFP – Gov.	B (0.50, 0.15)	0.76 [0.61; 0.91]	0.76 [0.62; 0.91]	0.76 [0.62; 0.92]	0.77 [0.62; 0.92]	0.76 [0.62; 0.92]	0.77 [0.62; 0.92]
μ_p	MA(1) Core Price Markup	B (0.50, 0.15)	0.68 [0.50; 0.89]	0.67 [0.47; 0.87]	0.67 [0.48; 0.87]	0.69 [0.51; 0.88]	0.64 [0.42; 0.86]	0.64 [0.41; 0.86]
μ_w	MA(1) Wage Markup	B (0.50, 0.15)	0.41 [0.15; 0.67]	0.42 [0.15; 0.67]	0.41 [0.15; 0.66]	0.41 [0.15; 0.67]	0.43 [0.17; 0.69]	0.43 [0.17; 0.69]
σ_T	Inno. Time Impatience	IG (0.10, 2)	0.04 [0.03; 0.06]	0.05 [0.03; 0.07]	0.05 [0.03; 0.06]	0.05 [0.03; 0.07]	0.05 [0.03; 0.07]	0.05 [0.03; 0.07]
σ_I	Inno. Inv. Spec. Tech.	IG (0.10, 2)	0.33 [0.26; 0.40]	0.33 [0.26; 0.40]	0.32 [0.25; 0.39]	0.32 [0.25; 0.39]	0.33 [0.26; 0.41]	0.34 [0.26; 0.41]
σ_G	Inno. Gov. Spending	IG (0.10, 2)	0.44 [0.38; 0.50]	0.44 [0.38; 0.50]	0.44 [0.38; 0.51]	0.45 [0.38; 0.51]	0.44 [0.38; 0.51]	0.45 [0.38; 0.51]
σ_Z	Inno. TFP	IG (0.10, 2)	0.49 [0.43; 0.55]	0.49 [0.43; 0.55]	0.49 [0.43; 0.55]	0.49 [0.43; 0.55]	0.49 [0.43; 0.55]	0.49 [0.43; 0.55]
σ_R	Inno. Monetary Policy	IG (0.10, 2)	0.11 [0.09; 0.13]	0.11 [0.09; 0.13]	0.11 [0.09; 0.13]	0.11 [0.09; 0.12]	0.11 [0.09; 0.13]	0.11 [0.10; 0.13]
σ_P	Inno. Core Price Markup	IG (0.10, 2)	0.16 [0.12; 0.19]	0.14 [0.11; 0.18]	0.16 [0.12; 0.20]	0.16 [0.12; 0.19]	0.15 [0.11; 0.18]	0.14 [0.10; 0.18]
σ_W	Inno. Wage Markup	IG (0.10, 2)	0.31 [0.25; 0.37]	0.31 [0.24; 0.37]	0.31 [0.25; 0.37]	0.31 [0.25; 0.37]	0.31 [0.25; 0.36]	0.30 [0.25; 0.36]
σ_{OS}	Inno. Oil Inventory	IG (0.05, 2)	0.06 [0.02; 0.11]	0.08 [0.03; 0.14]	0.10 [0.02; 0.20]	0.10 [0.02; 0.20]		
σ_{OE}	Inno. Oil Efficiency				2.13 [1.62; 2.63]	2.90 [2.17; 3.61]	3.29 [2.44; 4.11]	4.14 [3.05; 5.17]
σ_{OC}	Inno. Oil Capacity	IG (0.10, 2)	0.59 [0.52; 0.67]	0.59 [0.52; 0.66]	0.60 [0.52; 0.67]	0.59 [0.52; 0.67]	0.59 [0.52; 0.67]	0.59 [0.52; 0.67]
σ_O	Inno. Oil Markup	IG (0.10, 2)	21.2 [17.5; 24.8]	63.7 [55.8; 71.4]	28.1 [22.1; 33.8]	63.4 [55.7; 71.2]	31.2 [25.2; 37.1]	63.8 [55.5; 71.4]
σ_{OI}	Inno. Oil Investment	IG (0.10, 2)	6.99 [4.15; 9.77]	8.15 [5.42; 10.8]	7.31 [4.38; 10.2]	8.91 [5.58; 12.0]	7.11 [4.34; 9.78]	8.70 [5.30; 11.9]
σ_{RW}	Inno. RoW Oil Demand	IG (0.10, 2)	1.48 [1.28; 1.71]	2.25 [1.72; 2.74]	2.03 [1.73; 2.31]	2.02 [1.75; 2.30]	2.06 [1.80; 2.30]	2.05 [1.80; 2.30]
$\sigma_{mes,OS}$	Meas. Error Oil Inventory	IG (0.10, 2)	0.78 [0.65; 0.92]	0.48 [0.34; 0.69]	0.73 [0.59; 0.86]	0.73 [0.59; 0.86]		
$\sigma_{mes,OD}$	Meas. Error US Oil Cons.	IG (0.10, 2)	1.77 [1.55; 1.98]	1.74 [1.53; 1.96]				
$\sigma_{mes,CU}$	Meas. Error Oil Cap. Util.	IG (0.10, 2)	0.06 [0.02; 0.09]	0.06 [0.02; 0.09]	0.06 [0.03; 0.09]	0.06 [0.02; 0.09]	0.06 [0.03; 0.09]	0.06 [0.02; 0.09]

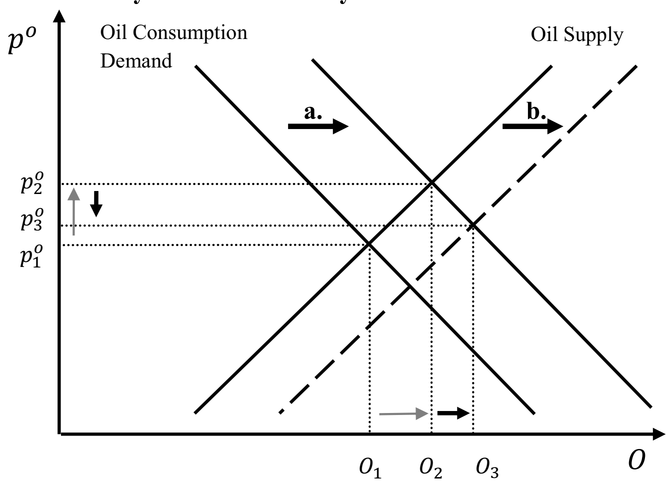
Figure 1: The role of oil storage behavior in the dynamic effects of RoW oil demand and US TFP shocks



Note: Impulse response functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in the real oil price.

Figure 2: Implications of oil storage for the dynamic responses of oil prices and quantities

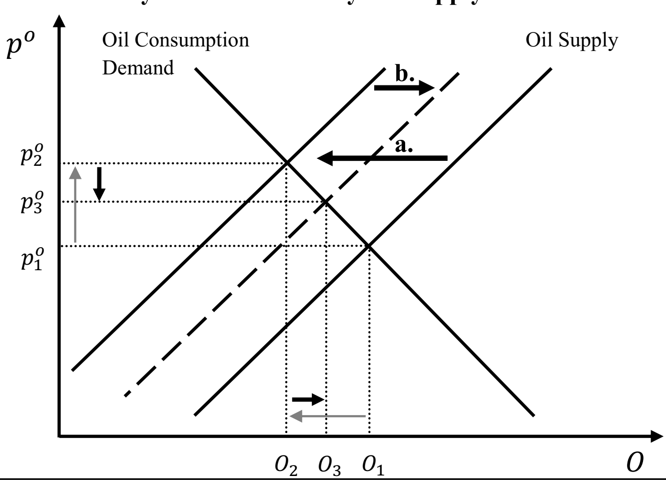
Dynamics Induced by Oil Demand Shocks



a. Consider an exogenous increase in oil demand.
<u>Implications:</u> Oil prices increase from p_1^o to p_2^o ; Oil supply increases from O_1 to O_2.

b. The oil price increase renders investments in oil inventories unprofitable. Therefore, oil storage declines, increasing oil supply.
<u>Implications:</u> The initial oil prices increase is dampened, from p_2^o to p_3^o;
The initial oil supply increase is strengthened, from O_2 to O_3

Dynamics Induced by Oil Supply Shocks

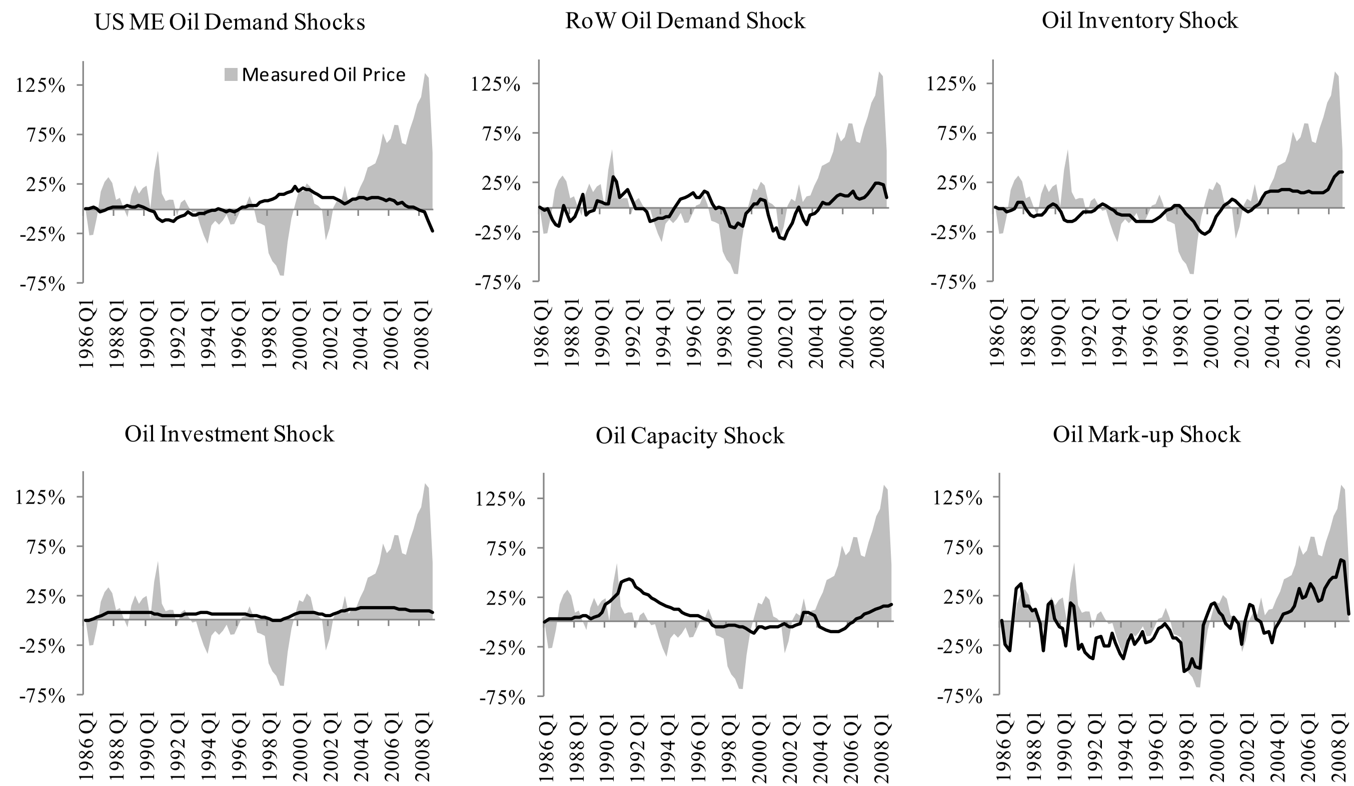


a. Consider an exogenous decline in oil supply.
<u>Implications:</u> Oil prices increase from p_1^o to p_2^o ; Oil supply decreases from O_1 to O_2.

b. The oil price increase renders investments in oil inventories unprofitable. Therefore, oil storage declines, increasing oil supply.
<u>Implications:</u> The initial oil price increase is dampened, from p_2^o to p_3^o;
The initial oil supply decrease is dampened, from O_2 to O_3.

Figure 3: Historical Decomposition of Real Oil Prices

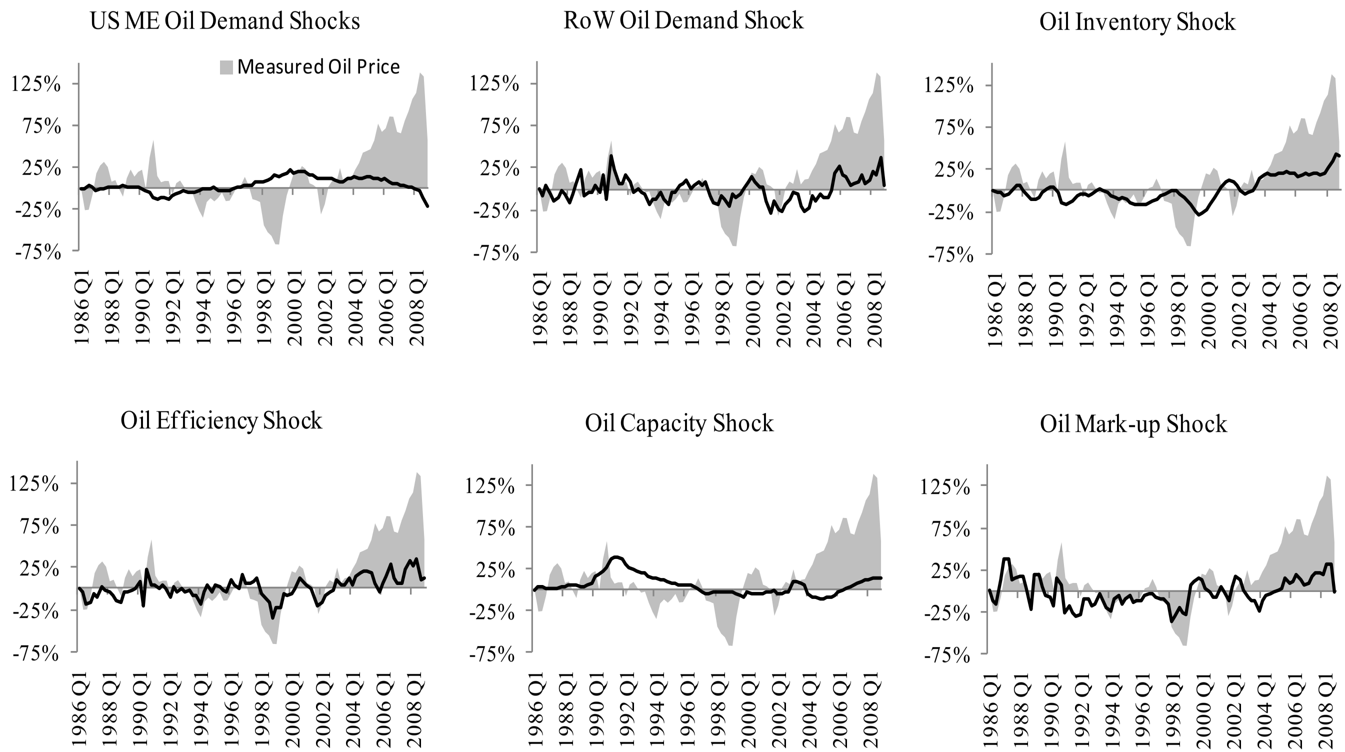
Panel A: Baseline Case: Including Oil inventory Shocks – Excluding Oil Efficiency Shocks



Note: The figure shows the contribution to the demeaned log real oil price of the smoothed estimates of the various oil shocks, ignoring initial conditions. Because the model is linear in the shocks, the contributions are additive. The shaded-area graphs depict the cumulative effect of all shocks, amounting to a measure of the real oil price as a percentage deviation from its sample mean. The solid lines present the cumulative effect of each shock separately. For ease of exposition, we present the combined historical contribution of the US ME oil demand shocks, rather than their individual contributions.

Figure 3 (Contd): Historical Decomposition of Real Oil Prices

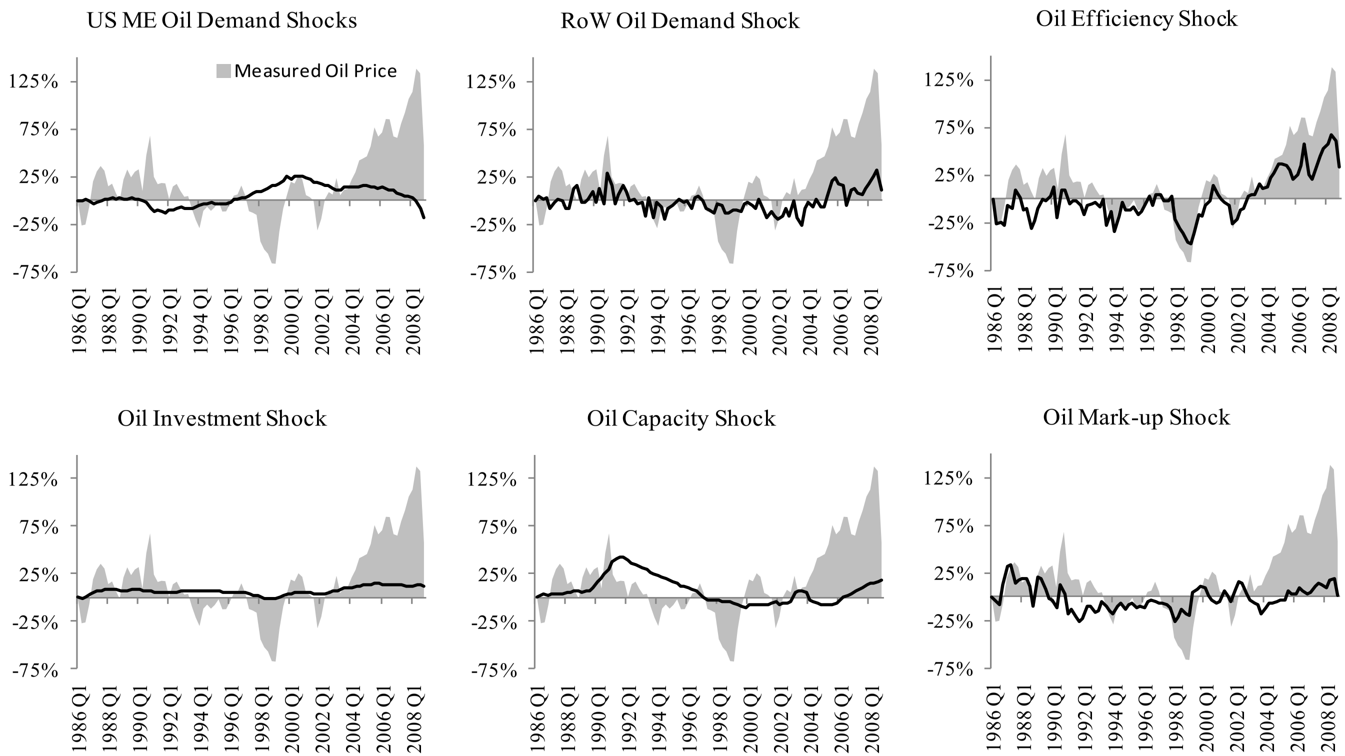
Panel B: '*Oil-Eff*' Model: Including Oil inventory Shocks – Including Oil Efficiency Shocks



Note: See Figure 3 – Panel A. Additionally, note from panel A of Figure 3 that the historical effects of oil investments shocks on the real oil price are negligible. Therefore, for ease of exposition, we do not present the historical contribution of this type of shock in the model variant that includes both oil inventory and oil efficiency shocks.

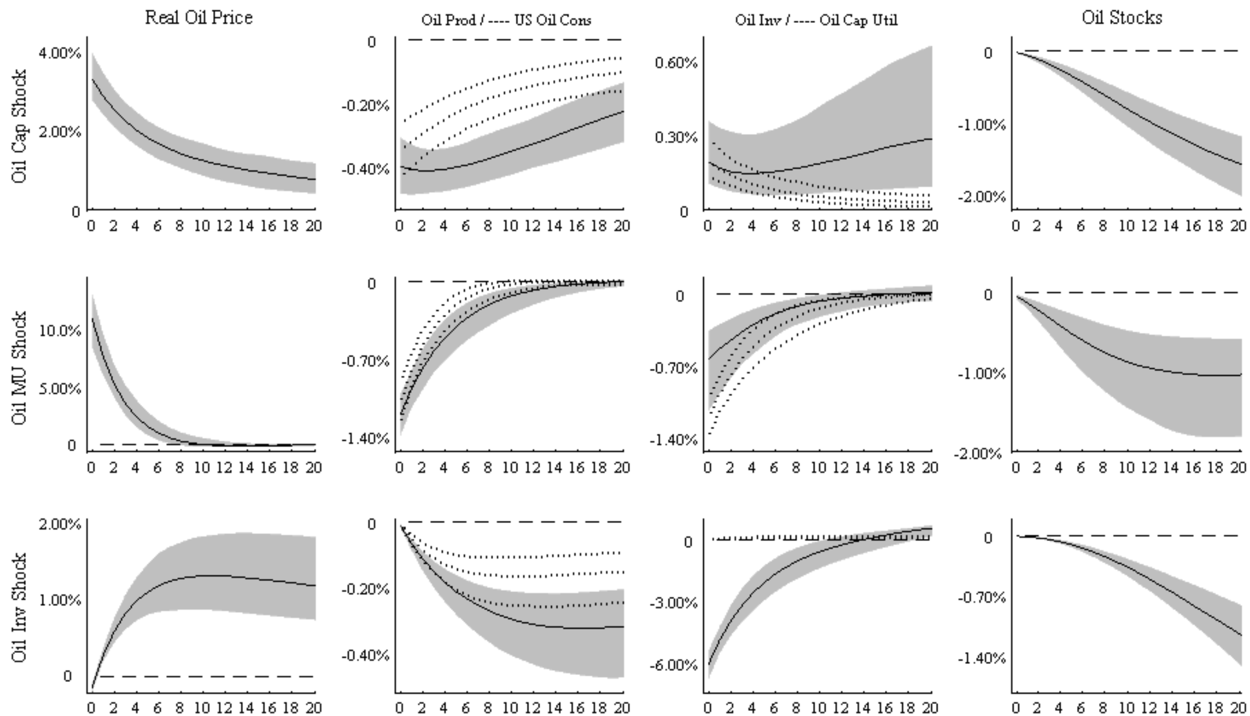
Figure 3 (Contd): Historical Decomposition of Real Oil Prices

Panel C: '*No-OS*' Model: Excluding Oil inventory Shocks – Including Oil Efficiency Shocks



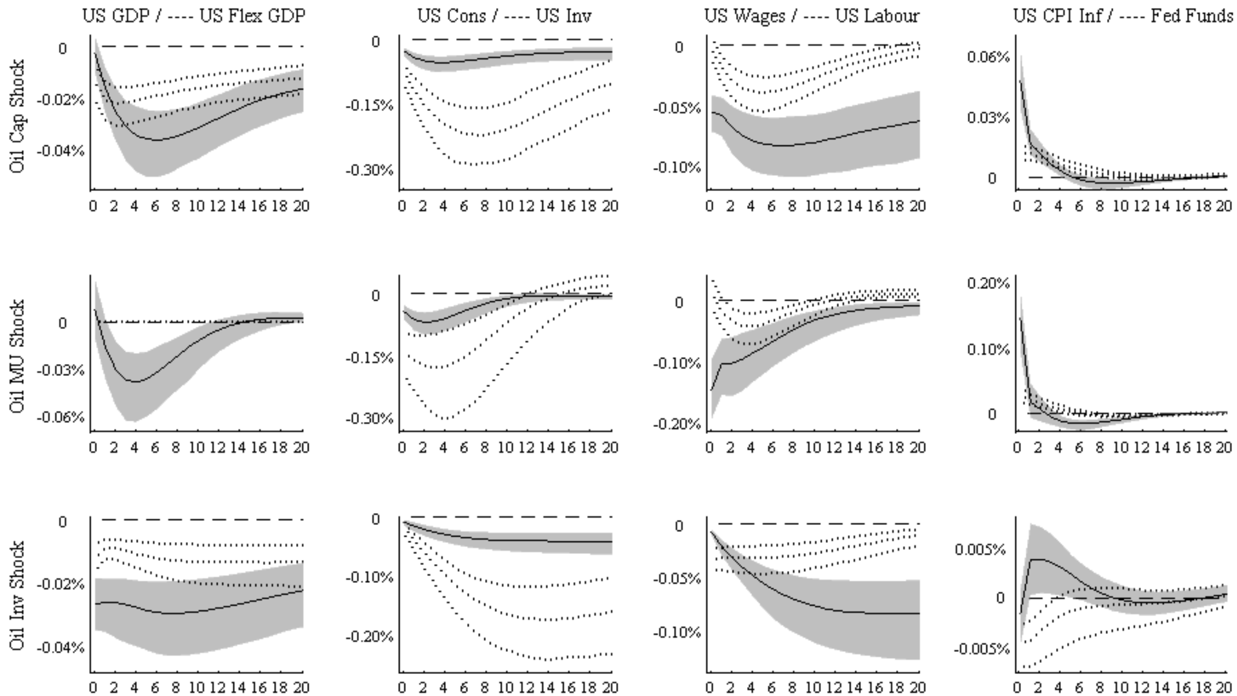
Note: See Figure 3 - Panel A.

Figure 4a: Impulse Responses of Oil Variables to Oil Supply Shocks



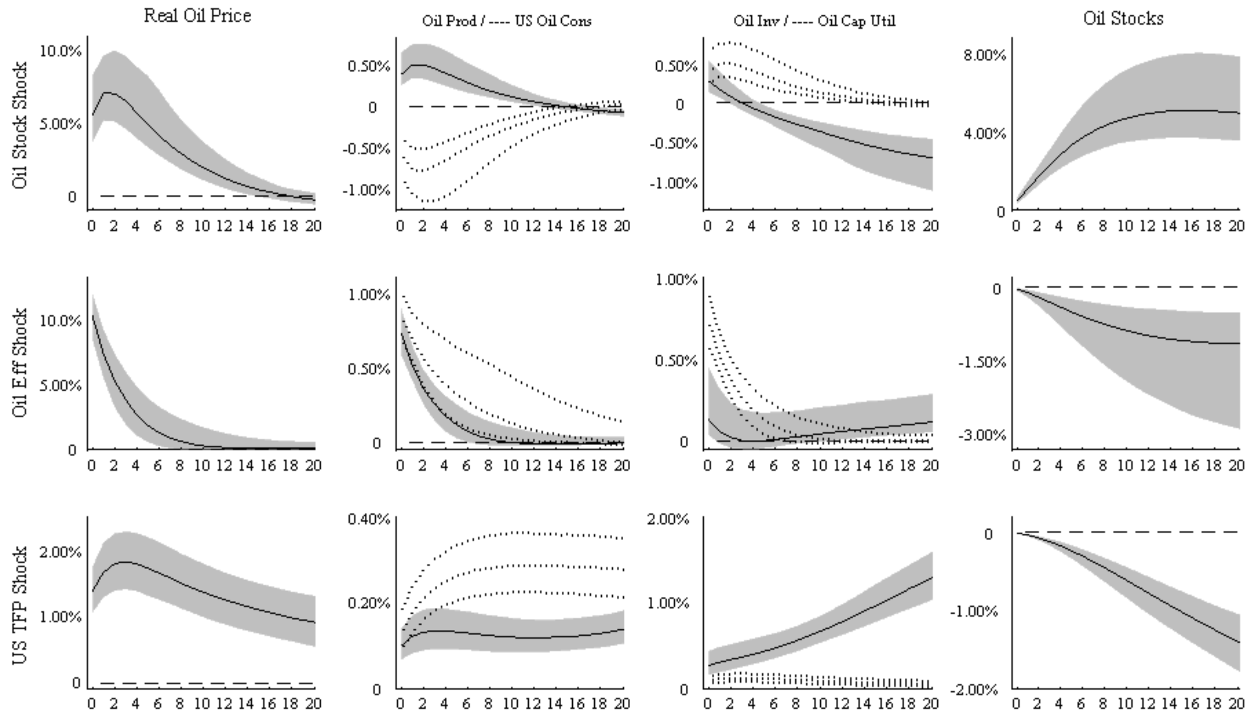
Note: Impulse response functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in the real oil price.

Figure 4b: Impulse Responses of US Variables to Oil Supply Shocks



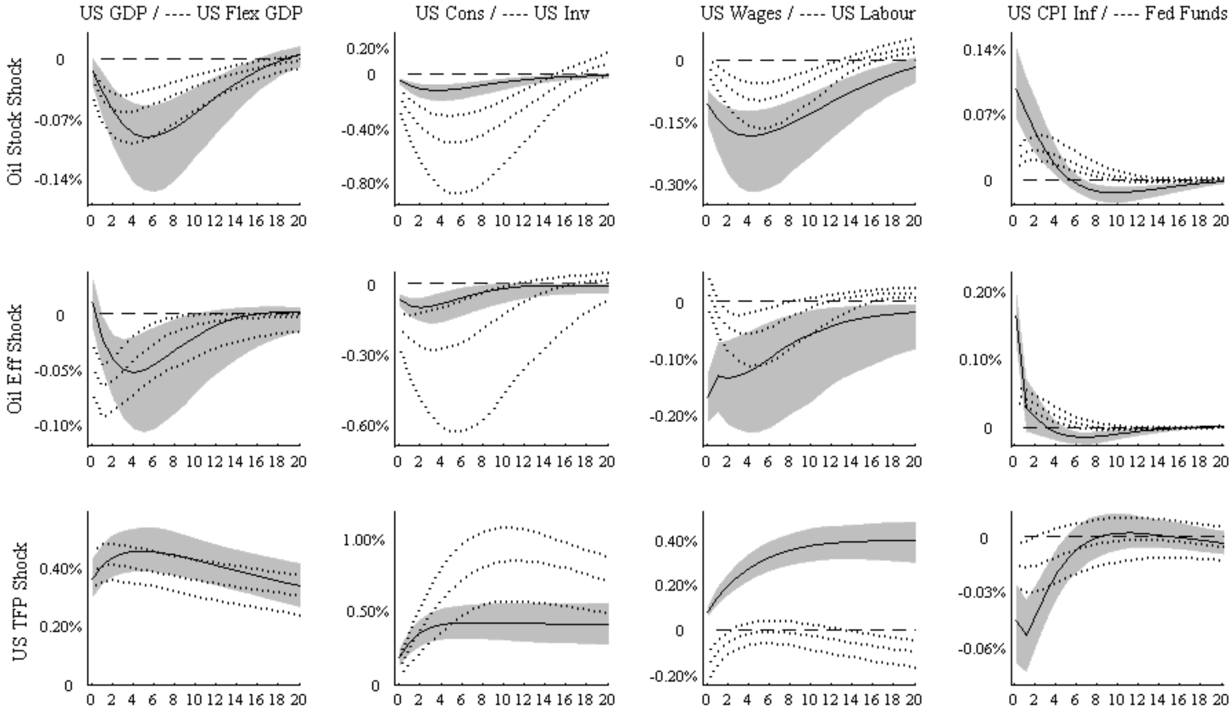
Note: Impulse response functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in the real oil price.

Figure 4c: Impulse Responses of Oil Variables to Oil Demand Shocks



Note: Impulse response functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in the real oil price.

Figure 4d: Impulse Responses of US Variables to Oil Demand Shocks



Note: Impulse response functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in the real oil price.

Chapter 2

Optimal Monetary Policy Response to Endogenous Oil Price Fluctuations

Optimal Monetary Policy Response to Endogenous Oil Price Fluctuations*

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Abstract

Should the central bank seek to identify the underlying causes of oil price hikes in determining appropriate policy responses to them? Most likely not. Within a calibrated new-Keynesian model of Oil-Importing and Oil-Producing Countries, I derive the Ramsey policy and analyze optimal monetary policy responses to different sources of oil price fluctuations. I find that oil-specific demand and supply shocks call for similar policy responses, given the low substitutability of oil in production and the incompleteness of international asset markets.

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1 Introduction

An emerging literature explores the implications of treating oil price shocks as endogenous with sources that could include both demand and supply. One important finding of this line of research is that the economic effects of an oil price change critically depend on the cause of the price change (see, e.g., Kilian 2009, Peersman and Van Robays 2009, Unalmis et al. 2009, Elekdag et al. 2008, Nakov and Pescatori 2010a, Balke et al. 2010, Bodenstein and Guerrieri 2011 and Peersman and Stevens 2013). This finding suggests that distinguishing between the causes of oil price shocks might be important in determining the appropriate policy responses to address them. However, the extent to which the design of optimal monetary policy should depend on the different origins of oil price fluctuations remains an unresolved question. Does the optimal monetary policy response to an oil price increase hinge on the underlying driving force? If so, how important are the differences in policy behavior?

In this paper, I seek to shed light on these questions by deriving the optimal Ramsey-type monetary policy for an oil-dependent economy that operates within an environment of endogenous oil price fluctuations. More specifically, I analyze the dynamic effects of different types of oil shocks and assess the differences in the optimal monetary policy response to these shocks. Furthermore, I compare the dynamics of the Ramsey economy with the dynamics of the model in which monetary policy follows a simple empirical Taylor-type rule to set interest rates. Doing so allows us to evaluate whether actual monetary policy, as captured by the empirical policy rule, either amplifies or dampens the recessionary effects of oil price hikes compared to what is optimal from a welfare point of view.

The framework I employ is based on the two-country dynamic stochastic general equilibrium (DSGE) model of Oil-Importing and Oil-Producing Countries proposed by Peersman and Stevens (2013). This model introduces an oil market in an otherwise standard medium-scale model based on those presented in Christiano et al. (2005) and Smets and Wouters (2007). Relative to Peersman and Stevens (2013), I simplify the model along two dimensions. First, I abstract from oil consumption by households and assume that the oil-importing country uses oil simply and solely as a production input. Second, I model the oil-exporting country in a more stylized way by assuming that oil productive capacity is exogenously given, i.e., the capital stock of oil producers is fixed. Although restrictive, these simplifications are intended to facilitate the interpretation of the results. Moreover, the paper aims to provide initial insights into the optimal monetary policy response to endogenous oil price fluctuations. Therefore, further refinements of the model are left for future research. Optimal monetary policy is studied applying the Ramsey approach, as in, e.g., Schmitt-Grohé and Uribe (2004a, 2005) and Levin et al. (2005). The alternative would be to employ the linear quadratic approach, first introduced by Rotemberg and Woodford (1997) and expanded by Woodford (2003) and Benigno and Woodford (2005). However, the disadvantage of this latter approach is that it relies on a quadratic welfare approximation before solving the policy problem and therefore potentially omits the effects of non-linearities.

This paper is not the first to investigate the relationship between oil price shocks and monetary policy. However, to my knowledge, it is the first to analyze the Ramsey optimal monetary policy response to different sources of oil price fluctuations. A first strand of the literature has focused on the role of monetary policy in the recessionary consequences of oil price hikes, treating oil prices as exogenous supply disturbances. Bernanke et al. (1997, 2004), Hamilton and Herrera (2004) and Dvir and Rogoff (2006) rely on counterfactual policy experiments within vector autoregressive (VAR) models to disentangle the direct effects of oil shocks from those that are due to the systematic monetary policy response. However, because VAR models are non-structural, these policy exercises suffer from a Lucas Critique Problem. Taking this critique seriously, Leduc and Sill (2004), Medina and Soto (2005) and Carlstrom and Fuerst (2006) conduct the same type of counterfactual analyses in microfounded DSGE models. All three contributions find that monetary policy plays an important role in shaping the recessionary effects of oil price hikes. Moreover, they show that the best policy for mitigating the economic downturn is one that stabilizes inflation.

Policies that focus on minimizing output fluctuations are not necessarily optimal from a welfare point of view. Therefore, a second strand of the literature has begun to investigate the optimal monetary policy response in the face of exogenous oil price changes. Wohltmann and Winkler (2008) compare the welfare effects of unanticipated and anticipated oil price shocks. They find that anticipated oil shocks lead to higher welfare losses than unanticipated shocks. Montoro (2010) and Natal (2012) show that when oil has low substitutability in production, exogenous oil price shocks generate an endogenous policy trade-off between inflation and output stabilization. Finally, Winkler (2009) and Kormilitsina (2011) derive the optimal policy response to exogenous oil price shocks and contrast optimal with actual monetary policy. They report conflicting results: Winkler (2009) finds that optimal policy requires a larger output drop than what is observed under a traditional Taylor rule, whereas according to Kormilitsina (2011), optimal policy dampens output fluctuations relative to the actual monetary policy behavior.

Importantly, the above-mentioned contributions on optimal policy behavior ascribe all variations in oil prices to a unique supply shock and hence do not take into account the deeper sources of these fluctuations. However, Bodenstein et al. (2012) argue that policy responses to oil price fluctuations without regard to the origins of these fluctuations are misguided. Within a two-country DSGE model featuring endogenous oil prices, they derive the optimal coefficients of a simple interest rate rule, i.e., the policy coefficient values that maximize welfare, and show that no two shocks induce the same policy response.[1] Although instructive, the approach of optimizing simple rules to study optimal policy behavior poses some problems. First, the coefficients of simple policy rules are invariant to the underlying sources of shocks and are dictated by those shocks that contribute the most to macroeconomic volatility. Therefore, if oil-specific shocks are only of minor importance in driving aggregate variability, the optimized simple rule is most likely not the optimal one to address these shocks. Second, a simple policy rule may be too simple, in that it neglects some important target variables. If this is the case, the optimized instrument rule could be quite different from the fully optimal policy. In this paper, I overcome these issues by deriving the globally optimal Ramsey monetary policy under commitment.

As a second contribution of the paper, I consider different channels through which oil price hikes generate a trade-off for policy makers between stabilizing inflation and output and assess their implications for the conduct of optimal monetary policy. More specifically, I investigate three sources of monetary policy trade-offs. The first source of trade-off is the traditional one in the new-Keynesian literature that arises from the simultaneous presence of price and wage stickiness, as explained by Erceg et al. (2000). The other two sources of policy trade-offs relate to two specific characteristics of the oil market, namely, the low substitutability of oil in production and the fact that oil is traded in an international environment of incomplete asset markets. Drawing on the insights of Montoro (2010), if oil is difficult to substitute, oil price fluctuations generate a time varying wedge between the natural and efficient levels of output. As shown by Corsetti et al. (2010, 2011), incomplete markets induce an additional policy trade-off, in that the central bank aims to counteract wealth-shifting effects across borders, in addition to stabilizing output and inflation.

The central result of this paper is that shocks that are specific to the oil market, such as oil supply disturbances and shifts in oil efficiency, call for rather similar policy responses once we acknowledge that oil is difficult to substitute in production and that international asset markets are incomplete. This suggests that monetary policy that neglects to identify

[1] A similar type of analysis is conducted by De Fiori et al. (2006). Using an open-economy framework that endogenizes the oil market, these authors analyze the performance of optimized simple rules. Their main finding is that the optimal interest rate rule reacts strongly to headline inflation but accommodates increases in oil price inflation.

the causes of oil price fluctuations is not significantly misguided. Intuitively, in a case with low substitutability of oil and incomplete markets, oil-specific demand and supply shocks induce similar welfare effects that call for similar policy responses. More specifically, when oil is difficult to substitute, oil price hikes generate a negative wedge between the natural and the efficient levels of output. Under incomplete markets, oil price hikes induce a shift in wealth from the oil-importing to oil-producing country. I also find that actual policy behavior, as captured by an empirical Taylor-type rule, is significantly different from the optimal conduct of monetary policy. However, whether actual monetary policy amplifies or dampens the recessionary effects of oil price hikes depends on the type of oil shock, the degree of oil substitutability and the degree of international risk sharing.

The paper proceeds as follows. In Section 2, I present the model. Section 3 outlines the calibration. Section 4 derives the optimal policy and assesses the differences in the policy responses to various oil shocks. In Section 5, I analyze the robustness of the results to alternative parameterizations of the price-elasticity of oil supply. Finally, Section 6 draws the main conclusion.

2 The Model

The model I present in this paper is closely related to the two-country model of Oil-Importing and Oil-Producing Countries described in Peersman and Stevens (2013). The oil-importing (domestic) country uses oil as production input. It produces differentiated manufactured goods and sells them on both local and foreign markets. The oil-producing (foreign) country only produces oil. Manufactured goods for consumption are entirely imported from the domestic economy. Conceptualizing the oil-importing country as the US, the oil-producing country maintains a currency peg against the dollar.[2] As a result, the foreign economy needs to adopt the US monetary policy.

The model includes real and nominal frictions standard in the recent generation of new-Keynesian models as proposed by Christiano et al. (2005) and Smets and Wouters (2007). Domestic labor and goods markets are characterized by monopolistic competition and nominal rigidities as in Calvo (1983). Oil producers also operate in a monopolistic market, but can set prices optimally at each point in time. Consumption decisions are subject to external habit formations, and investment adjustments are costly. I assume perfect risk sharing within each country but allow for incomplete international markets.

Following the convention in the optimal monetary policy literature, I assume that fiscal

[2] The main oil-producing countries do, indeed, peg their currencies to the dollar.

policy offsets distortions resulting from the monopolistic competition in labor and product markets. More specifically, production and labor income subsidies are set to restore the Pareto-optimality of the steady state. Therefore, the sole task of monetary policy is to stabilize the business cycle.

The rest of this section outlines the model's equilibrium conditions.[3] Unless otherwise noted, foreign region parameters and variables are denoted by the superscript '*'. Variables without a time subscript refer to the steady-state level. Given that the dollar is the common currency, I use the US Consumer Price Index (CPI) as the numeraire price index for each region.

2.1 Oil-Importing (Domestic) Country

Domestic Firms The domestic economy produces a fixed range of differentiated (non-oil) goods of measure 1, indexed by $i \in (0,1)$. A competitive firm bundles the intermediate goods Y_t^i into an aggregate final good $\widetilde{Y}_t$ according to the constant elasticity of substitution (CES) technology $\widetilde{Y}_t = \left(\int_0^1 Y_t^{i\,\frac{\varepsilon_p-1}{\varepsilon_p}} di\right)^{\frac{\varepsilon_p}{\varepsilon_p-1}}$, where $\varepsilon_p > 1$ is the elasticity of substitution across goods. The demand for each individual good is $Y_t^i = \left(\frac{P_t^i}{P_t}\right)^{-\varepsilon_p} \widetilde{Y}_t$, where P_t^i is the price of intermediate good i. The aggregate price index reads as $P_t = \left(\int_0^1 \left(P_t^i\right)^{1-\varepsilon_p} di\right)^{\frac{1}{1-\varepsilon_p}}$.

Each differentiated good Y_t^i is produced by a single firm, which, therefore, operates in a regime of monopolistic competition. The production of intermediate goods is modeled in the spirit of Rotemberg and Woodford (1996). First, the value added output VA_t^i (i.e., GDP) is produced under a Cobb-Douglas production function with labor $\widetilde{L}_t^i$ and capital services $K_t^{S,i}$, weighted by θ and $1-\theta$, respectively; i.e., $VA_t^i = \eta_t^a \left(\widetilde{L}_t^i\right)^{\theta} \left(K_t^{S,i}\right)^{1-\theta}$. Total factor productivity (TFP) η_t^a is assumed to follow an exogenous process. Second, value added is aggregated with oil O_t^i by means of a CES technology to produce gross output Y_t^i; i.e., $Y_t^i = \left(\eta^{\frac{1}{\alpha}} \left(VA_t^i\right)^{\frac{\alpha-1}{\alpha}} + (1-\eta)^{\frac{1}{\alpha}} \left(\eta_t^{oe} O_t^i\right)^{\frac{\alpha-1}{\alpha}}\right)^{\frac{\alpha}{\alpha-1}} - \Phi$, where $\alpha > 0$ defines the elasticity of substitution between value added and oil in production, η is the share of GDP in gross output and Φ denotes fixed costs. The term η_t^{oe} represents an exogenous shock that affects the relative efficiency of oil usage (henceforth, 'oil efficiency shock').

[3] An appendix containing detailed model derivations is available at http://users.ugent.be/~ansteven.

Cost minimization implies the following demand curves for labor and oil:

$$\widetilde{L}_t^i = \frac{\theta}{1-\theta}\frac{r_t^k}{w_t}K_t^{S,i}, \tag{1}$$

$$O_t^i = \left(\frac{s_t}{p_t^o}\right)^{\alpha}\frac{1-\eta}{\eta}VA_t^i\left(\eta_t^{oe}\right)^{\alpha-1}, \tag{2}$$

with,

$$s_t \equiv \left(\frac{r_t^k}{1-\theta}\right)^{1-\theta}\left(\frac{w_t}{\theta}\right)^{\theta}\frac{1}{\eta_t^a}, \tag{3}$$

where p_t^o denotes the real oil price, w_t represents the real wage rate and r_t^k is the rental rate of capital. The auxiliary variable s_t captures the GDP-deflator expressed in real terms of units of consumption. Real marginal costs are equal across firms and given by

$$mc_t = \left(\eta\left(s_t\right)^{1-\alpha} + (1-\eta)\left(\frac{p_t^o}{\eta_t^{oe}}\right)^{1-\alpha}\right)^{\frac{1}{1-\alpha}}. \tag{4}$$

Price decisions are subject to Calvo (1983)-staggering. Non-adjusted prices are indexed to lagged inflation. If $\xi_p \in (0,1)$ is the Calvo price stickiness parameter, $\gamma_p \in (0,1)$ denotes the degree of price indexation and $\beta \in (0,1)$ represents the discount factor, then the first-order condition of a firm that is able to re-optimize its price $\overline{P}_t^i$ is given by

$$(1+\tau_p)\frac{\overline{P}_t^i}{P_t} = (1+\lambda_p)\frac{\Psi_t^p}{\Phi_t^p}. \tag{5}$$

λ_p is the steady-state (net) price markup, which equals $\lambda_p = \frac{\varepsilon_p}{\varepsilon_p-1} - 1$. The parameter τ_p captures production subsidies. Following Schmitt-Grohé and Uribe (2004b) the variables Ψ_t^p and Φ_t^p are defined recursively as

$$\Psi_t^p = mc_t\tilde{Y}_t + \beta\xi_p E_t\left[\left(\frac{U_{c,t+1}}{U_{c,t}}\right)\left(\frac{\pi_{t+1}^p}{(\pi_t^p)^{\gamma_p}}\right)^{\varepsilon_p}\Psi_{t+1}^p\right], \tag{6}$$

$$\Phi_t^p = \tilde{Y}_t + \beta\xi_p E_t\left[\left(\frac{U_{c,t+1}}{U_{c,t}}\right)\left(\frac{\pi_{t+1}^p}{(\pi_t^p)^{\gamma_p}}\right)^{\varepsilon_p-1}\Phi_{t+1}^p\right], \tag{7}$$

where π_t^p denotes the gross price inflation rate, i.e., $\pi_t^p = P_t/P_{t-1}$, and E_t is the expectations operator conditional on the information set at the beginning of period t. The variable $\beta\frac{U_{c,t+1}}{U_{c,t}}$ represents the one-period stochastic discount factor, which depends on the households' marginal utility of consumption $U_{c,t}$ (discussed below). If prices are perfectly flexible, i.e., $\xi_p \to 0$, the optimality condition (5) simplifies to $(1+\tau_p)\overline{P}_t^i = (1+\lambda_p)P_t mc_t$. The monopolistic supplier of good i then sets its price $\bar{P}_t^i$ as a constant markup $\frac{(1+\lambda_p)}{(1+\tau_p)}$ over marginal costs. I assume that firm output is subsidized to eliminate the monopolistic distortion associated with a positive markup, i.e., $\tau_p = \lambda_p$.

Domestic Households The domestic economy is made up of a continuum of differentiated households, indexed by $\tau \in (0,1)$, which seek to maximize lifetime utility $E_0 \sum_{t=0}^{\infty} \beta^t U_t^\tau$. Period utility is a positive function of consumption C_t^τ and a negative function of hours worked L_t^τ, $U_t^\tau = \frac{1}{1-\sigma_c} \left(C_t^\tau - hC_{t-1}\right)^{1-\sigma_c} - \frac{1}{1+\sigma_l} \left(L_t^\tau\right)^{1+\sigma_l}$, where $\sigma_c > 0$ is the degree of risk aversion, $h \in (0,1)$ captures external habit formation in consumption and $\sigma_l > 0$ is the inverse Frisch elasticity of labor supply. The marginal utilities of consumption and labor are, respectively,[4]

$$U_{C,t} = \left(C_t - hC_{t-1}\right)^{-\sigma_c}, \tag{8}$$

$$U_{L,t} = -\left(L_t\right)^{\sigma_l}. \tag{9}$$

Households have access to several types of assets to facilitate the inter-temporal transfer of wealth. First, they can purchase domestic risk-free bonds, for which the gross nominal interest rate is given by R_t. The optimal choice of bonds yields the usual consumption Euler equation,

$$U_{c,t} = E_t \left(\beta \frac{R_t}{\pi_{t+1}^p} U_{c,t+1} \right). \tag{10}$$

Second, households hold international securities. I contrast the complete- and incomplete-market cases. Under complete markets, a full set of state-contingent claims is traded internationally, such that risk is equally shared across borders. Given that the foreign economy pegs its currency to the domestic currency, the international equilibrium risk-sharing condition reads as

$$U_{c,t} = U_{c,t}^*, \tag{11a}$$

where $U_{c,t}^*$ denotes the foreign households' marginal utility of consumption. Therefore, in the case of complete international capital markets, marginal consumption utilities are equal in both countries. Conversely, when markets are incomplete, only one non-state-contingent bond can be traded internationally. Then, the optimal choice of foreign bond holdings leads to the uncovered interest parity (UIP) condition,

$$R_t^* = R_t \left(1 + \kappa \left(\frac{NFA_t - NFA}{Y}\right)\right), \tag{11b}$$

which replaces the risk-sharing condition (11a) observed in the complete-market case. The non-state-contingent international bond pays interest R_t^*, which equals the domestic rate

[4] I assume the existence of complete domestic markets that insure the households against variations in household specific labor income, i.e., the marginal utility of wealth is identical across different types of households. Each household then chooses the same level of consumption and investment. Therefore, we can suppress the household specific index τ in the first order conditions reported below.

R_t, corrected for a default risk premium. This risk premium depends positively on the net foreign asset position NFA_t, with $\kappa > 0$, and acts as a stationarity-inducing device.[5]

In addition to accumulating financial wealth, households can invest I_t in the physical capital stock K_t. Capital services K_t^S are related to the physical stock of capital through $K_t^S = z_t K_{t-1}$, where z_t is the capital utilization rate set by the households. Variations in the capital utilization rate entail a cost in units of consumption, denoted by the increasing convex function $\chi(z_t)$.[6] The optimal condition for the utilization rate equates the rental price of capital with the marginal cost of higher capital utilization,

$$r_t^k = \chi'(z_t). \tag{12}$$

Accumulation of physical capital takes the form

$$K_t = (1-\delta_K)K_{t-1} + \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) I_t, \tag{13}$$

where $\delta_K \in (0,1)$ represents the depreciation rate of capital. Following Christiano et al. (2005), investment changes are assumed to be costly, measured by the investment adjustment cost function $S\left(I_t/I_{t-1}\right)$.[7] The optimal choice of physical capital gives rise to the usual Tobin's Q equation,

$$Q_t = E_t\left[\frac{\pi_{t+1}^p}{R_t}\left[\left(r_{t+1}^k z_{t+1} - \chi(z_{t+1})\right) + Q_{t+1}(1-\delta_K)\right]\right], \tag{14}$$

which equates the real return on bond holdings to the real return on capital accumulation. Investment adjustment costs imply that current investment is a function of its lagged and expected future value, as well as the current value of capital,

$$\begin{aligned} 1 \;=\; & Q_t\left\{1 - S\left(\frac{I_t}{I_{t-1}}\right)\right\} - Q_t I_t\left\{S'\left(\frac{I_t}{I_{t-1}}\right)\right\}\frac{1}{I_{t-1}} \\ & + E_t\left[\frac{\pi_{t+1}^p}{R_t} Q_{t+1} I_{t+1}\left\{S'\left(\frac{I_{t+1}}{I_t}\right)\right\}\left(\frac{I_{t+1}}{I_t{}^2}\right)\right]. \end{aligned} \tag{15}$$

Following Erceg et al. (2000), households are monopolistic suppliers of differentiated labor types l_t^τ and set wages in a Calvo (1983)-staggered manner. In addition, I stipulate

[5] See Benigno (2009) for details of the non-stationarity problem, and how to resolve it, in open-economy models with incomplete financial markets.

[6] As in Christiano et al. (2005), I impose that in steady state $z = 1$, $\chi(z) = 0$ and $\chi \equiv \frac{\chi''(z)}{\chi'(z)} \geqslant 0$. In Section 3, I discuss the functional form for $\chi(u_t)$ in greater detail.

[7] Following Christiano et al. (2005), I assume that the adjustment cost function $S(.)$ has the following steady-state properties: $S(1) = S'(1) = 0$ and $S''(1) > 0$. The specific functional form ascribed to $S(.)$ is presented in Section 3.

that non-adjusted wages are indexed to lagged price inflation. Analogously to final goods producers, a competitive labor bundler buys the differentiated labor types and aggregates them to $\widetilde{L}_t = \left(\int_0^1 l_t^{\tau\,\frac{\varepsilon_w-1}{\varepsilon_w}} d\tau\right)^{\frac{\varepsilon_w}{\varepsilon_w-1}}$, with $\varepsilon_w > 1$ denoting the elasticity of substitution between different labor types. Demand for labor is given by $l_t^\tau = \left(\frac{W_t^\tau}{W_t}\right)^{-\varepsilon_w} \widetilde{L}_t$, where W_t^τ is the price of labor type τ and W_t is the aggregate wage index, which reads as $W_t = \left(\int_0^1 W_t^{\tau\ 1-\varepsilon_w} d\tau\right)^{\frac{1}{1-\varepsilon_w}}$. A household τ that is able to re-optimize its nominal wage will set $\overline{W}_t^\tau$ such that

$$(1+\tau_w)\left(\frac{\overline{W}_t^\tau}{W_t}\right)^{1+\varepsilon_w\sigma_l} = (1+\lambda_w)\,\frac{\Psi_t^w}{\Phi_t^w}, \tag{16}$$

where λ_w is the steady-state (net) wage markup, which equals $\lambda_w = \frac{\varepsilon_w}{\varepsilon_w-1} - 1$, and τ_w are subsidies to labor income. Ψ_t^w and Φ_t^w are auxiliary variables, which according to Schmitt-Grohé and Uribe (2004b), can be expressed in recursive form as

$$\Psi_t^w = \left(\widetilde{L}_t\right)^{1+\sigma_l} + \beta\xi_w E_t\left[\left(\frac{1}{(\pi_t^p)^{\gamma_w}}\right)^{\varepsilon_w(1+\sigma_l)}\left(\pi_{t+1}^w\right)^{\varepsilon_w(1+\sigma_l)}\Psi_{t+1}^w\right], \tag{17}$$

$$\Phi_t^w = U_{c,t}^\tau w_t \widetilde{L}_t + \beta\xi_w E_t\left[\left(\frac{1}{(\pi_t^p)^{\gamma_w}}\right)^{\varepsilon_w-1}\left(\pi_{t+1}^w\right)^{\varepsilon_w-1}\Phi_{t+1}^w\right], \tag{18}$$

where $\xi_w \in (0,1)$ is the Calvo parameter for nominal wage stickiness, $\gamma_w \in (0,1)$ denotes the degree of wage indexation and π_t^w is the gross wage inflation rate. Wage subsidies τ_w are set equal to λ_w to eliminate the distortion resulting from monopolistic competition and to restore the efficiency of the steady state. As a result, if wages are perfectly flexible, i.e., $\xi_w \to 0$, the marginal rate of substitution between leisure and consumption equals the real wage, i.e., $w_t = -\frac{U_{l,t}}{U_{c,t}}$.

2.2 Oil-Exporting (Foreign) Country

Oil Producers Analogously to the (non-oil) goods producers in the oil-importing country, crude oil producers operate in a regime of monopolistic competition.[8] There is a continuum of oil producers, indexed by $j \in (0,1)$, with each producing one particular type of oil $O_t^{*,j}$. Oil production is described by an AK-technology, $O_t^{*,j} = \eta_t^{oc} D_t^{S,j}$, where $D_t^{S,j}$ represents capital services and η_t^{oc} is the exogenous oil production technology. The physical capital stock D_t^j should be interpreted as a combination of exploitable oil fields

[8] Because oil producing firms are situated all around the world, each produces a type of oil that is differentiated from the other oil producers' output in terms of geographical distance.

and the installed machinery on these fields. Given the small oil depletion rate and the substantial time required to develop new exploitable oil fields, I assume, for simplicity, that this physical capital stock is fixed, i.e., $D_t^j = \overline{D}$. Short-term fluctuations in capital services are captured by the variable utilization rate u_t, implying $D_t^{S,j} = u_t\bar{D}$. Oil production occurs at normal capacity, denoted $OCAP_t^*$, if $u_t = 1$; therefore, $OCAP_t^* = \eta_t^{oc}\bar{D}$. Accordingly, I refer to exogenous disturbances of the oil sector's TFP η_t^{oc} as 'oil capacity shocks'. Military conflicts or natural disasters that destroy oil productive capacity are examples of such exogenous oil supply events.

The real marginal costs of oil-producers mc_t^* equal the rental rate of capital services r_t^d divided by TFP,

$$mc_t^* = r_t^d \frac{1}{\eta_t^{oc}}. \tag{19}$$

Given the monopolistic competitive market structure, oil prices P_t^o are set as a markup $(1 + \lambda_{o,t})$ over marginal costs,[9]

$$(1 + \tau_o) P_t^o = (1 + \lambda_{o,t}) P_t mc_t^*, \tag{20}$$

where τ_o are production subsidies. In contrast to domestic goods prices, oil prices are perfectly flexible. Therefore, variations in the oil markup $\lambda_{o,t}$ are ascribed entirely to exogenous sources, denoted η_t^o, i.e., $\lambda_{o,t} = \eta_t^o$, that represent shifts in the market power of oil producers (henceforth, 'oil markup shocks').[10] Similar to the domestic economy, the government offsets the steady-state effect of monopolistic distortions in the oil sector by enacting the appropriate magnitude of production subsidies τ_o.

Foreign Households The representative foreign household seeks to maximize expected lifetime utility $E_0 \sum_{t=0}^{\infty} \beta^t U_t^*$. In contrast to domestic households, period t utility only depends on consumption C_t^*. In particular, I assume that $U_t^* = \frac{1}{1-\sigma_c^*}\left(C_t^* - h^* C_{t-1}^*\right)^{1-\sigma_c^*}$, where $\sigma_c^* > 0$ is the degree of risk aversion and $h^* \in (0,1)$ is the degree of external habit formation. Note that consumption goods C_t^* are entirely imported from the domestic economy. The optimal consumption path is determined by the familiar Euler equation,

$$U_{c,t}^* = E_t\left(\beta \frac{R_t^*}{\pi_{t+1}^p} U_{c,t+1}^*\right), \quad \text{where} \quad U_{c,t}^* = \left(C_t^* - h^* C_{t-1}^*\right)^{-\sigma_c^*}. \tag{21}$$

[9] Because oil prices are perfectly flexible, each intermediate oil producer optimally chooses the same price, i.e., $P_t^{o,j} = P_t^o$, and produces the same oil amount, i.e., $O_t^{*,j} = O_t^*$. Therefore, we can drop the index j from the oil producers' first order conditions.

[10] Modeling OPEC as a cartel would induce behavioral equations for oil producers that, up to the first order, are observationally equivalent to those obtained in my model. In that case, we could interpret oil markup shocks as shifts in the degree to which cartel agreements are observed by its members.

When there is a complete set of state-contingent claims in the international capital market, risk is equally shared across borders and $U^*_{c,t} = U_{c,t}$, see condition (11a).

Foreign households also choose the utilization rate of the oil capital stock, of which a level of u_t induces a utilization cost of $\vartheta(u_t)$ units of consumption goods. The first-order condition for this utilization rate is

$$r^d_t = \vartheta'(u_t). \tag{22}$$

Given the installed oil capital stock $\overline{D}$, the household increases the utilization rate up to the point where the marginal revenue equals the marginal cost of additional oil exploitation.

Oil Supply Curve By combining the aggregate oil production function, i.e., $O^*_t = \eta^{oc}_t D^S_t$, with equations (19), (20), and (22), we obtain the oil supply curve, the log-linearized form of which is

$$\widehat{O}^*_t = \hat{\eta}^{oc}_t + \frac{1}{\vartheta}\left(\widehat{p}^o_t\right) - \frac{1}{\vartheta}\left(\frac{1}{1+\lambda_o}\hat{\eta}^o_t - \hat{\eta}^{oc}_t\right), \tag{23}$$

where $\vartheta \equiv \frac{\vartheta''(u)u}{\vartheta'(u)}$ and variables in their log deviations around the deterministic steady state are denoted by the superscript '^', i.e., $\widehat{X}_t = \log\left(\frac{X_t}{X}\right)$. Note that the price-elasticity of the supply of oil equals the inverse of the elasticity of marginal utilization costs with respect to the utilization rate, i.e., $\frac{dO_t/O_t}{dp^o_t/p^o_t} = \frac{1}{\vartheta}$. Remarkably, both unfavorable oil capacity shocks and oil markup shocks cause an increase in oil prices for a given level of output; however, the resulting oil price increases operate through different transmission channels. Therefore, each category of oil supply shock produces a different effect on the oil capacity utilization rate. It is through these differing effects that these shocks can be identified. If oil producers increase their market power, they impose a higher price without affecting the oil capacity utilization rate, holding all other factors constant. Conversely, following an exogenous decline in oil productive capacity, oil fields must be utilized more intensively to maintain a given level of production. This effect generates upward pressure on the rental rate of oil fields, which increases marginal costs and oil prices.

2.3 Aggregation and Market Clearing

Labor market clearing implies

$$L_t = s^w_t \widetilde{L}_t, \tag{24}$$

where $\widetilde{L}_t = \int_0^1 \widetilde{L}^i_t di$ and $L_t = \int_0^1 L^\tau_t d\tau$ denote aggregate labor demand and aggregate labor supply, respectively. The term $s^w_t = \left(\int_0^1 \left(\frac{W^\tau_t}{W_t}\right)^{-\varepsilon_w} d\tau\right) \geqslant 1$ is a measure of wage dispersion, which according to Schmitt-Grohé and Uribe (2004b), can be rewritten to obtain

$$s_t^w = (1-\xi_w)\left(\frac{\overline{W}_t^\tau}{W_t}\right)^{-\varepsilon_w} + \xi_w\left(\left(\pi_{t-1}^p\right)^{\gamma_w}\right)^{-\varepsilon_w}\left(\frac{1}{\pi_t^w}\right)^{-\varepsilon_w} s_{t-1}^w. \tag{25}$$

The goods market clearing condition is given by

$$Y_t = s_t^p \widetilde{Y}_t, \tag{26}$$

where $\widetilde{Y}_t$ equals the aggregate demand for final goods, $Y_t = \int_0^1 Y_t^i di$ denotes the aggregate production of intermediate goods and $s_t^p = \left(\int_0^1 \left(\frac{P_t^i}{P_t}\right)^{-\varepsilon_p} di\right) \geqslant 1$ is a measure of price dispersion. Similar to the wage dispersion measure, price dispersion can be expressed recursively as

$$s_t^p = (1-\xi_p)\left(\frac{\overline{P}_t^i}{P_t}\right)^{-\varepsilon_p} + \xi_p\left(\left(\pi_{t-1}^p\right)^{\gamma_p}\right)^{-\varepsilon_p}\left(\frac{1}{\pi_t^p}\right)^{-\varepsilon_p} s_{t-1}^p. \tag{27}$$

Because oil prices are flexible, aggregate oil demand $O_t = \int_0^1 O_t^i di$ equals aggregate oil supply $O_t^* = \int_0^1 O_t^{*,j} dj$, i.e.,

$$O_t = O_t^*. \tag{28}$$

By integrating the budget constraints of all domestic households τ, we obtain, after some manipulations, the national income account of the domestic economy,[11]

$$\begin{aligned} \tilde{Y}_t &= C_t + I_t + \chi(z_t)K_{t-1} + p_t^o O_t + \eta_t^g \\ &\quad + \left(NFA_t - \frac{R_{t-1}^*}{\pi_t^p} NFA_{t-1}\right) + \frac{\kappa}{2}\frac{1}{Y}\left(NFA_t - \overline{NFA}\right)^2, \end{aligned} \tag{29}$$

where η_t^g denotes exogenous government consumption. Finally, the foreign income account (30) reads as

$$p_t^o O_t^* = C_t^* + \vartheta(u_t)\bar{D} - \left(NFA_t - \frac{R_{t-1}^*}{\pi_t^p} NFA_{t-1}\right). \tag{30}$$

2.4 Monetary Policy

The oil-exporting country adopts the domestic country's monetary policy because it pegs its currency to the dollar. With respect to the oil-importing country, I consider two

[11] One of the manipulations requires substituting out taxes using the government budget constraint. The government collects lump-sum taxes T_t^r from households to finance price and wage subsidies and its exogenously given consumption η_t^g, i.e., $T_t^r = \tau_p P_t \widetilde{Y}_t + \tau_w P_t w_t \widetilde{L}_t + \eta_t^g$.

different monetary policy regimes. First, I derive the optimal monetary policy under commitment. Second, I assume that the monetary authority commits itself to a simple instrument rule. I discuss these two policy regimes in turn. First, however, recall the inclusion in the analysis of fiscal subsidies that offset the steady-state monopolistic distortions of production and employment. As a result, the central bank plays no role in offsetting the effects of steady-state distortions and focuses exclusively on stabilizing the business cycle.

Optimal Policy Optimal monetary policy is studied using the Ramsey approach; i.e., the monetary authority maximizes conditional expected social welfare V_0, given the non-linear constraints of the competitive economy, where welfare V_0 equals the expected discounted sum of lifetime utilities of all domestic agents,

$$V_0 = E_0 \sum_{t=0}^{\infty} \beta^t U_t^{\tau}. \tag{31}$$

In solving the optimization problem, I assume that ex-ante commitment is feasible. Moreover, I focus on the optimal policy from a time-invariant monetary policy perspective, as proposed by Woodford (2003).[12] The alternative method of analyzing optimal monetary policy would be to employ the linear quadratic approach. In contrast to the Ramsey approach, this method relies on a quadratic welfare approximation prior to solving the policy problem. Specifically, in this case, optimal policy behavior is derived from maximizing the linear quadratic approximation of the welfare objective (31), subject to the first-order (or linear) approximations of the structural equations. The disadvantage of this approach is that it may neglect the effects of non-linearities in the model, due to its approximate nature.

To compute the Ramsey-optimal policy under timeless-perspective commitment, I formulate an infinite-horizon Lagrangian problem, in which the central bank maximizes conditional expected social welfare (31), subject to the full set of non-linear constraints implied by the private sector's behavioral equations and the market-clearing conditions of the model economy. The first-order conditions for this problem describe the Ramsey-optimal conduct of monetary policy. I employ the symbolic Matlab procedures developed by Levin and Lopez-Salido (2004) to derive the central bank's first-order conditions in practice. Under these procedures, the Lagrangian is first differentiated with respect to each endogenous variable, with the derivatives subsequently set to zero. Then, we obtain the model

[12] The time-invariant optimal monetary policy approach assumes that by the initial period, $t = 0$, the economy has been operating for an infinite number of periods. As a result, the planner's optimal rule at time $t = 0$ can be substituted for the optimal policy conditions derived for any arbitrary period $t > 0$.

economy under optimal policy by combining the optimal policy conditions with the private sector's behavioral equations and the market-clearing conditions

Taylor-type Policy The second policy regime that I consider is one in which the monetary authority follows a simple Taylor-type rule with interest rate smoothing,

$$R_t = R^{1-\tau_R} \left(R_{t-1}\right)^{\tau_R} \left(x_t\right)^{\tau_y(1-\tau_R)} \left(\frac{\pi_t^p}{\pi^p}\right)^{\tau_\pi(1-\tau_R)} \left(x_t/x_{t-1}\right)^{\tau_{dy}}. \tag{32}$$

Under this regime, the interest rate is adjusted in response to the level and growth rate of the output gap, price inflation, and the lagged interest rate. The corresponding feedback coefficients are, τ_y, τ_{dy}, τ_π, and τ_R, respectively. Throughout the paper, the output gap x_t is defined as the deviation of actual value added VA_t from potential value added VA_t^p, where the latter is the value added that would prevail under flexible prices and wages in the absence of the oil markup shock, i.e., $x_t = \frac{VA_t}{VA_t^p}$. Note the difference between the potential and natural level of output. The latter is the level of output that would prevail under flexible prices and wages but with markup shocks present. Therefore, in the analysis discussed below, the potential level of output differs from the natural level of output only following oil markup shocks. The values of the policy parameters are drawn from Peersman and Stevens (2013), who obtain estimates of the policy rule (32) in a full-fledged DSGE model of the US and oil-producing countries. Therefore, under the assumed calibration (outlined in Section 3), the simple Taylor-type rule can be viewed as describing the conduct of actual monetary policy.

3 Calibration

Functional Forms Before discussing the calibration, I first specify the functional forms of the investment adjustment cost $S\left(I_t/I_{t-1}\right)$ and the capacity utilization costs $\chi(z_t)$ and $\vartheta(u_t)$.

The investment adjustment cost function, taken from Levin et al. (2005), is

$$S\left(\frac{I_t}{I_{t-1}}\right) = \varsigma\frac{1}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2. \tag{33}$$

Note that in steady state, adjustment costs are zero, i.e., $S\left(1\right) = 0$, and of only second order, i.e., $S'\left(1\right) = 0$ and $S''\left(1\right) = \varsigma > 0$.

Again, following Levin et al. (2005), I define the capacity utilization cost $\chi(z_t)$ incurred by domestic households as a CES function of its capacity utilization rate z_t, i.e.,

$$\chi(z_t) = a\frac{(z_t)^{1+\chi} - 1}{1+\chi}, \tag{34}$$

where $\chi \geqslant 0$ is the elasticity of marginal utilization costs with respect to the utilization rate. The parameter $a > 0$ is selected such that steady-state utilization costs are zero. The same specification is used for the foreign capacity utilization cost function $\vartheta(u_t)$, where the inverse of the elasticity of the marginal utilization cost corresponds to the price-elasticity of oil supply, i.e., $1/\vartheta = \frac{dO_t/O_t}{dp_t^o/p_t^o}$ (see equation (23)).

Calibration Table 1 displays the calibration of the model. Unless otherwise noted, parameter values are drawn from Peersman and Stevens (2013), who estimate an extended version of the model using a full-information Bayesian approach. Before turning to the parameters that are specific to the oil market, I first comment on the standard parameters.

[insert Table 1 here]

In brief, most of the estimates of the standard parameters, reported in the companion paper, are in line with the literature. Considering a quarterly calibration of the model, the discount factor is set to $\beta = 0.99$. Physical capital depreciates at an annual rate of 10%, i.e., $\delta_K = 0.025$. The labor cost share of value added at steady state is calibrated as $\theta = 0.76$. Approximately one fifth of all manufactured goods are consumed by the government, $\eta^g/\widetilde{Y} = 0.21$. I assume that the utility parameters are symmetric across the two economies. More specifically, in both countries, the coefficient of habit formation is set at $h = h^* = 0.48$, and the degree of relative risk aversion is $\sigma_c = \sigma_c^* = 1.80$. Consistent with studies including nominal wage rigidities, the inverse Frisch elasticity of labor supply is given a relatively high value of $\sigma_l = 2.8$.[13] The elasticity of the cost of changing investments ς and the elasticity of utilization costs with respect to utilization χ are both set to six. I calibrate the Calvo price and wage adjustment cost parameters as $\xi_p = 0.8$ and $\xi_w = 0.75$, respectively, which implies an average contract duration of approximately five quarters for prices and four quarters for wages. The degree of indexation to past inflation is $\gamma_p = 0.25$ for prices and $\gamma_w = 0.45$ for wages. The long-run price markup is calibrated as $\lambda_p = 0.39$, whereas the wage markup takes a relatively lower value of $\lambda_w = 0.2$. Under the Taylor-type policy, the monetary policy rule exhibits a high degree of interest rate smoothing, with τ_R calibrated at 0.87, whereas the coefficients on inflation,

[13] See, e.g., Rabanal and Rubio-Ramirez (2005) for a comparison of estimates of the Frisch elasticity $1/\sigma_l$, obtained in flexible wage new-Keynesian models, with those observed in sticky wage environments.

the size of the output gap, and changes in the output gap are set at $\tau_\pi = 1.5$, $\tau_y = 0.05$ and $\tau_{dy} = 0.3$, respectively. In the case of incomplete international capital markets, we must consider a non-zero cost in acquiring net foreign assets to restore the stationarity of the model. Following Jacob and Peersman (2013), I assume that the elasticity of the cost of accumulating foreign debt is low, with $\kappa = 0.001$.

Turning to the parameters that are specific to the oil market, first note that I normalize the real steady-state oil price to one. The long-run oil price markup is calibrated as $\lambda_o = 0.75$.[14] I set $\eta = 0.95$, implying a share of oil in gross output of 5%. The degree of oil substitutability is considered to be low, with $\alpha = 0.03$. Note that the substitution elasticity coefficient equals the short-run oil demand elasticity (see equation (2)). Therefore, the calibrated value for α is consistent with reduced-form evidence on the steepness of the oil demand curve reported in, e.g., Dahl and Sterner (1991), Krichene (2002), Cooper (2003), and Atkins and Jazayeri (2004). In particular, all of these studies estimate the price-elasticity as lying between 0 and 0.11. The elasticity of the utilization cost of capital in the oil sector ϑ is selected to obtain a price-elasticity of oil supply of approximately 0.1, i.e., $\vartheta = 10$. This baseline calibration is based on evidence provided in Peersman and Stevens (2013). However, other recent empirical studies by Krichene (2002) and Baumeister and Peersman (2013) suggest that the oil supply elasticity coefficient is significantly positive but smaller than 0.1. Therefore, in Section 5, I investigate the sensitivity of the results to alternative parameterizations of ϑ. Finally, I assume that all stochastic disturbances follow $AR(1)$ processes in logarithmic terms, with a persistence parameter of 0.8.

4 Optimal Monetary Policy Response to Different Oil Shocks

I now investigate the extent to which the optimal monetary policy response to oil price fluctuations depends on the underlying source of the fluctuations. In doing so, I aim to assess the importance of different sources of the policy trade-off between stabilizing output and stabilizing inflation in driving the results. The most common explanation for this trade-off is that both prices and wages are sticky (see Erceg et al., 2000). In addition to this traditional explanation, the model features two other sources for the policy trade-off that relate to specific characteristics of the oil market. The first additional channel

[14] The literature provides little guidance on the size of the oil price markup λ_o. However, in an additional robustness check available upon request, I demonstrate that the results are robust to alternative specifications of λ_o. For instance, the results hold when we impose the relatively lower value of $\lambda_o = 0.36$, which corresponds to the size of the oil markup derived from the structural oil model of Nakov and Pescatori (2010a).

through which oil price increases generate a policy trade-off arises from the fact that oil is difficult to substitute in production, i.e., $\alpha < 1$. As shown by Montoro (2010), when oil is a gross complement to the domestic factors in production, real marginal costs are a convex function of the real oil price. Oil price fluctuations then generate non-linear distortions in the wedge between the natural and efficient levels of output, distortions that increase the tension between the objectives of stabilizing inflation and stabilizing economic activity. The second additional source of the trade-off relates to the fact that oil trade occurs in an environment of incomplete international asset markets. Corsetti et al. (2010, 2011) demonstrate that relative to the case of complete markets, the central bank's loss function in the incomplete-market case includes a welfare relevant measure of cross-country demand imbalances. Consequently, incomplete markets induce an additional policy trade-off, in that the central bank aims to counteract wealth-shifting effects across borders, in addition to stabilizing output and inflation. In the following, I first consider the more realistic environment in which oil has few substitutes and international asset markets are incomplete. Subsequently, I remove the assumptions of low substitutability of oil and incomplete international risk sharing one at the time to evaluate their respective implications for the conduct of optimal monetary policy.

4.1 Baseline Model Economy

Figures 1a and 1b depict the first-order dynamics of the Ramsey economy when international capital markets are incomplete and the elasticity of substitution between oil and value added is low, with $\alpha = 0.03$. To evaluate the contribution of actual monetary policy to the recessionary effects of oil price hikes, I also plot the impulse responses for the model under the Taylor-rule policy (32). I distinguish three types of oil shocks. First, oil capacity shocks η_t^{oc} and oil markup shocks η_t^{o} represent 'oil supply shocks'. Second, the oil efficiency shock constitutes an 'oil-specific demand shock'. Finally, domestic TFP and government spending shocks are classified as 'macro-economic (ME)-driven oil demand shocks', which affect oil demand indirectly through changes in domestic economic activity. I mainly focus on the dynamics of the oil supply and oil-specific demand shocks because these factors have been shown to be the main driving forces of oil price fluctuations.[15]

[15] There is considerable disagreement in the literature regarding the relative importance of oil supply and demand shocks in driving oil prices. For instance, Hamilton (1983, 2009), Nakov and Pescatori (2010b), and Peersman and Stevens (2013) find that variations in oil prices are mainly driven by oil supply disruptions. Conversely, Kilian (2009), Balke et al. (2010) and Bodenstein and Guerrieri (2011) argue that shocks to oil demand have driven oil prices historically. However, despite these different results, there is consensus in these studies that ME-driven oil demand shocks play only a minor role in determining oil prices, i.e.,

Note that to facilitate the comparison, all shocks have been normalized to produce a 10% maximum increase in the real oil price under the Taylor-type policy. Before assessing the differences in the policy responses to the various types of oil shocks, I first briefly discuss the key transmission channels of each of these shocks, assuming the monetary authority follows the Taylor-type rule.

[insert Figures 1a and 1b here]

Key Dynamics The first two panels of Figure 1a depict the impulse responses of selected variables to the two types of oil supply shock.[16] Unfavorable movements in both shocks, i.e., positive oil markup shocks and negative oil capacity shocks, lower oil production. The resulting rise in real oil prices entails a negative income effect on domestic output. Due to staggered price contracts, this negative effect is partially counteracted by an endogenous decrease in the price markup, reflected by the higher inflation rate. Furthermore, intermediate goods producers hire additional domestic input factors to substitute for the more expensive oil. Following an exogenous decline in oil productive capacity, this positive substitution effect dominates the negative income effect in the very short run (three quarters or less). Therefore, on impact, labor demand, the value-added output of domestic productive factors (not shown), and gross output increase. After approximately 2.5 quarters, employment and output fall below steady-state levels. In contrast, in response to a negative oil markup shock, the income effect prevails over the substitution effect over all horizons, such that employment, value added, and gross output immediately fall. These different effects on labor demand and output derive from the different trade dynamics that both shocks trigger. In the case of a negative oil capacity shock, oil fields must be utilized more intensively to maintain production at its pre-shock levels. This occurrence raises the oil capacity utilization costs, expressed in terms of forgone consumption. As a result, exports of manufactured goods from the oil-importing to oil-producing country rise, which weakens the negative income effect triggered by the oil price increase. In the case of a positive oil markup shock, oil producers impose a higher price for a given productive capacity. The resulting decline in oil demand lowers the oil capacity utilization rate. Therefore, domestic exports of manufactured goods fall, which strengthens the negative income effect on domestic output induced by the oil price increase.[17] Remarkably, despite their differential effects on labor demand, both types of oil supply shock entail a decline

oil prices are mainly driven by shocks that are specific to the oil market.

[16] Additional impulse responses of other variables not presented in Figures 1a and 1b are reported in the Appendix (available at http://users.ugent.be/∼ansteven).

[17] Note that after approximately 2.5 years, both types of oil supply shock cause employment and output to increase before turning back to their long-run steady-state levels because unfavorable movements in

in the real wage rate over the entire transition period. This result is due to the decline in consumption, which increases labor supply and depresses wages. Finally, applying the Taylor-type rule, monetary policy makers raise the interest rate—following both types of supply shock—in an attempt to curb inflation.

The third panel of Figure 1a illustrates that the dynamics induced by a negative oil efficiency shock are similar to those produced by an unfavorable oil capacity shock. A decline in oil efficiency leads to an increase in oil demand and oil prices. This oil price increase in turn raises marginal production costs and inflation while putting downward pressure on gross output and employment. However, both output and employment rise on impact. Similar to the case of an oil capacity shock, this result is due to an increase in the oil capacity utilization rate, which increases the domestic exports of manufactured goods.

One important policy objective is to close output gaps. Therefore, it is instructive to note the differences in the output-gap dynamics produced by the different types of oil shocks. An exogenous increase in the oil markup does not affect the potential level of output and therefore produces a negative output gap. In contrast, unfavorable shifts in oil productive capacity and oil efficiency produce a positive output gap on impact. These shocks induce an oil price increase that works like a negative technology shock to generate contraction in the domestic economy. More specifically, the rise in oil prices lowers output and raises marginal production costs. Due to price stickiness, prices do not fully adjust, such that markups decline and inflation increases. These markup dynamics mitigate the recessionary consequences of the oil price hike, implying a positive gap between actual and potential output.

The responses to TFP and government spending shocks (displayed in Figure 1b) are well described in the literature. Following a positive productivity shock, output, consumption, investment, and real wages rise, whereas employment falls. Inflation also falls due to the depressing effects of the technological improvements on marginal costs. The overall increase in domestic economic activity raises oil demand and oil prices. Under the Taylor-rule policy, nominal and real interest rates fall but not to an extent that prevents an output gap from opening up or a fall in inflation. Turning to the public spending shock, an exogenous increase in government consumption raises output and puts upward pressure on real factor prices, including oil prices, and inflation. To stem these inflationary pressures, real interest rates rise. As is standard in the DSGE literature, government spending shocks entail a strong crowding-out effect on both private consumption and investment.

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oil supply induce a transfer of wealth from the oil-importing to oil-producing country, driving up foreign consumption and domestic exports.

Ramsey Policy In the following, I investigate the optimal monetary policy responses to the different types of oil shocks. The results are presented in Figures 1a and 1b along with the dynamics for the model under the Taylor-type rule. To facilitate the interpretation of the results, I also plot the dynamic responses of the potential level of output that would prevail under flexible prices and wages in the absence of markup shocks. In the canonical new-Keynesian model, the potential output level corresponds to the efficient output level, provided that fiscal instruments are used to address inefficiencies in the steady state. The benevolent central banker aims to replicate the Pareto-optimal equilibrium. However, this policy objective conflicts with the objective of stabilizing inflation.[18] Investigations of this policy trade-off typically conclude that policies that keep output close to potential are nearly optimal (e.g., Levin et al. 2005). Moreover, Bodenstein et al. (2008) show that this conclusion carries over to model environments with exogenous energy price shocks. Therefore, the standard optimal policy prescriptions in the new-Keynesian tradition suggest that the Ramsey policy tends to close the gap between actual and potential output.

A comparison of oil supply and oil-specific demand shocks in Figure 1a reveals that shocks that are specific to the oil market optimally require similar policy responses. More specifically, in response to unfavorable oil supply and oil efficiency shocks, the Ramsey policy calls for a steep but short-lived increase in the real interest rate. Compared to the Taylor-type rule, this approach amplifies the recessionary consequences of the oil price hike on impact. However, after approximately one year, the Ramsey economy experiences smaller drops in output, consumption, and hours worked. Remarkably, in contrast to what we may expect from the standard new-Keynesian policy prescriptions, the optimal output gap is strongly negative within the first year following adverse oil supply and oil-specific demand shocks. In the following subsections, I investigate this anomaly in greater detail.

Turning to the TFP shock presented in Figure 1b, optimal policy tends to close the negative output gap and reduces the deflationary effects on prices. This expansionary policy puts upward pressure on oil demand and therefore raises oil prices above their baseline levels. Similarly, the Ramsey response to government spending shocks yields an output path that closely resembles that of the flexible economy (see panel 2 in Figure 1b). However, in contrast to technology shocks, demand shocks induce a positive output gap. As a result, relative to the policy under the Taylor-type rule, the Ramsey policy reduces output and mitigates the increase in oil demand and prices.

[18] Under Calvo staggering, variations in prices and wages entail negative welfare effects, as these variations generate cross-sectional dispersion in labor supply and goods production. As shown by Erceg et al. (2000), when both prices and wages are sticky, monetary policy can stabilize the output gap only at the expense of higher price and wage inflation rates.

In summary, if international capital markets are incomplete and oil cannot easily be substituted for other factors of production, the model predicts that shocks that are specific to the oil market call for rather similar policy responses. More specifically, in response to unfavorable shifts in oil supply or oil efficiency, the optimal policy is highly restrictive and exacerbates the recession compared to actual monetary policy. Because the literature indicates that oil-specific demand and supply shocks are of primary importance in the determination of oil prices, this result suggests that monetary policy that neglects to identify the causes of oil price fluctuations is not significantly misguided. Importantly, these conclusions contrast with the standard predictions of the new-Keynesian tradition. To close output gaps, we may expect optimal policy to be restrictive following adverse oil capacity and oil efficiency shocks while being accommodative in response to adverse oil markup shocks. As I demonstrate below, the finding that typical oil price shocks, in contrast to the standard new-Keynesian prescriptions, call for similar policy responses results from the observations that the degree of substitutability between oil and other factors of production is low and that oil is traded in an international environment of incomplete asset markets. Intuitively, given low substitutability of oil and incomplete asset markets, oil-specific demand and supply shocks induce similar welfare effects that should call for similar policy responses. Specifically, when oil is difficult to substitute in production, oil price hikes generate a negative wedge between the natural and efficient levels of output. Furthermore, under incomplete markets, oil price hikes induce a shift in wealth from the oil-importing to oil-producing country. In the following two subsections, I demonstrate these statements in greater detail. I remove the assumptions of incomplete international risk sharing and low oil substitutability one at a time and contrast the Ramsey policy derived under these alternative model specifications with the policy behavior observed in the baseline case.

4.2 The Role of the Degree of International Risk Sharing

I first investigate the importance of incomplete risk sharing between the oil-importing and oil-producing countries in shaping policy behavior. As shown by Corsetti et al. (2010, 2011), asset market imperfections result in inefficient capital flows and global demand imbalances, which in turn induce a policy trade-off between internal and external objectives. More specifically, relative to the case of complete markets, the central bank's loss function in the incomplete-markets case depends not only on inflation rates and the output gap but also on the wedge D_t between the cross-country marginal utility differentials $\frac{U^*_{c,t}}{U_{c,t}}$ and real exchange rate Q_t. In logarithmic terms, wedge D_t is given by

$$\ln(D_t) = \ln\left(\frac{U^*_{c,t}}{U_{c,t}}\right) - \ln(Q_t), \tag{35}$$

where $Q_t = S_t \frac{P^*_t}{P_t}$ and S_t is the nominal exchange rate expressed as the home currency price of foreign currency. Corsetti et al. (2011) define this wedge as the 'relative demand gap'. In the efficient equilibrium, households across different countries are equally well off, implying that the relative demand gap (35) is constant and equal to zero; i.e., $\frac{U^*_{c,t}}{U_{c,t}} = Q_t$. Complete markets provide full insurance against country-specific risk and therefore replicate the optimality condition of zero cross-country demand imbalances. In contrast, incomplete markets induce inefficient international capital flows that lead to endogenous fluctuations in the relative demand gap. Monetary policy then faces an additional trade-off in that it aims to counteract wealth-shifting effects across borders, in addition to seeking to stabilize both output and inflation. Note that because the oil-producing country pegs its currency to the US dollar, the real exchange rate Q_t is constant and equal to one in our model. Therefore, the relative demand gap simplifies to the cross-country differences in marginal consumption utilities, i.e., $D_t = \frac{U^*_{c,t}}{U_{c,t}}$.

To assess the role of the degree of international risk sharing in the conduct of optimal monetary policy, I derive the Ramsey policy under complete markets and contrast it with the policy behavior observed under incomplete markets. Figures 2a and 2b display the impulse responses predicted by the simplified model in which international financial markets are complete. Again, all shocks have been normalized to produce a 10% maximum increase in the real oil price under the Taylor-type policy.

[insert Figures 2a and 2b here]

Comparing the complete-market case to the incomplete-market case, we first observe that the optimal policy responses to ME-driven oil demand shocks are similar under both market structures. Therefore, the remainder of this section is devoted to the analysis of the oil-specific demand shock and the two types of oil supply shock. Figure 2a illustrates that in the case of complete markets and unfavorable shifts in oil supply or oil efficiency, the optimal response of the interest rate to oil price shocks depends strongly on the underlying cause of the oil price increase. More specifically, Ramsey policy is restrictive and raises the real interest rate following oil capacity and oil efficiency shocks, whereas it is accommodative and lowers the real interest rate in response to oil markup shocks. Despite these differences in the optimal monetary policy stance, the Ramsey policy aligns the recessionary consequences of all three shocks in that it reduces the output slump compared to the Taylor-type rule. In particular, output, consumption, investment, and employment all contract by less, at the expense of slightly higher price and wage inflation rates. Note that in response to oil capacity and oil efficiency shocks, the real interest rate rises on impact more under the Ramsey policy than under the Taylor-type rule. Therefore, for these shocks, the result that the Ramsey policy is looser than the Taylor-type policy may seem counterintuitive, as rising interest rates typically indicate monetary policy tightening. However, compared to the Taylor-type rule, the increase in the Ramsey real interest rate is less persistent. Given the forward-looking behavior of households, consumption and investment are affected by the short-run rates only if these rates bring about variations in the long-run real rate of interest, i.e., if the rise in short-run rates is persistent.

Importantly, the finding that relative to the Taylor-type rule, Ramsey policy, under complete markets, mitigates the recessionary consequences of oil-specific demand and supply shocks contrasts with the outcome observed under incomplete markets. In the latter case, optimal policy worsens the economic downturn in the short run. The contrasting results stem from dissimilarity in the risk-sharing conditions between the two market structures. First, note that contractionary oil supply and oil efficiency shocks raise the oil-exporting country's oil revenues (not shown). If international asset markets are frictionless, trade in state-contingent claims provide efficient insurance against country-specific risk. As a result, part of the increased oil revenue returns to the domestic country until the two countries achieve equal consumption levels. In the case of incomplete markets, the higher oil revenues are partially absorbed by increased foreign consumption, i.e., there is a transfer of wealth from the oil-importing to oil-producing country. To curb this wealth-shifting effect, the benevolent central banker puts the economy into a severe but short-lived recession, as such a recession mitigates the increase in oil prices and revenues. Relative to the Taylor-type rule, real oil prices fall by approximately 1.5 percentage points (see Figure 1a).

The above analysis provides an explanation of why, under incomplete markets, oil supply and oil-specific demand shocks call for similar policy responses and generate optimal output dynamics that differ considerably from potential output. In particular, the focus on external objectives reduces the benevolent central banker's concern about internal objectives, such as stabilizing the output gap. Because the different types of oil-specific demand and supply shocks produce similar cross-country wealth-shifting effects, this approach aligns the optimal policy responses across these shocks. Note, however, from Figure 2a, that although the assumption of complete markets reverses the sign of the optimal output gap relative to the incomplete-market case, this alternative environment still implies a significant wedge between optimal and potential output in the wake of oil capacity and oil efficiency shocks. Specifically, the optimal output gap is positive and larger than the gap observed under a Taylor-type policy. This finding contrasts with the standard new-Keynesian policy prescription that optimal policy should seek to replicate the potential equilibrium. In the following subsection, I demonstrate that the friction that drives this result stems from the observation that oil has low substitutability in production.

4.3 The Role of the Degree of Oil Substitutability

Montoro (2010) demonstrates that when oil is a gross complement to domestic production factors, i.e., $\alpha < 1$, oil price fluctuations induce a time-varying wedge between the natural and efficient levels of output. This result creates an additional source of the policy trade-off between stabilizing inflation and stabilizing economic activity, one that may have important implications for the welfare analysis of monetary policy. Therefore, in this section, I wish to analyze the role of the degree of oil substitutability in determining the optimal monetary policy response to oil price shocks. To this end, I assess the robustness of the baseline results to an alternative environment in which oil enters the production function with unit elasticity of substitution, i.e., $\alpha = 1$, and production takes the Cobb-Douglas form.[19] I first conduct this robustness assessment for the case of complete international capital markets. This approach allows us to analyze the implications of the frictions induced by the low substitutability of oil in isolation from the welfare effects implied by the incompleteness of international risk sharing. Subsequently, I demonstrate that the main conclusions carry over to a more realistic environment in which international asset markets are incomplete. The results are presented in Figures 3-5. Before discussing these results, I provide intuitive support for the policy trade-off induced by CES production technology.

Sources of the Additional Policy Trade-off The time-varying gap between the natural and efficient levels of output, which arises when it is difficult to substitute other factors of production for oil, results from the dynamic behavior of marginal production costs. To demonstrate this effect, I derive the log-quadratic (Taylor-series) approximation of the domestic real marginal cost equation (4). In doing so, recall that variables that are presented as log deviations from the deterministic steady-state are denoted by the superscript '^'. If we define the effective real oil price $\widetilde{p}_t^o$ as the ratio of the actual real oil price p_t^o to the relative oil efficiency η_t^{oe}, i.e., $\widetilde{p}_t^o \equiv \frac{p_t^o}{\eta_t^{oe}}$, then the second-order approximation

[19] In an additional exercise, I consider lower values, within the range $\alpha \in (0.03, 1)$, for the degree of oil substitutability. See the next subsections.

of real marginal costs is given by

$$\widehat{mc}_t = \tilde{\eta}\hat{s}_t + (1-\tilde{\eta})\,\widehat{\tilde{p}}_t^o + \frac{1}{2}(1-\alpha)\,\tilde{\eta}\,(1-\tilde{\eta})\left[\hat{s}_t - \widehat{\tilde{p}}_t^o\right]^2 + \Xi, \tag{36}$$

where $\tilde{\eta} \equiv \eta\left(\frac{s}{mc}\right)^{1-\alpha}$ is the share of the value added output in total costs in steady state, $(1-\tilde{\eta}) \equiv (1-\eta)\left(\frac{\tilde{p}^o}{mc}\right)^{1-\alpha}$ is the steady-state share of oil in total costs and Ξ denotes the error incurred in approximating the marginal cost function. The equations for the GDP-deflator s_t and the effective real oil price $\widetilde{p}_t^o$ have the following second-order expansion:

$$\begin{aligned} \hat{s}_t &= (1-\theta)\,\hat{r}_t^k + \theta\hat{w}_t - d\hat{\eta}_t^a, \qquad (37)\\ \widehat{\tilde{p}}_t^o &= \widehat{p}_t^o - \widehat{\eta}_t^{oe}. \qquad (38)\end{aligned}$$

Note that equations (37) and (38) are exact expressions rather than approximations.

From equation (36), we can see that CES production with an elasticity of substitution less than one, i.e., $\alpha < 1$, entails two sources of inefficient marginal cost dynamics.[20] First, as stressed by Natal (2012), the coefficients of the first-order terms, i.e., $\tilde{\eta}$ and $(1-\tilde{\eta})$, depend on the degree of monopolistic distortion in the goods market unless $\alpha = 1$, as in the Cobb-Douglas case. To see this result, note that according to equation (5), the steady-state real marginal cost equals the ratio of production subsidies to the gross price markup, i.e., $mc = \frac{1+\tau_p}{1+\lambda_p}$. Consider an exogenous rise in real oil prices. As the economy becomes less competitive, i.e., λ_p increases, the oil cost share $(1-\tilde{\eta})$ increases and real marginal costs become more sensitive to increases in oil prices. As perfect price stability entails constant real marginal costs, i.e., $\widehat{mc}_t = 0$ to a first-order approximation, the drop in domestic factor prices required to compensate for the higher oil price becomes larger as the economy's steady state becomes more distorted. Therefore, natural output falls more than efficient output, which creates an endogenous monetary policy trade-off between output and inflation stabilization.

Second, as shown by Montoro (2010), in contrast to the Cobb-Douglas case, where $\alpha = 1$, the Taylor expansion of real marginal costs in the CES case contains non-zero quadratic terms. More specifically, when oil has low substitutability in production, real marginal costs become a convex function of the real oil price. An exogenous increase in oil prices then raises marginal production costs above their linear counterpart; the latter,

[20] In the Appendix, I replicate Montoro's (2010) solution to the equilibrium real marginal cost, which provides further insights into the policy trade-off induced by CES production technology. In brief, under several simplifying assumptions, the second order approximation of real marginal costs (36) can be expressed as a function of the gap between the actual and natural levels of output. Within this setup, it can then be shown that inflation stabilization does not automatically stabilize the welfare relevant output gap (see Section 2.5 of the Appendix for details).

given by $\tilde{\eta}\widehat{s}_t + (1-\tilde{\eta})\,\widehat{\tilde{p}}_t^o$. If firms can adjust their prices to maintain markups, i.e., if the economy is in equilibrium at its natural level and prices are flexible, real marginal costs decline to a first-order approximation. As a result, price markups increase up to the first order, which produces a negative gap between the natural and efficient levels of output; i.e., efficient output is less responsive to oil price fluctuations than natural output.

Two remarks are in order. First, in the case of a Cobb-Douglas production function, the elasticity of substitution between value added and oil is unity, i.e., $\alpha = 1$. In this case, the Taylor expansion of real marginal costs depends only on the first-order terms, with coefficients that are independent of the degree of monopolistic distortion, i.e., $\widehat{mc}_t = \eta\widehat{s}_t + (1-\eta)\,\widehat{\tilde{p}}_t^o$. In this case, the gap between the natural and efficient levels of output is constant over time. Second, as shown by Montoro (2010), eliminating the distortions in the steady state—as I do in my analysis—reduces but does not eliminate the inefficient fluctuations in natural output. More specifically, when setting the production subsidies equal to the steady-state net price markup, i.e., $\tau_p = \lambda_p$, the oil cost share no longer depends on the steady-state distortions. However, because of the convexity of marginal costs, oil price fluctuations still induce a time-varying wedge between the natural and efficient levels of output. Thus, in the analysis below, inefficient fluctuations in natural output only arise from the convexity of marginal costs inherent in CES production technology.

Results Under Complete Markets Figures 3a and 3b depict how the substitutability of oil influences the propagation of oil shocks and the conduct of optimal monetary policy in the model variant that features complete markets.

[insert Figures 3a and 3b here]

Several observations stand out. First, when production is characterized by a unit elasticity of substitution between oil and value added, the substitution effect gains in importance in the dynamic responses to a temporary oil price increase. Relative to the case of CES production, this effect augments the differences between the dynamic effects of oil capacity, oil markup and oil efficiency shocks on factor markets. More specifically, whereas the substitution effect dominates and employment increases following unfavorable movements in oil productive capacity and oil efficiency, the income effect prevails and employment falls in response to an increase in the oil markup. Similarly, if the underlying technology of production is Cobb-Douglas instead of CES, firms tend to substitute domestic productive factors for oil in response to an exogenous rise in TFP. As a result, in contrast to the case of CES production, positive TFP shocks lower oil demand and prices on impact.

After only approximately five quarters, the overall increase in domestic economic activity dominates the substitution effect, leading to an increase in oil demand and prices. Additionally, note that the dynamic responses to oil demand shocks are far stronger in the Cobb-Douglas case than in the CES case. The high substitutability of oil inherent in the Cobb-Douglas production technology implies that oil demand is highly responsive to price changes. Therefore, to achieve a 10% increase in oil prices as a result of demand-side disturbances, we must consider relatively large shocks that induce relatively large effects on the domestic economy. In the case of TFP and government spending shocks, the implied shock sizes are unrealistically high, generating output increases of 20-30%.

Second, the optimal monetary policy response to oil supply and oil-specific demand shocks critically depends on the degree of substitutability of oil. First, consider unfavorable oil capacity and oil efficiency shocks. Figure 3a reveals that, similar to the case of CES production, Ramsey policy in the Cobb-Douglas case raises the real interest rate in response to both shocks. However, in contrast to the CES case, the optimal monetary policy stance is tighter than suggested by the Taylor-type rule; Ramsey policy augments the recessionary consequences of the oil price hike. The different results observed in the CES and Cobb-Douglas cases arise from the different welfare effects inherent in the different degrees of oil substitutability in production. Under Cobb-Douglas production technology, the elasticity of substitution between value added and oil is unity and the natural (or potential) output level corresponds to the efficient output level. The benevolent central banker aims to replicate the efficient equilibrium. Therefore, in this model variant, Ramsey policy acts to close the gap between actual and natural output. Compared to the Taylor-type rule, optimal policy then amplifies the output slump and reduces price inflation. As noted above, under CES production technology, low substitutability of oil induces an additional policy trade-off in that efficient output becomes less responsive than natural output to oil price fluctuations. As a result, in the CES case, adverse oil capacity and oil efficiency shocks drive a negative wedge between the natural and efficient levels of output. Then, under the Taylor-type rule, the central bank primarily focuses on inflation and attempts to bring the economy near the natural output level. In contrast, the Ramsey policy aims to replicate the efficient level of output and is therefore not as tight as the Taylor-type rule.

With respect to the oil markup shock, we note that optimal policy keeps the real interest rate nearly constant in the case of a unit oil elasticity of substitution (see Figure 3a), whereas it lowers real interest rates if oil is difficult to substitute (see Figure 2a). Recall that an exogenous increase in the oil markup drives a negative wedge between the actual and potential levels of output. This effect magnifies the trade-off between stabilizing output and stabilizing price and wage inflation. Specifically, monetary policy should lower the real interest rate to close the output gap, whereas it should raise the real interest rate to curb price and wage inflation. Panel 2 of Figure 3a reveals that in the case of Cobb-Douglas production, optimal policy puts equal weights on both targets by holding the real interest rate nearly constant. Therefore, in this model variant, in contrast to oil capacity and oil efficiency shocks, the Taylor-rule based monetary policy response to an oil markup shock closely mimics the optimal response; the Ramsey policy dampens the recession compared to the Taylor-type rule but only to a minor extent. Conversely, under the CES production technology (see panel 2 of Figure 2a), the low substitutability of oil further widens the negative output gap. Therefore, relative to the Cobb-Douglas case, the optimal policy is more concerned with output gap stabilization and thus entails a reduction in the real interest rate. Similar to the cases of oil capacity and oil efficiency shocks, the Ramsey policy then reduces the recessionary consequences of the oil markup shock compared to the actual monetary policy response.

Finally, comparing Figures 2b and 3b, we observe that the degree of oil substitutability in production does not significantly influence the optimal monetary policy response to ME-driven oil demand shocks. Expansionary TFP and government spending shocks only raise oil prices indirectly, i.e., through increased economic activity that drives up oil demand. Because of this indirect transmission channel, the expansion of the gap between natural and efficient output observed under CES production technology is small and of minor concern to the benevolent central banker. As a result, in both the CES and Cobb-Douglas cases, Ramsey policy tends to close the gap between the actual and natural levels of output.

Concerning oil supply and oil-specific demand shocks, we conclude that the welfare effects induced by the low substitutability of oil align the optimal output responses to different sources of oil price fluctuations; specifically, Ramsey policy mitigates the recession relative to actual policy. Importantly, if oil and other factors of production were perfect substitutes, then the optimal monetary policy response to oil shocks would strongly depend on the underlying cause of the oil price increase. In particular, in accordance with the standard new-Keynesian policy prescription to close output gaps, optimal policy would be restrictive following oil capacity and oil efficiency shocks, while it would be accommodative in response to oil markup shocks.

Sensitivity Analysis Thus far, I have assumed that the true oil substitution elasticity is low, with $\alpha = 0.03$. Although this calibrated value is similar to many reduced-form estimates of the price-elasticity of oil demand, it is considerably lower than more recent estimates derived from structural models of the oil market. For instance, Baumeister and Peersman (2013), Kilian and Murphy (2010), and Bodenstein and Guerrieri (2011) all report oil demand elasticity estimates centered around 0.5. Therefore, as a robustness check, I contrast the optimal policy with the baseline Taylor-type rule for different degrees of oil substitutability in production, i.e., $\alpha \in (0.03, 0.25, 0.5, 0.75, 1)$. Figure 4 summarizes the respective output responses in this exercise to unfavorable oil capacity, oil markup, and oil efficiency shocks.

[insert Figure 4 here]

We notice that the impact of monetary policy on output in the aftermath of a typical oil price shock depends crucially on the degree of oil substitutability α. Specifically, the actual monetary policy, as determined by the Taylor-type rule, is more likely to amplify the recessionary effects of the oil price hike relative to what is optimal from a welfare perspective when the value of α is lower. Importantly, only near the Leontief-case, i.e., α close to zero, does optimal policy cause smaller output declines during the entire transition period. This result might explain the contradictory conclusions reported in Winkler (2009) and Kormilitsina (2011) regarding the contribution of monetary policy to recessions generated by exogenous oil price increases. Both authors derive the Ramsey-optimal conduct of monetary policy and compare it to actual policy. However, they consider different price elasticities of oil demand. In a calibration exercise, Winkler (2009) fixes the oil elasticity of substitution at $\alpha = 0.5$ and finds that optimal policy calls for a stronger and more prolonged recession compared to the standard Taylor rule. Applying impulse response matching techniques, Kormilitsina (2011) finds that the elasticity of substitution between production factors is not significantly different from zero and that optimal policy dampens the recession relative to the actual monetary policy response.

Results Under Incomplete Markets In Section 4.2, we concluded that the cross-country wealth-shifting effects induced by asset market imperfections align the optimal policy responses to oil-specific demand and supply shocks. Note that this conclusion is contingent on the observation that oil is a gross complement of domestic factors of production. In an additional robustness check, I derive the Ramsey policy under incomplete markets in the model featuring Cobb-Douglas production (see Figure 5) and contrast it with the policy behavior observed under complete markets (see Figure 3a).

[insert Figure 5 here]

We find that in the case of Cobb-Douglas production, the welfare implications of incomplete international risk sharing do not importantly affect the optimal monetary policy response to oil price hikes. Specifically, when production takes the Cobb-Douglas form, the impulse responses observed under incomplete markets (See Figure 5) resemble those observed under complete markets (see Figure 3a), implying that the optimal monetary policy response to oil price fluctuations critically depends on the underlying driving source. Intuitively, when the elasticity of substitution between oil and value added is high, at $\alpha = 1$, the oil price increase induces a strong negative substitution effect on oil demand. This effect dampens the rise in oil revenues and the related shift in wealth observed under incomplete markets. As a result, relative to the model with CES production, the benevolent central banker is less aggressive in combating global demand imbalances and, similar to the complete-markets case, tends to replicate the natural equilibrium.

5 On the Importance of the Oil Supply Elasticity

The two most important parameters characterizing the oil market are the price-elasticity coefficients of oil demand and oil supply. In the preceding analysis, I analyzed the role of the degree of oil substitutability α and the implied steepness of the oil demand curve in shaping policy responses to oil price fluctuations. In this section, I focus on the sensitivity of the results to alternative parameterizations of the oil supply elasticity $1/\vartheta$.[21] The baseline calibration of $1/\vartheta = 0.1$ is based on evidence reported in Peersman and Stevens (2013). However, structural analyses of the oil market typically consider a very steep oil supply curve with a price-elasticity close to zero. Therefore, as a first alternative calibration, I set $1/\vartheta = 0.025$. This value is based on the work of Kilian and Murphy (2010), who impose an upper bound of approximately 0.025 on the impact oil supply elasticity. For completeness, I also consider a value for $1/\vartheta$ above its baseline calibration, specifically, $1/\vartheta = 0.2$. For each of these calibrations, I contrast the Ramsey policy with the Taylor-type rule. The respective output responses in this sensitivity analysis to unfavorable oil capacity, oil markup, and oil efficiency shocks are presented in Figure 6.[22] Similar to the main analysis, I consider three model environments, namely, the baseline case with incomplete markets and CES production technology (see panel A), the model variant with complete markets (see panel B), and the environment that also assumes that

[21] The main conclusion that typical oil price shocks call for similar policy responses under incomplete international risk sharing is also robust to other model specifications that I do not present here. For example, the results hold when we abstract from variable capital utilization (i.e., $\chi \rightarrow \infty$) and remove investment adjustment costs (i.e., $\varsigma = 0$). Detailed impulse responses pertaining to these additional specifications are reported in the Appendix (available at http://users.ugent.be/∼ansteven).

[22] Other impulse responses pertaining to this robustness assessment are reported in the appendix (available at http://users.ugent.be/∼ansteven).

the production function is Cobb-Douglas (see panel C).

[insert Figure 6 here]

Two conclusions stand out. First, consider the case of complete markets. Comparing panels B and C of Figure 6 reveals that the benevolent central banker's concern about the opening of the gap between natural and efficient output induced by the low substitutability of oil is not affected by the magnitude of the oil supply elasticity. Similar to the baseline calibration, where $1/\vartheta = 0.1$, if oil has low substitutability in production, the optimal monetary policy stance in the aftermath of a typical oil price shock is looser than the Taylor-type rule suggests in cases of lower or higher values of $1/\vartheta$. As a result, the conclusion that the Ramsey policy aligns the recessionary consequences of the various oil supply and oil efficiency shocks under complete markets is robust to alternative specifications of the price-elasticity of oil supply.

Second, turning to panel C of Figure 6, we observe that the weight that optimal policy places on counteracting the cross-border wealth-shifting effects induced by incomplete international risk sharing depends heavily on the oil supply elasticity coefficient $1/\vartheta$. Specifically, for lower values of $1/\vartheta$, the benevolent central banker is more concerned with stabilizing global demand imbalances and the Ramsey policy is more likely to amplify the recessionary consequences of an oil price shock compared to the Taylor-type rule. When the oil supply curve is steep, small declines in oil demand produce relatively large declines in oil prices. Therefore, relative to an environment with a more elastic oil supply curve, policy makers can, by provoking a recession and reducing oil demand, more easily mitigate oil price hikes and the associated shift of wealth across borders. As a result, because it is easier to combat cross-country wealth-shifting effects, policy makers will also pay more attention to this issue. Importantly, when the oil supply elasticity is high, at $1/\vartheta = 0.2$, the optimal weight on stabilizing global demand imbalances is so low that, similar to the case of complete markets, optimal policy dampens the recession relative to actual monetary policy. However, note that estimates of the price-elasticity of oil supply are typically low between 0 and 0.1 (e.g., Krichene 2002 and Baumeister and Peersman 2013). Therefore, to the extent that the baseline calibration of $1/\vartheta = 0.1$ is at the high end of the estimates reported in the literature, my main analysis may understate the importance of global demand imbalances in shaping optimal policy. This observation strengthens the conclusion that oil-specific demand and supply shocks call for similar policy responses, given that international asset markets are incomplete.

6 Conclusion

This paper studies optimal Ramsey-type monetary policy in the presence of endogenous oil price fluctuations. More specifically, I investigate the extent to which the optimal monetary policy response to an oil price increase depends on the underlying driving force of the price increase. I obtain two main results. First, I demonstrate that the types of shock identified in the literature as the main drivers of oil price fluctuations, i.e., oil supply and oil-specific demand shocks, call for similar policy responses, given the low substitutability of oil in production and the incompleteness of international asset markets. This approach suggests that monetary policy that fails to identify the causes of oil price fluctuations is not significantly misguided. Intuitively, if oil is a gross complement of domestic factors of production, real marginal costs are a convex function of the real oil price. Independent of their underlying cause, oil price hikes then induce a negative wedge between the natural and efficient levels of output. By aiming to close this gap, the Ramsey policy aligns the recessionary consequences of the various oil supply and oil efficiency shocks. If, additionally, international financial markets are incomplete, unfavorable oil supply and oil-specific demand shocks both induce a shift in wealth from the oil-importing to oil-producing country. To curb this wealth-shifting effect, optimal policy calls for a large but short-lived increase in the real interest rate, as this increase reduces oil demand and mitigates the oil price increase. The second key finding is that actual policy behavior, as captured by an empirical Taylor-type rule, is significantly different from the optimal conduct of monetary policy. However, whether actual monetary policy amplifies or dampens the recessionary effects of oil price hikes depends on the type of oil shock that occurs, the degree of oil substitutability and the degree of international risk sharing.

Needless to say, the model used in this paper could be refined along several lines. I highlight three possible shortcomings. First, I abstract from oil consumption by households. Treating oil as an input in consumption causes the responses of core and headline inflation to oil price increases to diverge. Because oil prices are viewed as flexible, the direct effects of oil prices on the CPI are not expected to complicate monetary policy analysis. Aoki (2001) demonstrates that monetary policy should seek to stabilize only those components of the price index that are sticky, i.e., the core price index. Despite this prescription, the inclusion of oil in the consumption basket may affect policy analysis to the extent that under this approach, the second-round effects of oil price shocks on core inflation are intensified. Stronger second-round effects increase the central bank's concern about inflation stabilization relative to output stabilization. However, studying exogenous energy price fluctuations in an environment that includes distinct core and headline inflation rates, Bodenstein et al. (2008) find that rules that target the output gap are nearly optimal. Although caution is warranted, this result suggests that my main conclusions are robust to the inclusion of oil in consumption. Second, in the present model specification, the oil-importing country is treated as a relatively closed economy that only engages in trade with oil-producing countries. This assumption may be too simplifying, as it ignores the open-economy aspects of the transmission of oil price shocks, e.g., changes in the nominal exchange rate and in the terms of trade. Opening up the economy by including a second oil-importing country would greatly complicate the Ramsey analysis of optimal monetary policy, as this consideration entails strategic interactions between the independent policy makers of both countries. Thus, for now, I leave this issue as an interesting topic for further research. Third, the model neglects investments in oil inventories through which expectations of future oil prices affect the current price of oil. Examples of models that include oil in the investment portfolio can be found in Unalmis et al. (2009) and Peersman and Stevens (2013). However, these contributions rely on a reduced-form approach rather than on microfoundations to model inventory behavior. Although this approach can be justified for positive analysis, it cannot be applied in normative work. Overcoming these problems is another fruitful area for future research.

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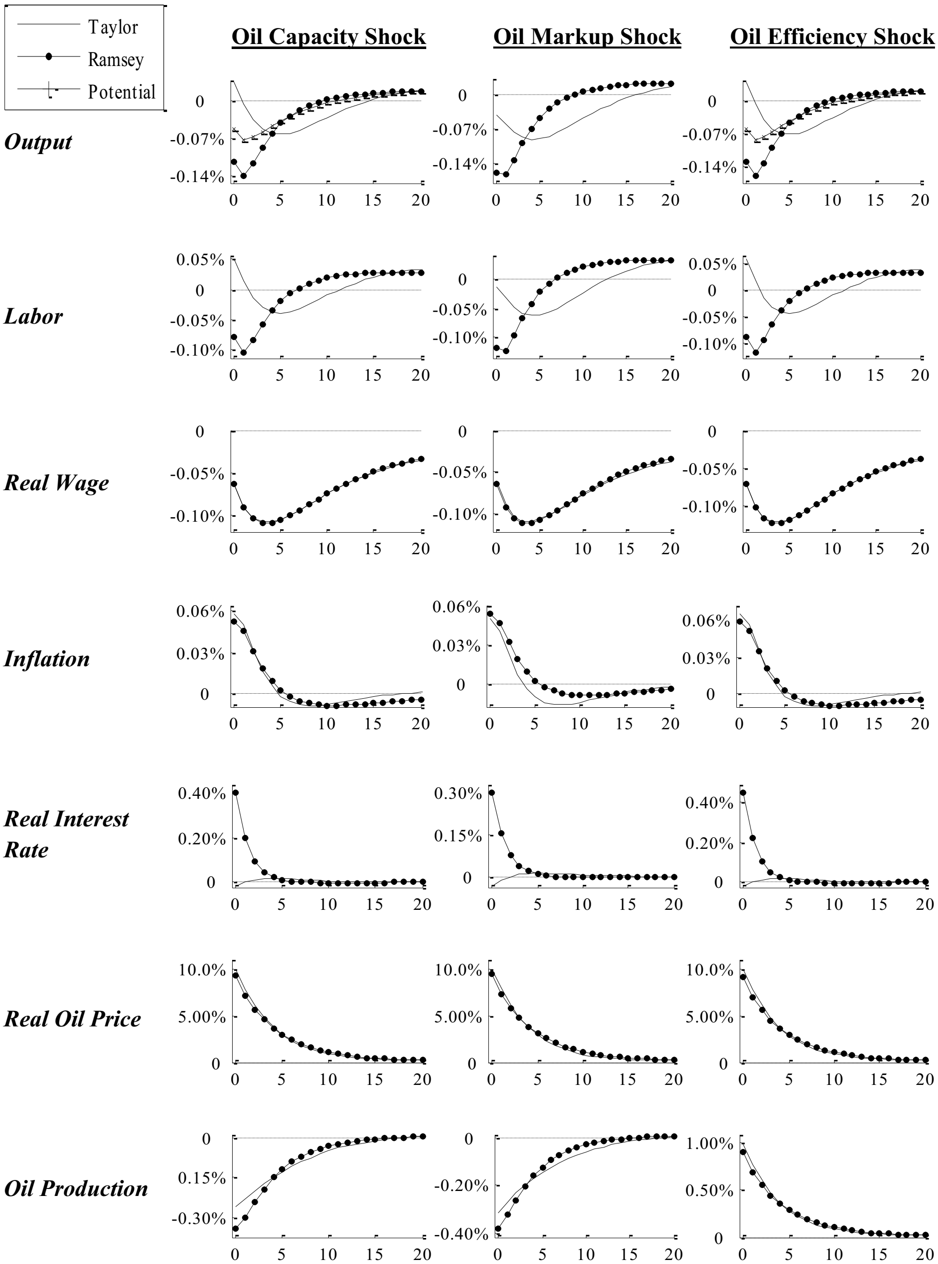
Table 1: Calibrated parameter values

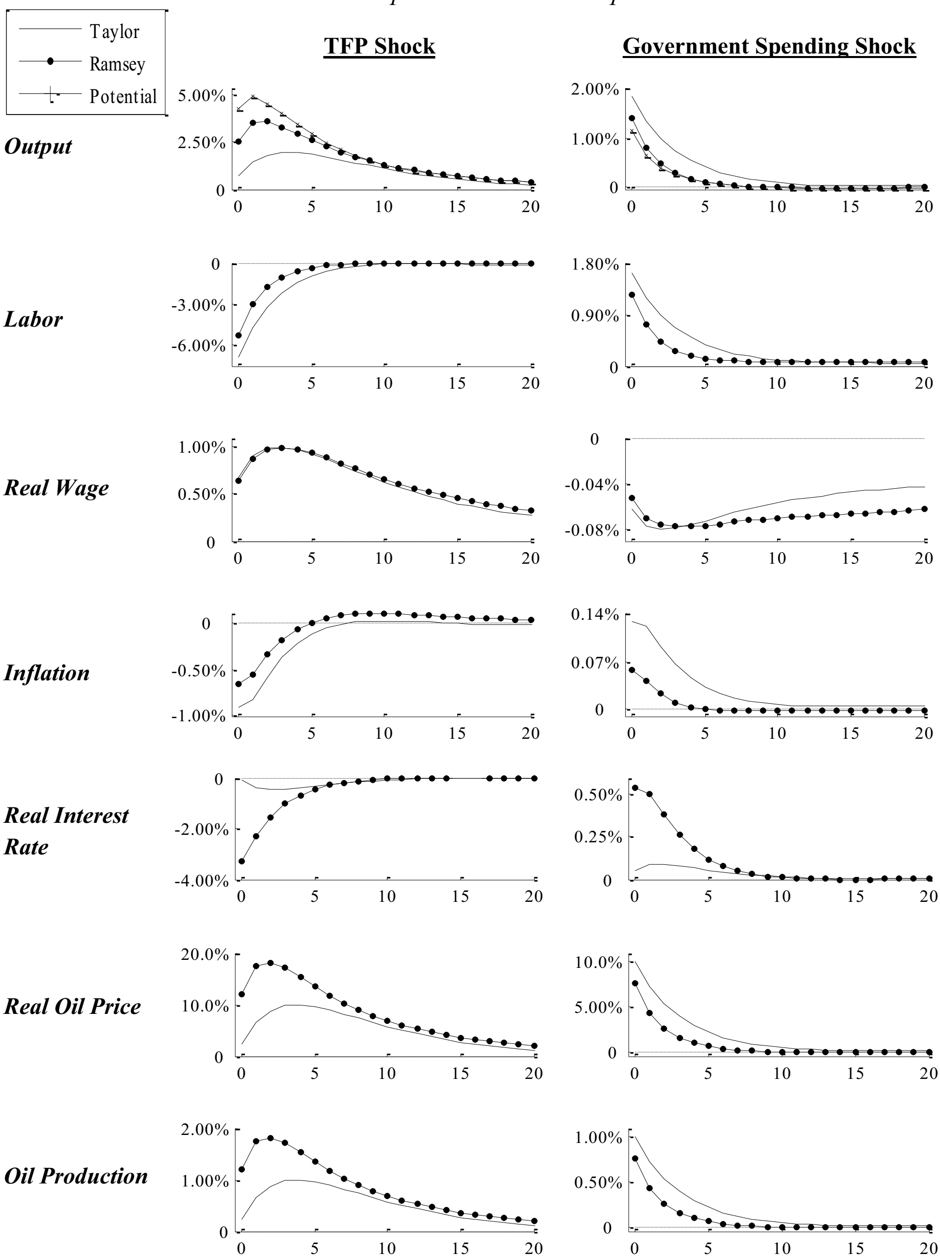
SYMBOL	DESCRIPTION	VALUE	
Standard Parameters			
β	Subjective discount factor	0.99	
θ	Labor share in production	0.76	
$\eta^g/\tilde{Y}$	Government spending share	0.21	
ϕ/Y	Share of fixed costs in production	0.44	
h	Consumption habit (home & foreign)	0.48	
σ_c	Risk aversion (home & foreign)	1.80	
σ_l	Labor utility	2.80	
δ_K	Capital depreciation rate	0.025	
ς	Investment adjustment costs	6.00	
χ	Capacity utilization cost - goods sector	6.00	
ξ_p	Price rigidity	0.80	
γ_p	Price indexation	0.25	
λ_p	Price markup	0.44	
ξ_w	Wage rigidity	0.75	
γ_w	Wage indexation	0.45	
λ_w	Wage markup	0.20	
τ_R	Interest rate smoothing	0.87	
τ_π	Interest rate response to inflation	1.50	
τ_y	Interest rate response to outputgap	0.05	
τ_{dy}	Interest rate response to Δ outputgap	0.30	
Parameters Specific to the Oil Market			
$1-\eta$	Share of oil in gross output	0.05	
λ_o	Oil price markup	0.75	
ϑ	Capacity utilization cost - oil sector	10	
α	Oil elasticity of substitution	CES	Cobb Douglas
		0.03	1
Additional Parameters in the Model with Incomplete Markets			
κ	Cost of adjusting foreign assets	0.001	

Figure 1a: Impulse responses to oil supply and oil-specific demand shocks
incomplete markets ─ CES production



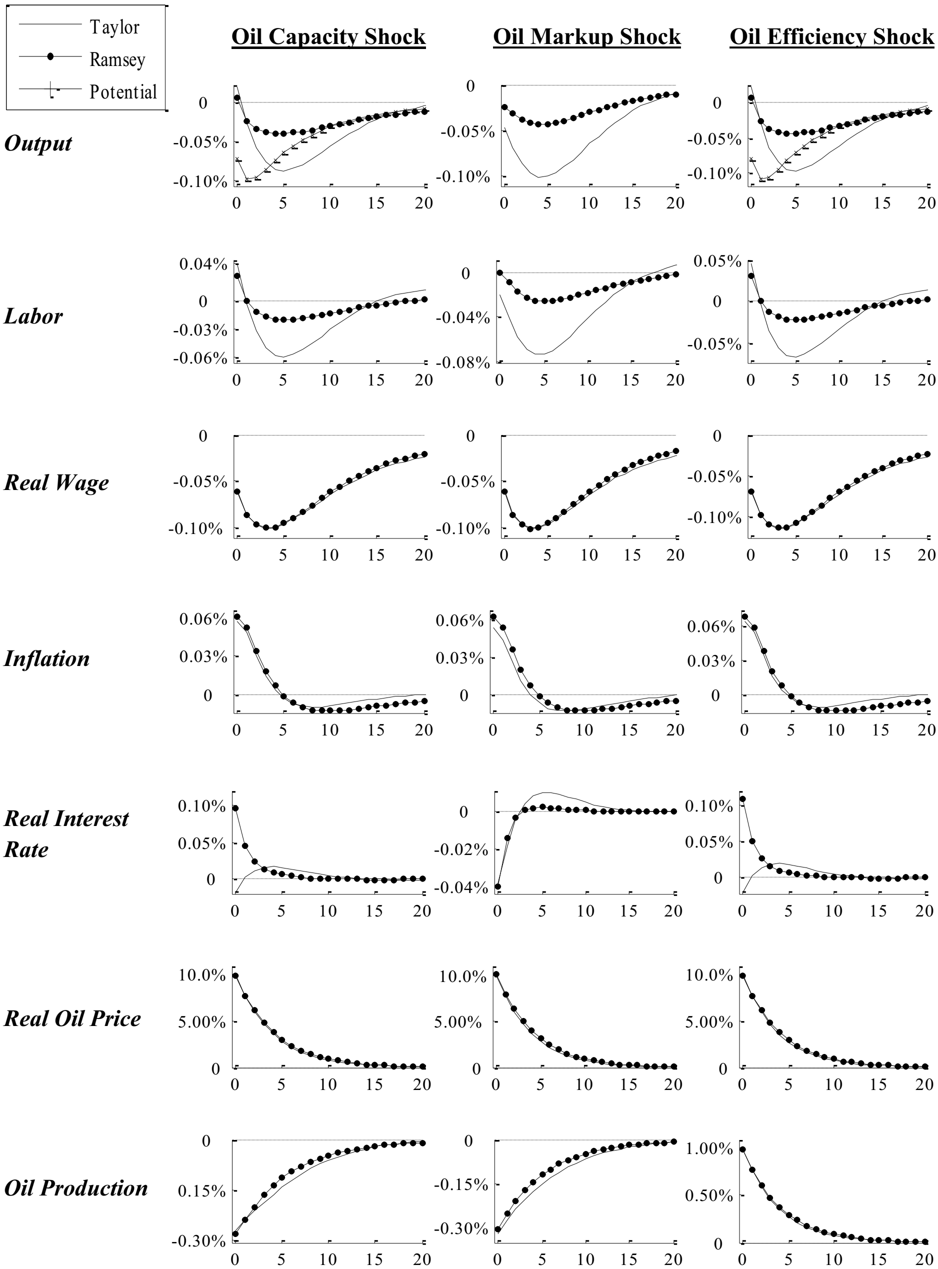
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 1b: Impulse responses to ME-driven oil demand shocks
in*complete markets* – *CES production*



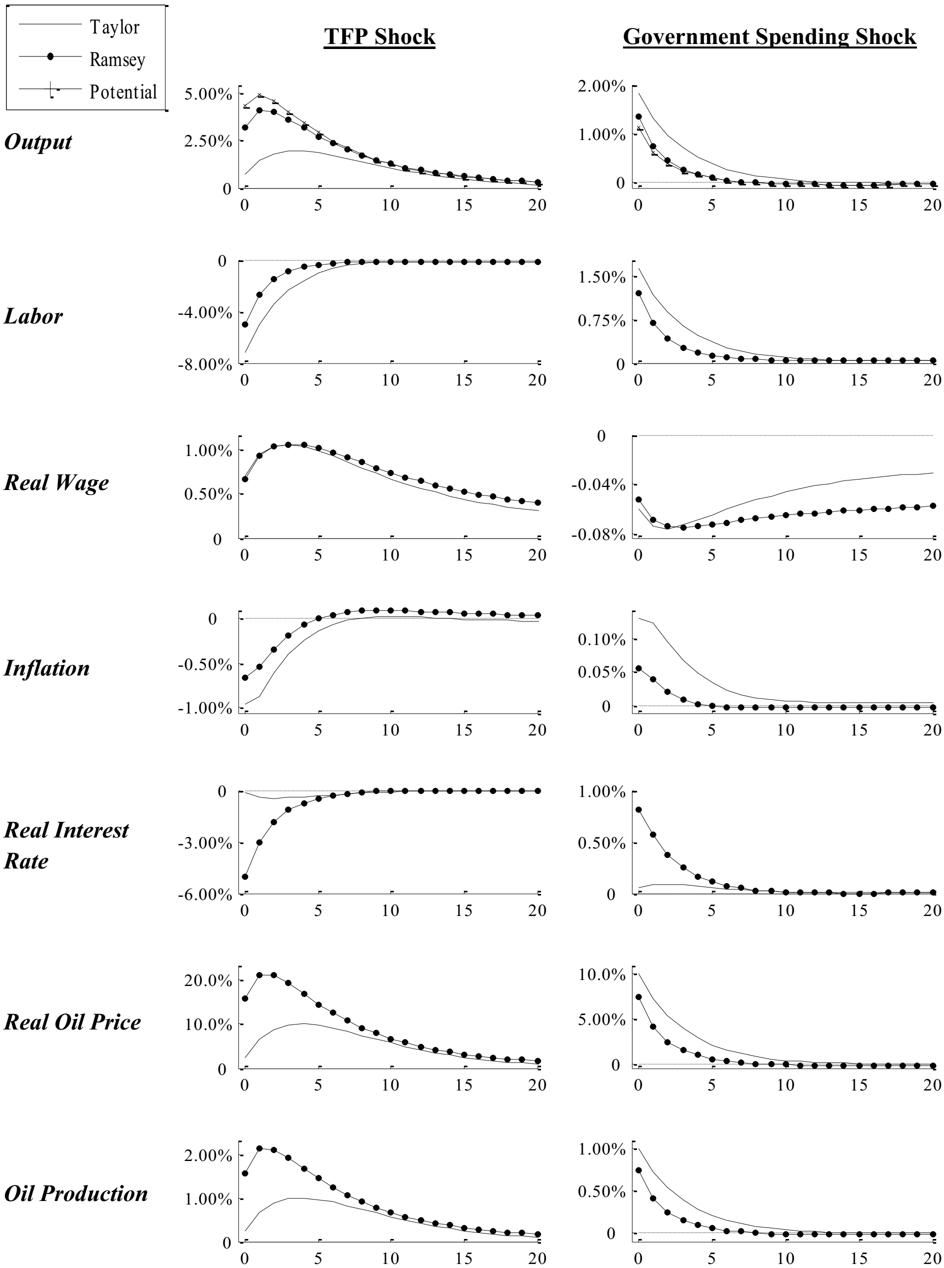
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 2a: Impulse responses to oil supply and oil-specific demand shocks
complete markets ─ CES production



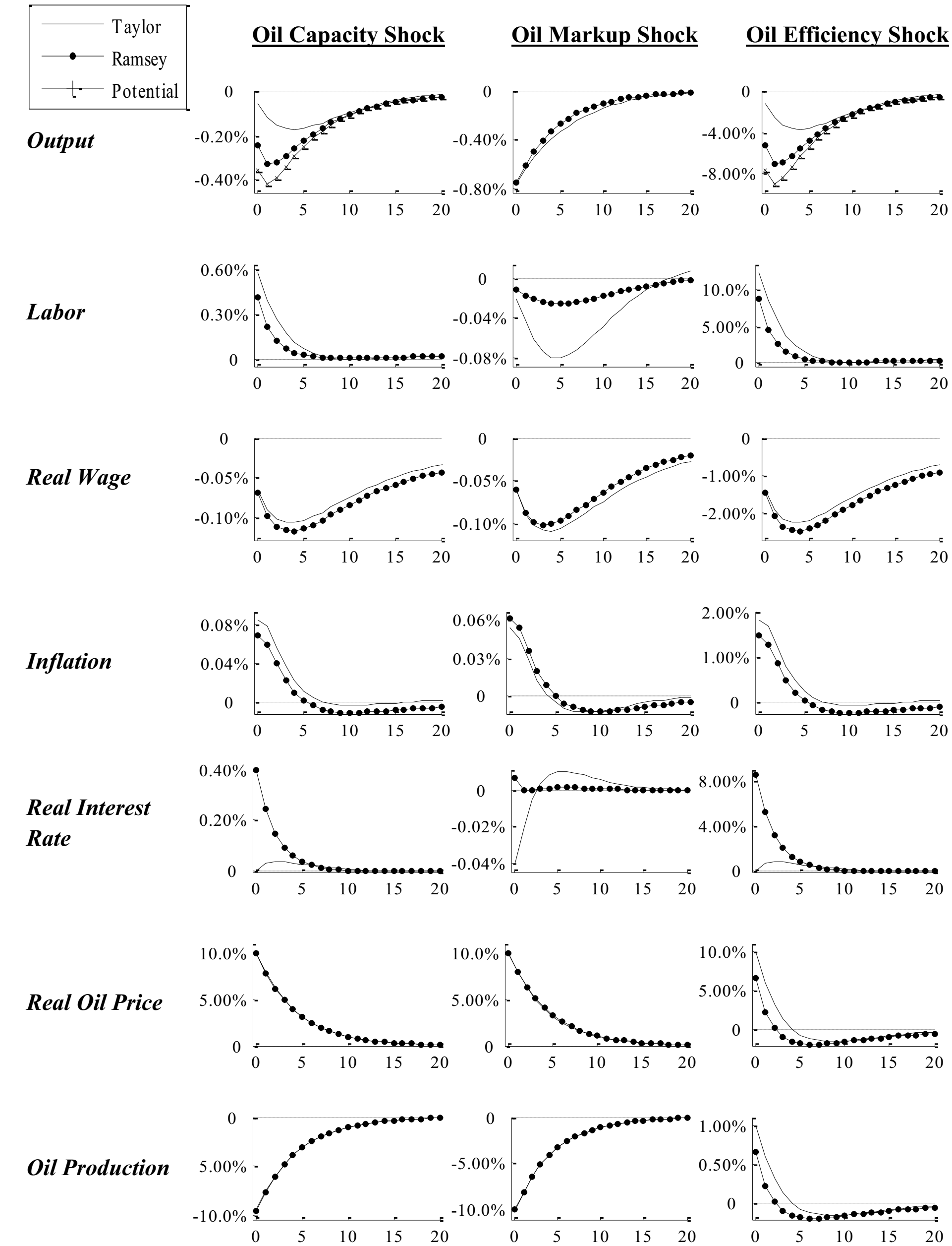
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 2b: Impulse responses to ME-driven oil demand shocks
complete markets ─ CES production



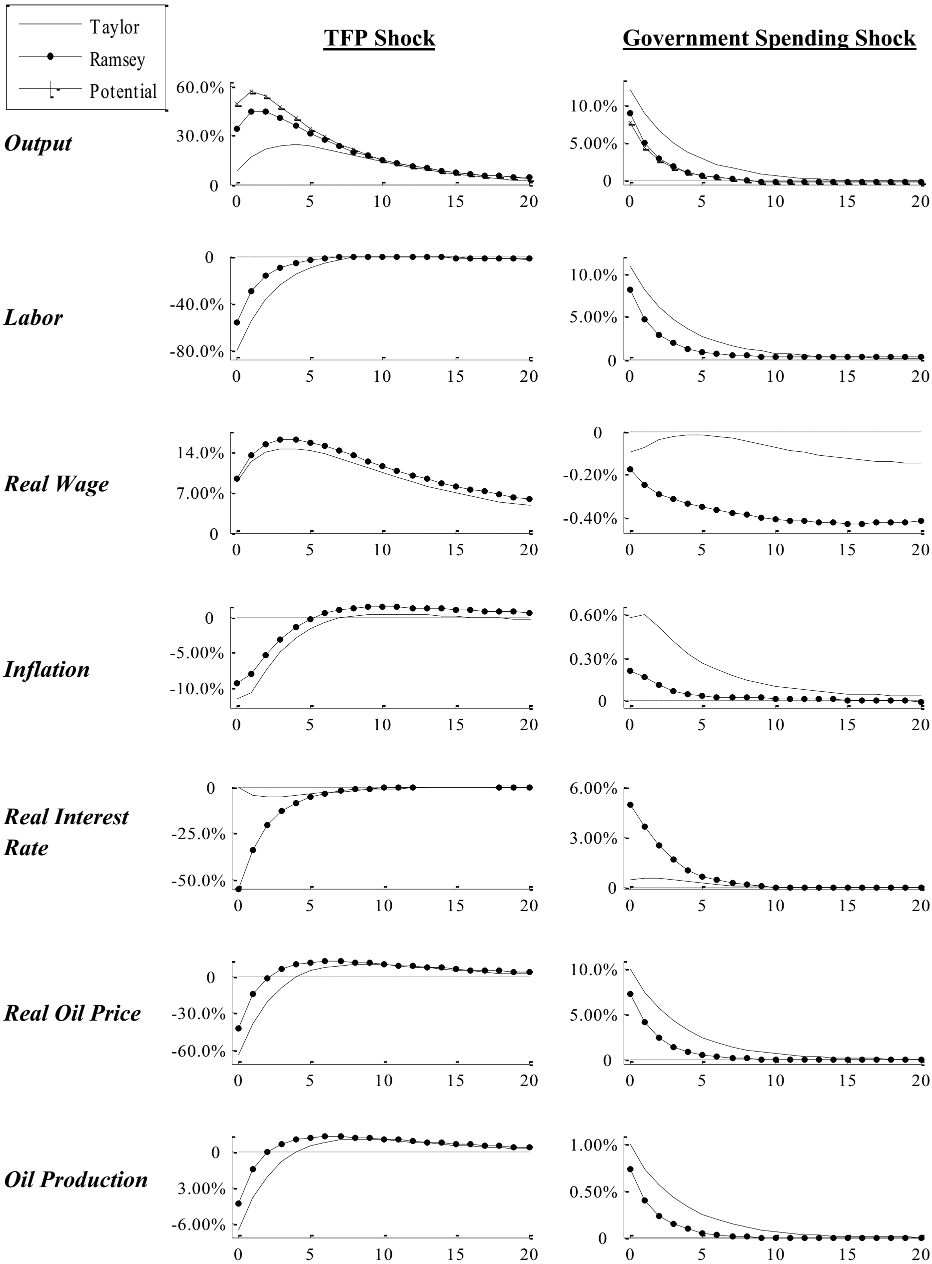
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 3a: Impulse responses to oil supply and oil-specific demand shocks
complete markets ─ Cobb Douglas production



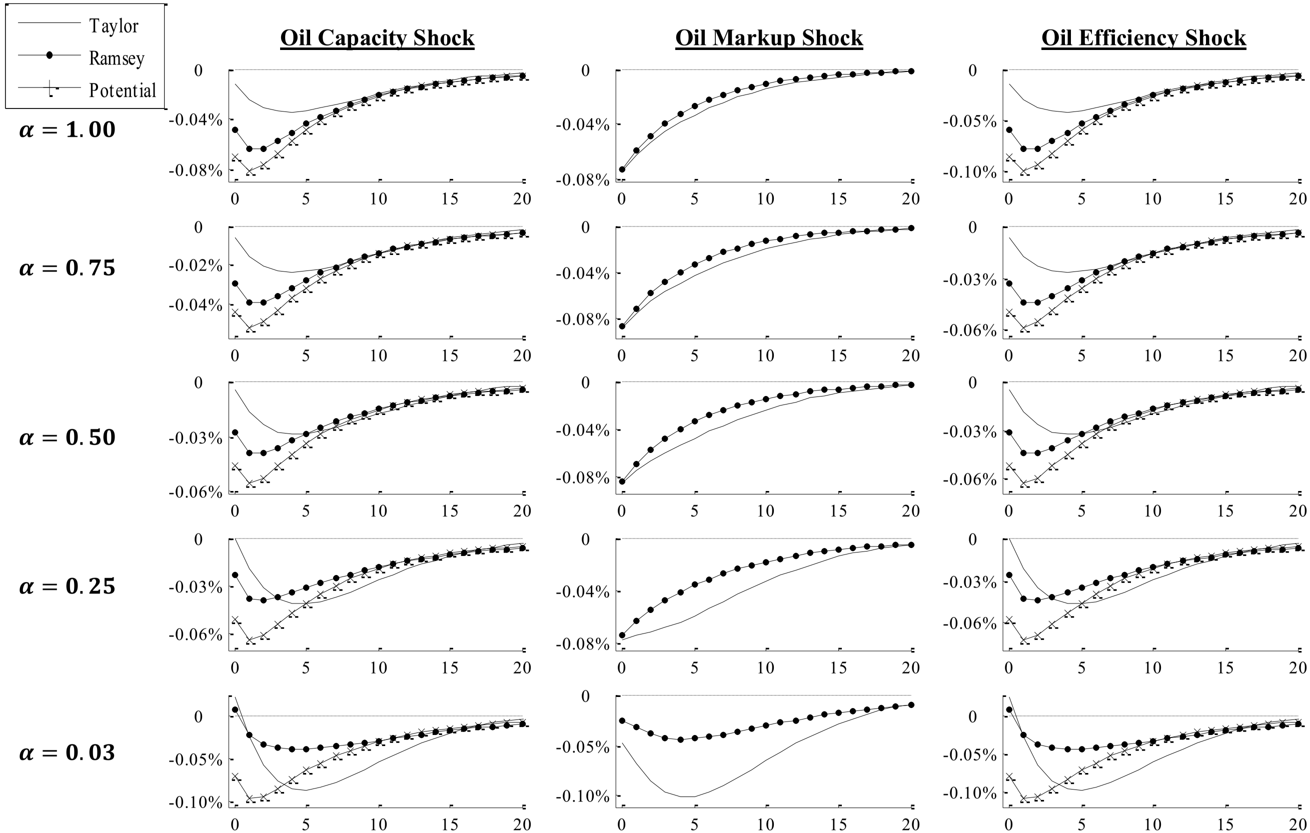
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 3b: Impulse responses to ME-driven oil demand shocks
complete markets ─ Cobb Douglas production



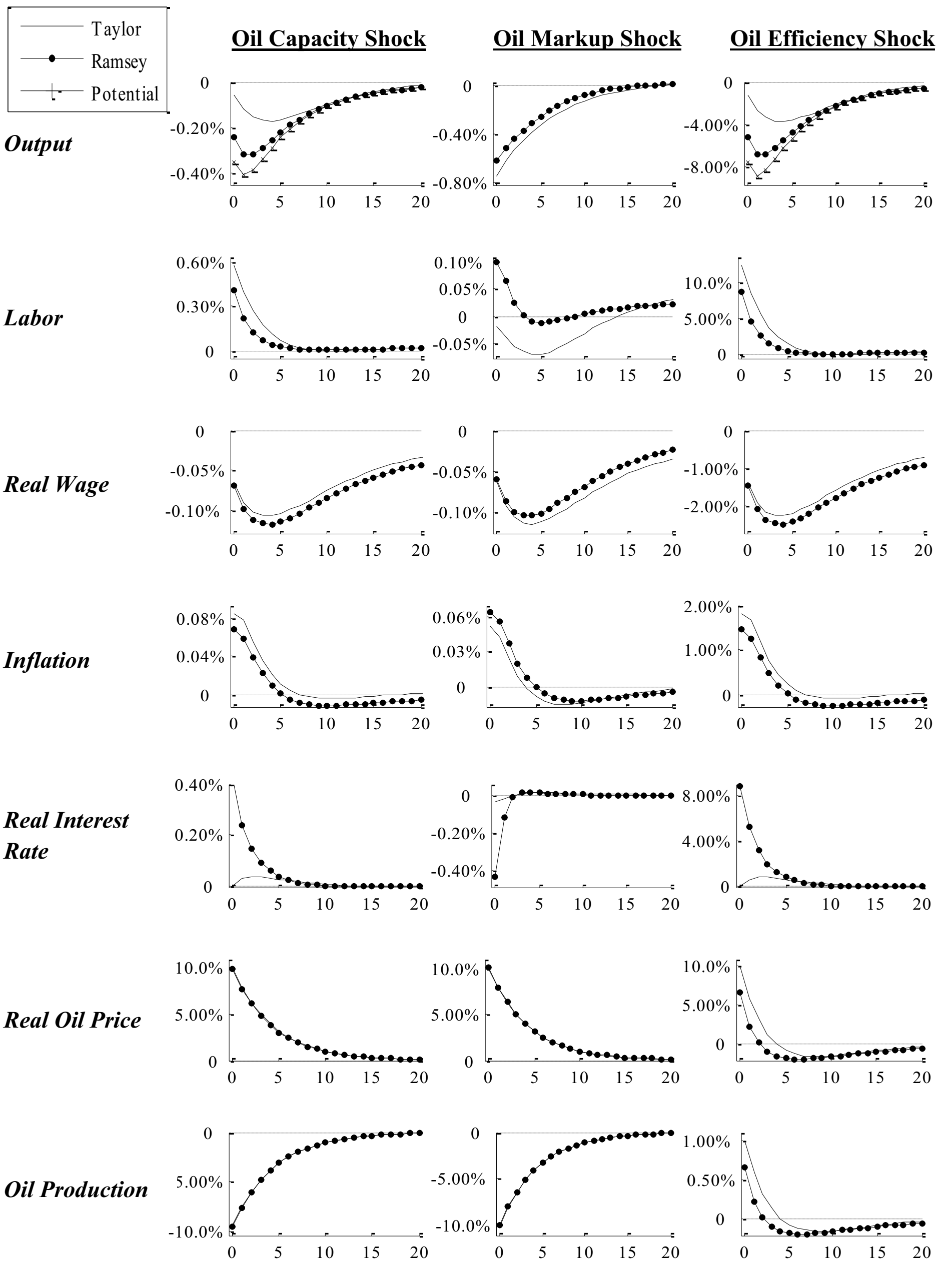
Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 4: Output responses to oil supply and oil-specific demand shocks for different degrees of oil substitutability α (*complete markets*)



Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present output responses under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices in case the substitutability of oil is low at $\alpha = 0.03$ and monetary policy follows the Taylor-type rule.

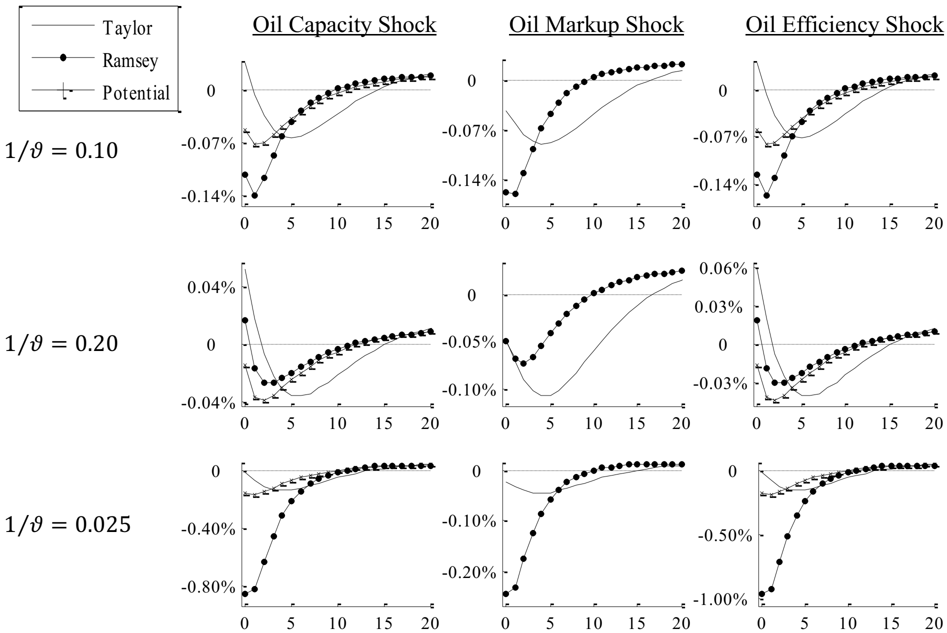
Figure 5: Impulse responses to oil supply and oil-specific demand shocks
incomplete markets ─ Cobb Douglas production



Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present IRFs under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices under Taylor-type policy.

Figure 6: Sensitivity of output responses to alternative values of the oil supply elasticity $1/\vartheta$

Panel A: Baseline Case: Incomplete Markets and CES Production Technology



Panel B: Complete Markets and CES Production Technology

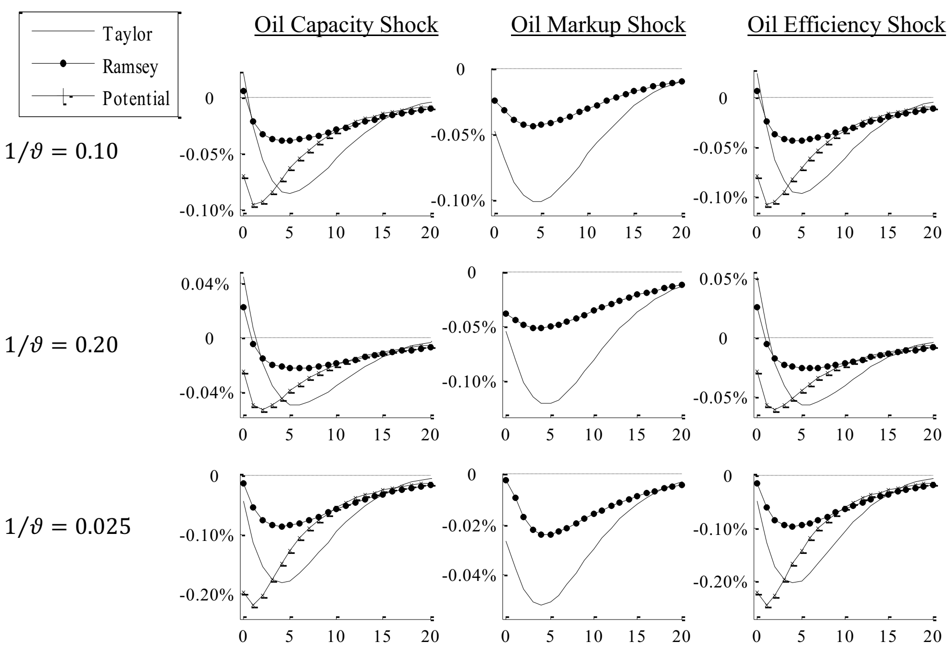
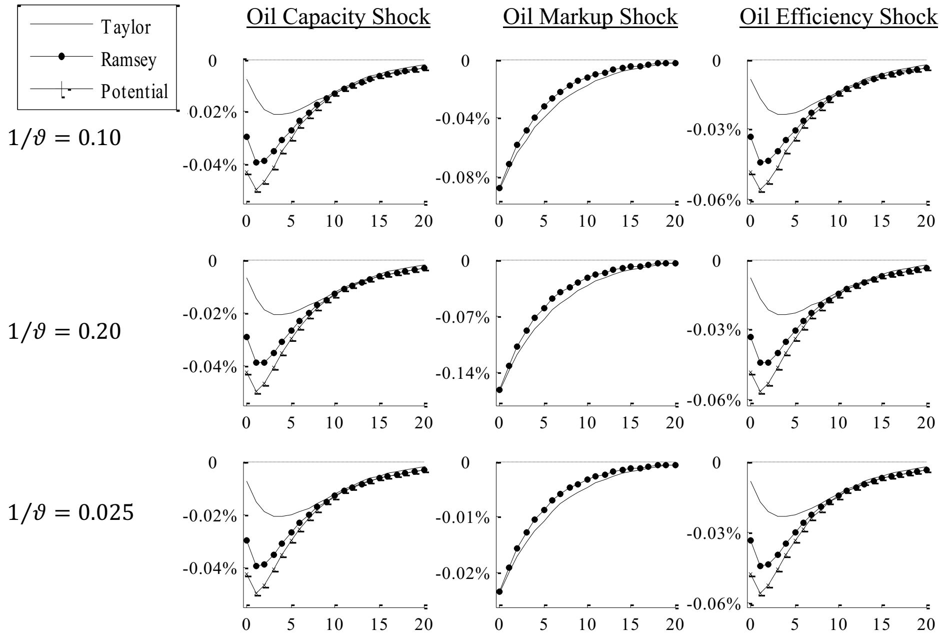


Figure 6 (Contd): Sensitivity of output responses to alternative values of the oil supply elasticity $1/\vartheta$

Panel C: Complete Markets and Cobb-Douglas Production Technology



Note: Impulse responses (IRFs) are measured in percentage deviations from steady state. Solid lines present output responses under the Taylor rule. Solid lines with point markers depict the Ramsey economy. Solid lines with crosses denote IRFs of potential output. All shocks have been normalized to produce a 10% increase in real oil prices in case the price-elasticity of oil supply equals $1/\vartheta = 0.1$ and monetary policy follows the Taylor-type rule.

Chapter 3

Competition, Price Stickiness and the Propagation of Technology Shocks

Competition, Price Stickiness and the Propagation of Technology Shocks*

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Abstract

Floetotto and Jaimovich (2008) show that oligopolistic behavior entails a 'competition effect', by which higher competition lowers desired markups and boosts economic activity. Because competitive pressures tend to be procyclical, this competition effect magnifies the propagation of productivity shocks. Within a flexible real business cycle model, Floetotto and Jaimovich (2008) quantify this internal magnification mechanism and find that it drives down the volatility of technology shocks by approximately 50%. In this paper, I show that increasing price stickiness considerably weakens the countercyclical movement that technology shocks induce in oligopolistic price markups. Therefore, the internal magnification effects on output and consumption are at least halved.

JEL classification: E23, E32, L11.
Keywords: Competition, Sticky Prices, Markups, Productivity, Business Cycles.

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1 Introduction

A well-known deficiency of the basic real business cycle (RBC) model is the lack of a quantitatively important magnification mechanism.[1] To account for the observed macroeconomic fluctuations, the RBC model must rely on highly volatile technology shocks. A number of studies, e.g., Portier (1995), Floetotto and Jaimovich (2008) and Colciago and Etro (2010), ascribe this problem to the monopolistic market structure considered in the canonical RBC framework. They show that oligopolistic behavior in combination with endogenous firm entry induces an important internal magnification mechanism for technology shocks, which operates through an endogenous mechanism of markup variation. Intuitively, technological advances lead to profit opportunities and firm entry, which raises market competition. Within oligopolistic markets, competition takes place between a small number of firms, such that the actions of one firm influence the price decisions of their competitors. These strategic interactions induce a 'competition effect', by which the increase in the number of competitors reduces desired markups. As emphasized by Rotemberg and Woodford (1993), countercyclical variations in the markup in turn magnify shock propagation.

Each of the contributions discussed above has an important shortcoming, in that it ignores nominal rigidities in price setting. In the canonical new-Keynesian model, featuring monopolistic competition and price stickiness, an exogenous increase in technology lowers marginal production costs more than prices, such that markups increase. This weakens the propagation of technology shocks instead of amplifying it. Therefore, the question arises whether in the presence of price stickiness the magnification mechanism inherent in oligopolistic behavior still prevails in the propagation of technology shocks. This is also of importance to policy makers, who seek to counteract inefficient fluctuations in markups. Depending on which of the two dynamics dominates, i.e., the competition effect or the sticky price channel, markups either fall or rise, respectively, in response to technological advances.

To analyze the relative importance of sticky prices and competition effects for the propagation of technology shocks, I endogenize the market structure in the canonical new-Keynesian model. I accomplish this by modeling firm dynamics and by considering oligopolistic competition along the lines of Floetotto and Jaimovich (2008), instead of monopolistic competition à la Dixit and Stiglitz (1977). More specifically, I consider an economy with a fixed range of industries, with each industry consisting of a small, but time-

[1] See e.g., Cogley and Nason (1995), Devereux et al. (1996), Hall (1999), King and Rebelo (2000) and Den Haan et al. (2000).

varying number of large firms that compete in prices. Strategic interactions between the oligopolists induce a competition effect, by which firm entry lowers the price setting power of firms. To assess the robustness of the analysis, I consider two popular specifications discussed in the literature for the entry mechanism: the first specification is that entry is frictionless, as discussed by Floetotto and Jaimovich (2008). Entry, in this case, drives profits to zero in every period. Second, I assume that firms face a sunk startup cost prior to entry, as discussed by Bilbiie et al. (2007). Free entry then equates the firm's value to the sunk cost and profits fluctuate endogenously. Price stickiness is introduced by assuming Rotemberg (1982)-style price adjustment costs.

This paper is not the first to combine competition effects in oligopolistic markets with nominal rigidities in price setting behavior. It is, however, the first to investigate the interaction between these two economic features to assess their implications for markup fluctuations and shock propagation. Using single equation estimation methods, Cecioni (2010) finds that the new-Keynesian Phillips curve becomes steeper when firm entry and competition effects are taken into account. Lewis and Poilly (2012) estimate the competition effect in a fully fledged dynamic stochastic general equilibrium (DSGE) model, featuring nominal rigidities in both prices and wages, by minimizing the distance between the model-based impulse responses to a monetary policy shock and their empirical counterparts. They find that oligopolistic behavior cannot generate an empirically relevant competition effect and therefore their model is statistically equivalent to a Dixit-Stiglitz type monopolistic competition. Finally, Stevens (2012) derives the Calvo sticky price model under oligopolistic markets and shows that a permanent rise in competition increases the slope of the Phillips curve. The oligopolistic competition model entails a supply-driven explanation for the competition effect. Alternatively, Bilbiie et al. (2007, 2012) offer a demand-side explanation by combining entry dynamics with the translog preferences introduced by Feenstra (2003). In such a framework, increased entry raises the substitutability between goods, which eventually translates into a lower markup. Lewis and Poilly (2012) re-estimate their model with this demand-type competition effect and find evidence of a small, but statistically significant, competition effect. Similar results are obtained by Lewis and Stevens (2012) who estimate a monetary DSGE model with endogenous firm entry and a translog expenditure function using a full-information Bayesian approach.

The central result of this paper is that the magnification mechanism inherent in oligopolistic behavior critically depends on the degree of price stickiness. Starting with an oligopolistic competition model with flexible prices, I sequentially add higher degrees of price rigidity. Simulations of the sticky price model suggest that the internal magnification mechanism that the competition effect delivers in response to technology shocks is considerably weakened by the sluggish adjustment on the nominal side. Overall, the amplification effects on output and consumption are reduced by at least half. As Floetotto and Jaimovich (2008) show, small competition effects are all that are required to generate a powerful magnification mechanism in the flexible-price environment. However, this conclusion changes dramatically once prices are rigid. For reasonable degrees of nominal rigidities, the magnification induced by the competition effect is entirely nullified. Therefore, markups increase in response to technology shocks, which dampen propagation as observed in traditional new-Keynesian models featuring monopolistic competition.

This paper proceeds as follows: in Section 2, I present the linearized model. Section 3 outlines the calibration of our model economy and studies the effect of nominal price rigidities on the competition channel of shock magnification. Finally, Section 4 draws the main conclusions.

2 The Oligopolistic Competition Model

This section extends the canonical new-Keynesian model to include oligopolistic competition as well as firm entry and exit dynamics. I abstract from capital accumulation and assume that production in each firm only requires labor. Investment is, therefore, entirely along the extensive margin, which leads to an increase in the number of firms, leaving firms' labor productivity unaltered. Oligopolistic markets are modeled along the lines of Floetotto and Jaimovich (2008); i.e., the economy consists of a fixed range of industries, each one characterized by a small number of large firms, taking strategic interactions into account and competing in prices. Price setting behavior of oligopolists is subject to the Rotemberg (1982)-type adjustment cost. I consider the following two entry mechanisms: first, as discussed in Floetotto and Jaimovich (2008), I derive the model under the assumption that entry is frictionless, while firms face a fixed cost of production. In this case, entry drives profits to zero in every period. Second, I assume that firms face a sunk startup cost prior to entry, as in Bilbiie et al. (2007). Free entry then equates the value of a firm (the present discounted value of profits) to the sunk cost; subsequent to entry, the per-period profits fluctuate endogenously. I proceed to the log-linearized versions of the model equations except in cases that are less standard in the literature.[2] Hatted variables denote deviations from the deterministic steady state. Variables without a hat or time

[2] A model appendix with the full derivation (Appendix A) and an appendix that analyzes the robustness of the results to the inclusion of capital in the model (Appendix B) are available at http://users.ugent.be/∼ansteven.

subscript refer to the steady state level. The equilibrium I consider is symmetric: all households, firms and entrants are identical.

2.1 Firms

Production in the economy occurs in two layers as in Floetotto and Jaimovich (2008). The economy is characterized by a fixed range of industries of measure 1, indexed by $j \in (0,1)$. The final consumption good Y_t^C is a constant elasticity of substitution (CES) composite of industry goods $Y_t(j)$ which have an elasticity of substitution $\omega > 1$, i.e.,

$$Y_t^C = \left[\int_0^1 Y_t(j)^{\frac{\omega-1}{\omega}} dj \right]^{\frac{\omega}{\omega-1}}. \tag{1}$$

Within each industry j, there is a finite number N_t of firms, indexed by $i \in (1, N_t)$, with each producing differentiated intermediate goods $y_t(j,i)$. An industry good $Y_t(j)$ bundles intermediate goods according to a CES aggregator with elasticity $\tau > 1$, this is[3]

$$Y_t(j) = N_t^{-\frac{1}{\tau-1}} \left[\sum_{i=1}^{N_t} y_t(j,i)^{\frac{\tau-1}{\tau}} \right]^{\frac{\tau}{\tau-1}}. \tag{2}$$

Importantly, goods are less substitutable across industries than within an industry, such that $\tau > \omega$.[4] Intermediate goods firms in each industry operate in a regime of oligopolistic competition with strategic interactions. In oligopolistic markets, each firm supplies a large portion of industry output. Then, a firm's price setting decision takes into account its effect on the industry price, taking as given the prices of other firms in the industry and the price levels of other industries. As shown in detail in Floetotto and Jaimovich (2008), these strategic interactions in turn imply that the price-elasticity of demand varies in the number of operating firms. More specifically, the demand elasticity ε_t is given by

$$\varepsilon_t (N_t) = \tau - (\tau - \omega) N_t^{-1}. \tag{3}$$

With a time-varying demand elasticity, the desired markup defined as $\mu_t^d (N_t) \equiv \frac{\varepsilon_t(N_t)}{\varepsilon_t(N_t)-1}$ is also time-varying. In linearized form, the desired markup is

$$\hat{\mu}_t^d = -\eta \hat{N}_t, \text{ where} \tag{4}$$

$$\eta = \frac{\tau - \varepsilon}{\varepsilon(\varepsilon - 1)} \geqslant 0. \tag{5}$$

[3] The term $N_t^{-\frac{1}{\tau-1}}$ in the CES aggregator of intermediate goods eliminates the 'love of variety' effect in the model; i.e., we eliminate the channel by which consumers can increase their utility by spreading their consumption expenditure across more differentiated goods.

[4] Evidence for this is given in Broda and Weinstein (2006).

η is the steady state elasticity of the desired markup to the number of firms, and it captures the competition effect of entry. The parameter ε represents the long-run (i.e., steady state) price-elasticity of demand which increases in the number of firms N. When there are an infinite number of firms in the economy, the price-elasticity of demand equals τ and the desired markup is constant, i.e., $\eta = 0$. For any finite number of firms we have $\omega \leqslant \varepsilon < \tau$, which implies a positive coefficient for the elasticity of the desired markup to the number of firms, i.e., $\eta > 0$. The firms' monopoly power is then eroded by the arrival of new entrants.

Aggregate production of intermediate goods is the sum of firm output $\hat{y}_t$ and the stock of firms $\hat{N}_t$,

$$\hat{y}_t + \hat{N}_t = \left(1 + \frac{\phi}{y}\right)\left[\hat{Z}_t + \hat{L}_{C,t}\right] - \frac{\phi}{y}\hat{N}_t, \tag{6}$$

where $\hat{L}_{C,t}$ is the amount of the labor bundle $\hat{L}_t$ used for the production of goods. The variable $\hat{Z}_t$ denotes exogenous total factor productivity (TFP) and follows an AR(1)-process with autoregressive coefficient ρ_Z and standard deviation σ_Z. The coefficient $\frac{\phi}{y} \geqslant 0$ represents the share of fixed costs in production. The role of these fixed costs is discussed below. Total output of final consumption goods $\hat{Y}_t^C$ equals aggregate production,

$$\hat{Y}_t^C = \hat{y}_t + \hat{N}_t. \tag{7}$$

Real marginal costs are equal across firms and are equal to the real wage $\hat{w}_t$ less TFP,

$$\widehat{mc}_t = \hat{w}_t - \hat{Z}_t. \tag{8}$$

Oligopolistic firms set prices P_t as a markup μ_t over nominal marginal costs, i.e., $P_t = \mu_t\left(P_t mc_t\right)$, which implies $\frac{1}{\mu_t} = mc_t$. Therefore, in linearized form, the actual markup reads as

$$\hat{\mu}_t = -\widehat{mc}_t. \tag{9}$$

Price setters are subject to a Rotemberg (1982)-type quadratic price adjustment cost. If $\kappa > 0$ denotes the Rotemberg price stickiness parameter, $\beta \in (0,1)$ represents the discount factor and $\delta \in (0,1)$ is the exogenous probability of exiting the market, then the new-Keynesian Phillips curve is given by

$$\hat{\pi}_t = \beta\left(1 - \delta\right) E_t \pi_{t+1} - \frac{(\varepsilon - 1)}{\kappa}\left(\hat{\mu}_t - \hat{\mu}_t^d\right), \tag{10}$$

where E_t is the expectations operator conditional on the information set at the beginning of period t. Inflation $\hat{\pi}_t$ depends positively on expected future inflation and negatively on the difference between the actual and desired price markup. If prices are flexible, i.e., $\kappa \to 0$, the actual markup equals its desired level, and price inflation is fixed at the long-run target.

2.2 Households

Households derive utility from consuming $\hat{C}_t$ and disutility from working $\hat{L}_t$. The respective marginal utilities are given by

$$\hat{U}_{C,t} = -\sigma_c \hat{C}_t \quad \text{and} \quad \hat{U}_{L,t} = \sigma_l \hat{L}_t, \tag{11}$$

where $\sigma_c > 0$ is the degree of risk aversion, and $\sigma_l > 0$ is the inverse Frisch elasticity of labor supply.

The household has access to a risk-free one-period nominal bond to facilitate the intertemporal transfer of wealth. The nominal gross interest rate $\hat{R}_t$ on this bond is set by the monetary authority. Optimization yields the usual consumption Euler equation,

$$\hat{U}_{C,t} = \left(\hat{R}_t - E_t\hat{\pi}_{t+1}\right) + E_t\hat{U}_{C,t+1}. \tag{12}$$

The first order condition for labor supply is

$$\hat{w}_t = \hat{U}_{L,t} - \hat{U}_{C,t}. \tag{13}$$

The labor market is perfectly flexible, therefore, the household supplies hours so that the marginal rate of substitution between leisure and consumption equals the real wage.

2.3 Firm Entry

I consider two entry mechanisms.

Frictionless Entry First, following Floetotto and Jaimovich (2008), I model entry in a frictionless way, where entry drives profits to zero in every period. Firm-level profits are expressed as $d_t = (1 - mc_t)\, y_t - \phi mc_t$. Given the relation between the actual markup and marginal production costs, i.e., $\frac{1}{\mu_t} = mc_t$, the zero profit condition is, therefore, $(\mu_t - 1)\, y_t = \phi$. In linearized form, this is

$$\hat{y}_t = -\varepsilon\hat{\mu}_t, \tag{14}$$

where $\varepsilon = \tau - (\tau - \omega)\, N^{-1}$ is the steady state price-elasticity of demand, see (3). The number of firms $\hat{N}_t$ is a flow variable, which is adjusted to satisfy (14). Note that fixed costs in production act as a stationarity-inducing device by bounding the number of operating firms. In the absence of fixed production costs, i.e., $\frac{\phi}{y} = 0$ in (6), long-run profits are above zero, which in turn would lead to unlimited entry of new firms and an entire erosion of firms' monopoly power.

Sunk Entry Costs Second, as in Bilbiie et al. (2007), I assume that prior to entry, firms face an exogenous sunk startup cost of η^E effective labor units. Given TFP, denoted by Z_t, the cost of entry then equals $\Psi_t = w_t \frac{\eta^E}{Z_t}$, where $\frac{\eta^E}{Z_t}$ is the amount of labor used in the production of a new firm. In linearized form, the entry cost $\hat{\Psi}_t$ is

$$\hat{\Psi}_t = \hat{w}_t - \hat{Z}_t. \tag{15}$$

Setting up $N_{E,t}$ firms requires $L_{E,t} \equiv N_{E,t}\frac{\eta^E}{Z_t}$ units of the labor bundle, with a linear counterpart of

$$\hat{L}_{E,t} = \hat{N}_{E,t} - \hat{Z}_t. \tag{16}$$

All firms that enter the economy produce in every period, until they are hit with a 'death' shock, which occurs with probability $\delta \in (0,1)$. Additionally, there is time-to-build in firm entry. The number of firms $\hat{N}_t$ is then a state variable that evolves according to

$$\hat{N}_{t+1} = (1-\delta)\hat{N}_t + \delta\hat{N}_{E,t}. \tag{17}$$

Potential entrants compare the discounted stream of future profits, i.e., the firm value $\hat{v}_t$, with the entry cost $\hat{\Psi}_t$. I allow for adjustment costs in establishing new firms, measured by the parameter φ.[5] As a result, the firm value can differ from the entry cost and new firms $\hat{N}_{E,t}$ enter into the market according to

$$\hat{N}_{E,t} = \frac{1}{(1+\beta)}\hat{N}_{E,t-1} + \frac{\beta}{(1+\beta)}E_t\hat{N}_{E,t+1} + \frac{1}{(1+\beta)\varphi}\left(\hat{v}_t - \hat{\Psi}_t\right). \tag{18}$$

Arbitrage equates the real return on bond holdings with the real return on equity and yields the following asset-pricing condition for the value of firms $\hat{v}_t$,

$$\hat{v}_t = -(R_t - E_t\hat{\pi}_{t+1}) + (1-\beta(1-\delta))E_t\hat{d}_{t+1} + \beta(1-\delta)E_t\hat{v}_{t+1}, \tag{19}$$

where $\hat{d}_t$ are firm-level profits that fluctuate endogenously according to

$$\hat{d}_t = \hat{y}_t + (\varepsilon - 1)\hat{\mu}_t. \tag{20}$$

Profits depend positively on both firms' output and actual price markup. Finally, in the case of sunk entry costs we do not need to consider fixed production costs to obtain a finite number of firms. Therefore, I set $\frac{\phi}{y} = 0$ in (6).

[5] I introduce a small degree of investment adjustments costs to solve for a non-stationarity problem that arises when assuming simultaneously a zero love of variety and sunk entry costs.

2.4 Market Clearing and Policy

The labor and goods market clearing conditions depend on the entry-cost specification, i.e., either frictionless entry or sunk entry costs. I describe the market clearing conditions for the case of sunk entry costs, because these nest the corresponding conditions under frictionless entry.

Total labor supply $\hat{L}_t$ equals labor used in the production of intermediate goods $\hat{L}_{C,t}$ plus labor used in the production of new firms $\hat{L}_{E,t}$,

$$\hat{L}_t = \left(1 - \frac{L_E}{L}\right)\hat{L}_{C,t} + \frac{L_E}{L}\hat{L}_{E,t}. \tag{21}$$

In the case of frictionless entry, $\frac{L_E}{L} = 0$ and therefore (21) simplifies to $\hat{L}_t = \hat{L}_{C,t}$; otherwise $\frac{L_E}{L} \in (0, 1)$.

Total output of final goods $\hat{Y}_t^C$ equals private consumption $\hat{C}_t$,

$$\hat{Y}_t^C = \hat{C}_t. \tag{22}$$

Let $\hat{Y}_t$ denote GDP, which equals consumption output and investment at the extensive margin,

$$\hat{Y}_t = \left(1 - \frac{vN_E}{Y}\right)\hat{Y}_t^C + \frac{vN_E}{Y}\left(\hat{\Psi}_t + \hat{N}_{E,t}\right). \tag{23}$$

If the creation of new firms is costless, then $\Psi = 0$, which by (18) implies that the steady state share price v equals zero as well. As a result, $\frac{vN_E}{Y} = 0$ and (23) simplifies to $\hat{Y}_t = \hat{Y}_t^C$.

To close the model, I assume that the monetary authority follows a simple empirical Taylor-type rule to set the nominal interest rate $\hat{R}_t$, given by

$$\hat{R}_t = \tau_R \hat{R}_{t-1} + (1 - \tau_R)\left(\tau_\pi \hat{\pi}_t + \tau_y \hat{Y}_t\right). \tag{24}$$

The central bank targets both inflation and the level of output. However, the interest rate is only gradually adjusted, which gives rise to interest rate smoothing of degree τ_R.

3 Simulation

3.1 Calibration

Table 1 displays all the parameter values that are used in the stochastic simulation of the model. The monetary policy rule exhibits a high degree of interest rate smoothing with τ_R calibrated at 0.80, while the coefficients on inflation, τ_π, and output, τ_y, are set at 1.5 and 0.1, respectively. These values are within the ballpark of the estimates in the empirical literature (e.g., Smets and Wouters, 2007). Unless otherwise noted, other parameter values are drawn from Floetotto and Jaimovich (2008). The autoregressive parameter of the TFP shock is set at $\rho_Z = 0.94$. The Frisch elasticity is given a relatively high value of $1/\sigma_l = 2$. Utility in consumption is logarithmic, implying risk aversion to be equal to $\sigma_c = 1$. Considering a quarterly calibration of the model, the discount factor is set at $\beta = 0.99$. The long-run price markup is calibrated to $\mu = 1.3$, which roughly implies an average demand elasticity of $\varepsilon = 4.3$. Based on the empirical evidence provided in Floetotto and Jaimovich (2008), the baseline case fixes the elasticity of substitution within industries at $\tau = 20$. By equation (5), the calibrated values for ε and τ then imply an approximate competition effect of $\eta = 1.1$, which lies in the middle of the estimates reported in Cecioni (2010).[6] More recent estimates of the competition effect in fully fledged DSGE models by Lewis and Poilly (2012) and Lewis and Stevens (2012) point toward lower values close to $\eta = 0.2$. Therefore, in Section 3.3, I investigate the sensitivity of the results to alternative parameterizations of τ, which in turn lead to different values for η. Finally, I turn to the parameters which are specific to the entry-cost specification considered. In case entrants face a sunk startup cost, our model features two additional parameters. The first is the firm exit rate, which is set to $\delta = 0.025$ to fit the annual job destruction rate of 10% as is observed in US data. Second, our model features adjustment costs in firm entry, which are fixed at $\varphi = 0.01$.[7] In the case where entry is frictionless, we need to consider non-zero fixed production costs, to bound the number of operating firms. By the steady state conditions, the share of fixed cost in firm output equals $\phi/y = \mu - 1$, i.e., $\phi/y = 0.3$. I comment on the values assigned to the degree of price stickiness κ in the next subsection.

[insert Table 1 here]

[6] Note that the steady state demand elasticity ε is a reduced form parameter that depends on both the within- and across-industry substitution elasticity, i.e., τ and ω, and on the steady state number of firms N, see equation (3). Among other structural parameters, the latter, in turn, depends on the cost parameters that determine entry, i.e., the share of fixed costs in production ϕ/y, or the sunk entry cost η^E. In contrast to the demand elasticity, there exists no direct evidence for the value of these cost parameters. Therefore, instead of fixing the cost parameters and deriving the demand elasticity ε from the model's steady state, I do the opposite and immediately calibrate ε. Setting the elasticity of substitution between sectoral goods at $\omega = 1.25$, my calibration then implies $\eta^E = 5.73$ and $\phi/y = 0.3$.

[7] Adjustment costs in firm entry act as a stationarity-inducing device in our model and are therefore considered to be small. The non-stationarity problem arises when assuming that both a zero love of variety and sunk entry costs exist simultaneously.

3.2 Propagation of Technology Shocks

I now examine the dynamic responses of key variables to a temporary increase in technology, triggered by an exogenous innovation of one percent to exogenous TFP $\hat{Z}_t$. My aim in this section is to assess the relative importance of the competition effect and of price stickiness for the propagation of technology shocks. I first replicate the internal magnification mechanism provided by procyclical competition effects, as it was obtained in original contributions to the literature that considered flexible prices. In doing so, I follow Floetotto and Jaimovich (2008) and assume that entry is frictionless.[8] I then examine how incomplete price adjustment affects this channel of shock magnification. Finally, I assess the robustness of the results to the specification of the alternative model where firms face a sunk startup cost prior to entry as in Bilbiie et al. (2007).

The Competition Effect as a Channel of Shock Magnification Figure 1 depicts the impulse responses for the oligopolistic competition model when prices are flexible, i.e., $\kappa \to 0$, and entry is frictionless. To demonstrate the shock magnification provided by oligopolistic competition, I also plot the dynamics induced by the technology shock in a traditional flexible price RBC model that features monopolistic competition.[9] Under both frameworks, the temporary rise in TFP increases output and profits on impact. This attracts entry of new firms until all profit opportunities are exploited, i.e., profits are zero. In contrast to the standard RBC model, where markups are constant, the oligopolistic counterpart entails strategic interactions through which the desired markup declines in response to the increased number of competitors, see equation (4). This competition effect increases labor demand and real wages, which in turn induces a stronger intertemporal substitution effect in favor of current consumption and labor supply through equation (13). As a result, output which equals consumption rises further. Thus, the decline in the desired markup, which occurs due to the competition effect, magnifies the effects of the technology shock compared to the monopolistic competitive model. Note that the positive substitution effect on labor supply due to the rise in the real wage rate is completely offset by the negative income effect induced by the increase in consumption. As a result, the number of hours worked remains constant over the entire transition period and is therefore

[8] Under this specification, my model differs from Jaimovich and Floetotto's (2008) only because I abstract from physical capital accumulation.

[9] The traditional RBC-model is implied from the oligopolistic framework by matching the within-industry elasticity of substitution τ to the steady state demand elasticity ε in (3). This calibration entails an infinite number of firms in the economy and eliminates the competition effect.

not presented in Figure 1.[10]

[insert Figure 1 here]

To quantify the relative strength of the internal magnification mechanism, in Table 2 I compare the volatility of output in the oligopolistic competition model with what is indicated in the traditional RBC model. The competition effect raises output volatility by roughly 50% when compared to the standard RBC model. This amplification mechanism implies that, relative to monopolistic markets, oligopolistic markets require much less volatile technology shocks to account for the same output variability. The third column in Table 2 reports the ratio of the variances of TFP and output for both model specifications and reveals that the competition effect generates output volatility from technology shocks that are about 34% less volatile than those in the standard RBC model. Jaimovich and Floetotto (2008) report an even stronger internal magnification mechanism, driving down the volatility of technology shocks by approximately 50%. In the flexible price case, my model variant with frictionless entry differs from Jaimovich and Floetotto's (2008) model only because I abstract from physical capital accumulation. As Colciago and Etro (2010) show, investment behavior strengthens the propagation mechanism.[11]

[insert Table 2 here]

Impact of Increasingly Sticky Prices I now consider an environment where the presence of adjustment costs makes it increasingly difficult for the firm to change prices to respond to movements in TFP. Keeping all other parameters constant, I increase the degree of price stickiness κ. The results are presented in Figure 1 along with the dynamics in the flexible price case. To facilitate the interpretation of the Rotemberg cost, I comment on the corresponding price duration in the Calvo analog of the Phillips curve (10).[12]

[10] This result is contingent on the assumptions that consumption utility takes the log form and GDP is entirely absorbed by consumption.

[11] In an additional robustness check, presented in Appendix B, I include capital in the model. In this case, the competition effect's magnification of the dynamics of technology shocks is hardly affected by price stickiness. However, this conclusion is contingent on abstracting from real rigidities in investment behavior. Even for a very mild degree of investment adjustment costs, price stickiness induces effects similar to the ones described in my analysis without physical capital accumulation (see the next section).

[12] As seen in equation (10), the Rotemberg adjustment scheme delivers a coefficient $\frac{(\varepsilon-1)}{\kappa}$ on the markup gap in the NKPC. In the Calvo analog of the traditional NKPC this slope coefficient is $\frac{(1-\beta\xi)(1-\xi)}{\xi}$, where $\frac{1}{1-\xi}$ determines the duration of price stickiness. Therefore, it is possible to compare the slope coefficients given by both schemes of price adjustment, to interpret the Rotemberg cost in price duration terms. Strictly speaking, however, we cannot compute an average price contract duration in our model, as this requires a constant population of price setters.

An exogenous increase in technology lowers marginal production costs. In the presence of price stickiness, prices do not fully adjust, such that—holding everything else constant—markups increase and inflation declines. This weakens the propagation of technology shocks and thus counteracts the internal magnification mechanism induced by the competition effect. For a very mild degree of price inflexibility, by fixing the price duration at approximately 2 quarters, the competition effect prevails and the actual markup falls on net. Relative to the standard RBC model, this magnifies the dynamic responses of the labor market variables, consumption and output over the entire transition period, but to a smaller extent than compared to those obtained in the oligopolistic flexible price case.

When we increase the price adjustment cost to the corresponding price contract duration of approximately 4 quarters, the actual price markup increases at impact. This dampens the real wage increase, which in turn mitigates the positive response of consumption and output. Only after close to 2 quarters does the competition effect dominate the sticky price channel, inducing the actual markup to decline and output to rise above its RBC-level. In the short run, consequently, the internal magnification mechanism that the competition effect delivers is nullified by the sluggish adjustment in prices. As we gradually increase the price adjustment cost, the countercyclical effect of competition on markups is further eroded. Consider a relatively high degree of price inflexibility, where prices change roughly every 2 years, actual markups decrease only after approximately 1.5 years. Table 2 allows us to assess the relative strength of the competition effect over the entire transition period. Relative to the oligopolistic environment with flexible prices, reasonable degrees of price rigidity (i.e., a price contract duration of 4 to 5 quarters) weaken the competition effect's amplification on output volatility from 50% to approximately 20%. Alternatively, the internal magnification effect on output is roughly halved, which dampens the decline in relative volatility of TFP to output from −35% to about −17%.

Finally, even though for the propagation of technology shocks, the relative importance of the competition effect declines as price stickiness increases, its countercyclical effect on desired markups increases. Compared to the flexible price case, the higher markups observed under inflexible prices generate larger profit opportunities, which in turn attract more firms to enter. Therefore, less frequent price revisions induce a higher rate of firm entry, which through the competition effect translates into stronger declines of the desired markup. As a direct result of this process, the gap between the actual and the desired price markup rises and inflation declines (not shown).

Sunk Startup Costs The frictionless-entry model implies that profits are zero in all periods and the number of firms is not a state variable. These features are inconsistent with evidence on the procyclicality of profits and the sluggish dynamics of the number of competitors.[13] In response to these challenges, Bilbiie et al. (2007, 2012) propose an alternative setup where entry is subject to sunk entry costs and a time-to-build lag. In that model profits are allowed to vary and the number of firms is a state variable. Colciago and Etro (2010) show that the sunk-entry-cost model outperforms the frictionless-entry model in matching second moments of certain variables in the data. Therefore, in this section, I wish to assess the robustness of the results to this alternative entry model.

Figure 2 examines how costs in firm entry behavior influence the propagation and magnification of technology shocks. Relative to the model with frictionless entry, two observations stand out. First, due to the time-to-build in firm entry, a positive technology shock induces a persistent and hump-shaped increase in market competition in all model specifications. Through the competition effect, this implies an equally sluggish decline in the desired price markup.

Second, when entrants face a sunk startup cost, the competition effect greatly strengthens the dynamic responses of labor market variables and of consumption, whereas its magnification effect on output is negligible. Variations in startup costs have a direct impact on output, which can be interpreted as investments along the extensive margin, see equation (23). In contrast to the frictionless-entry model, the competition effect then induces two opposite effects on output. On the one hand, it magnifies consumption by reducing markups and increasing real wages. On the other hand, it depresses investment along the extensive margin, because the decline in markup pushes down profits, firm value and firm entry. Table 2 quantifies the relative importance of these two channels. First, let us consider flexible prices, i.e., $\kappa \to 0$. The competition effect, in this case, increases output volatility by only nearly 4%, compared to RBC model. Clearly, even with very mild price inflexibility, the negative sticky price effect on output negates this small positive competition effect, resulting in a dampened rise in GDP like in traditional new-Keynesian models without competition effects. In contrast to the output dynamics, the competition effect induces a strong internal magnification effect on consumption. In the flexible price case, the competition effect generates consumption volatility that is approximately 144% higher than what is observed in the traditional RBC model. As we increase the price adjustment cost, the magnification of consumption is only mildly weakened; e.g., a price contract duration of 4 to 5 quarters dampens the increase in consumption variability from

[13] See Bilbiie et al. (2012) and the reference therein.

144% to approximately 100%, which is still remarkably high.

[insert Figure 2 here]

Concerning output, in contrast to the model with frictionless entry, we conclude that the competition effect in the sunk-entry-cost model does not provide a strong magnification mechanism. Therefore, the sticky price channel prevails in the propagation of technology shocks, which dampens the output response relative to the RBC model. However, comparing the relative volatilities of TFP to output between the two entry mechanisms in Table 2 reveals that the startup cost itself generates an amplification mechanism. In the sunk-entry-cost model, the amount of volatility of technology shocks required to account for the same fluctuations in output is always lower than what is required by the frictionless-entry model.

3.3 Alternative Parameter Specifications

This section focuses on the sensitivity of the results to alternative parameter specifications. First, I alter the size of the elasticity of substitution within industries τ, in order to obtain different values for the competition effect η. Second, I vary the degree of monetary policy reaction to inflation τ_π. For each parameterization, I investigate the impact of the competition effect and price stickiness on output and consumption dynamics by calculating the percentage change in the corresponding volatilities relative to those obtained in the RBC model. The results of both robustness checks are summarized in figures 3a and 3b, for the frictionless-entry and sunk-entry-cost cases, respectively. I discuss them in turn.

[insert Figures 3a and 3b here]

The literature provides little guidance on the size of the competition effect η. Based on the evidence provided in Jaimovich and Floetotto (2008) and Cecioni (2010), the baseline calibration was considered in terms of a more optimistic environment, implying a competition effect of approximately $\eta = 1.08$. However, more recent estimates of the competition effect in fully fledged DSGE models by Lewis and Poilly (2011) and Lewis and Stevens (2012) point toward lower values of η, that lie between 0.1 and 0.3. To change the size of the competition effect η, I vary the within-industry substitution elasticity τ in equation (5), while holding fixed the demand elasticity ε at its baseline level. By equation (3), an increase in product substitutability must be accompanied by a decline in the steady state number of firms N, to keep the demand elasticity unaltered. Consequently, higher values for τ lower competition and, therefore, increase the competition effect η. In the remainder of this section, I comment directly on the values of the competition effect. First, I consider variations in η under flexible prices. Naturally, as we decrease the size of the competition effect, its magnification on the propagation of technology shocks is weakened. However, this is only a mild weakening. At $\eta = 0.39$, the magnification effect on consumption is only approximately $1/3$ lower for both model specifications when compared to our baseline calibration of $\eta = 1.08$. Therefore, only small cyclical variations in competition are required to generate a powerful magnification mechanism. This result has originally been described by Floetotto and Jaimovich (2008). However, my analysis shows that the conclusion changes dramatically when prices are sticky. The magnification induced by the competition effect is entirely nullified by the sluggish adjustment in nominal prices for low values of η when we consider the range $\eta \in (0.12, 0.39)$. Relative to the traditional RBC model, output and consumption variability decreases. This sharply contrasts the mild weakening effect of nominal price rigidities on the magnification of consumption that is observed when competition effects are high at about $\eta = 1.08$, and when entrants face a sunk startup cost.

Next, I vary the degree of inflation targeting τ_π in the monetary policy rule (24). The canonical new-Keynesian paradigm differs from the RBC setup along two dimensions, i.e., prices are sticky and monetary policy affects the real economy. Therefore, the effect of nominal rigidities on the competition channel of shock magnification is contingent on monetary policy behavior. As policy focuses more on inflation stabilization, the real effects of price stickiness become progressively dampened. Consequently, as τ_π increases, the competition effect prevails in the propagation of technology shocks and the relative strength of the internal magnification mechanism approaches its level observed under flexible prices. Conversely, figures 3a and 3b reveal that the magnification effect on output quickly recedes as the focus on inflation diminishes. The magnification of consumption in the model with sunk entry costs is more robust to variations in τ_π.

4 Conclusion

This paper provides a closer examination of oligopolistic behavior as a source of propagation and magnification for technology shocks, as documented by e.g., Portier (1995), Floetotto and Jaimovich (2008) and Colciago and Etro (2010). Strategic interactions between oligopolists induce a competition effect by which firm entry lowers the price setting power of firms. In response to a positive TFP shock, profits increase, attracting entry of new firms. The resulting increase in competition reduces desired markups and therefore magnifies the propagation of the technology shock. I find that this internal magnification mechanism, delivered by the competition effect, is considerably weakened once we relax the assumption of perfectly flexible prices. Overall, when nominal prices are sluggish to adjust, the countercyclical movement that the technology shock induces in the markup is milder and the magnification effects on output and consumption are nearly halved. As shown by Floetotto and Jaimovich (2008), and confirmed by this paper, only a small competition effect is required to generate a powerful magnification mechanism in the case when prices are flexible. However, as prices become increasingly sticky, this magnification mechanism is entirely nullified. For reasonable degrees of nominal rigidities, markups increase in response to the technology shock and consequently the positive impact effects on output and consumption are mitigated as observed in traditional new-Keynesian models featuring monopolistic competition.

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Table 1: Calibrated parameter values

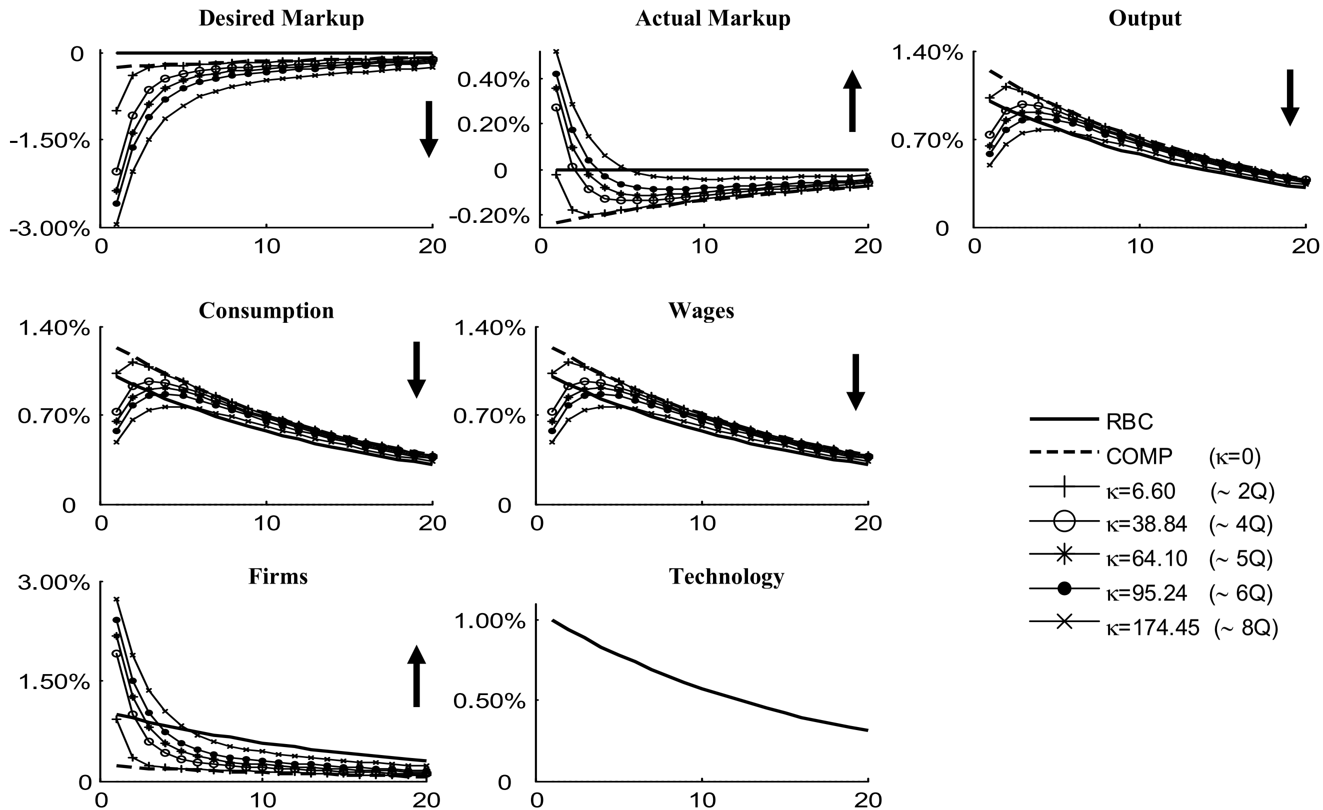
SYMBOL	DESCRIPTION	VALUE	
Common Parameters			
β	Subjective discount factor	0.99	
σ_c	Risk aversion	1.00	
$1/\sigma_l$	Frisch elasticity	2.00	
μ	Steady state markup	1.30	
τ	Substitution elasticity within industries	20	
ω	Substitution elasticity across industries	1.25	
ρ_Z	Persistence of the technology shock	0.94	
Implied Parameters			
η	Competition effect	1.08	
Parameters Related to Sunk Startup Costs			
δ	Firm exit rate	0.025	
φ	Entry adjustment costs	0.01	
Parameters Related to Frictionless Entry			
ϕ/y	Share of fixed costs in production	0.30	
Additional Parameters in Models with Nominal Price Stickiness			
τ_R	Interest rate smoothing	0.80	
τ_π	Interest rate response to inflation	1.50	
τ_y	Interest rate response to output	0.10	
κ	Rotemberg price adjustment cost	Value	Price Duration (Calvo Analog)
		6.60	~ 2 Q
		38.84	~ 4 Q
		64.10	~ 5 Q
		95.24	~ 6 Q
		174.45	~ 8 Q

Table 2: Impact of price stickiness on the internal magnification mechanism

Model Types ↓	**Frictionless Entry**			**Sunk Entry Costs**					
	$\frac{\sigma_Y^2}{\sigma_{Y,RBC}^2}$	$\frac{\sigma_Z^2}{\sigma_Y^2}$		$\frac{\sigma_Y^2}{\sigma_{Y,RBC}^2}$	$\frac{\sigma_Z^2}{\sigma_Y^2}$		$\frac{\sigma_C^2}{\sigma_{C,RBC}^2}$	$\frac{\sigma_Z^2}{\sigma_C^2}$	
RBC	1	1	%Δ RBC	1	0.59	%Δ RBC	1	1.46	%Δ RBC
COMP ($\kappa = 0$)	1.53	0.66	-34%	1.04	0.57	-3.6%	2.44	0.60	-59%
$\kappa = 6.60$ (≈ 2 Q)	1.44	0.69	-31%	1	0.59	-0.3%	2.35	0.61	-57%
$\kappa = 38.84$ (≈ 4 Q)	1.25	0.80	-20%	0.94	0.62	6.0%	2.08	0.70	-52%
$\kappa = 64.10$ (≈ 5 Q)	1.15	0.87	-13%	0.92	0.64	8.8%	1.93	0.76	-48%
$\kappa = 95.24$ (≈ 6 Q)	1.16	0.94	-6.6%	0.90	0.66	11%	1.79	0.82	-44%
$\kappa = 174.45$ (≈ 8 Q)	0.88	1.12	12%	0.86	0.68	16%	1.49	0.98	-33%

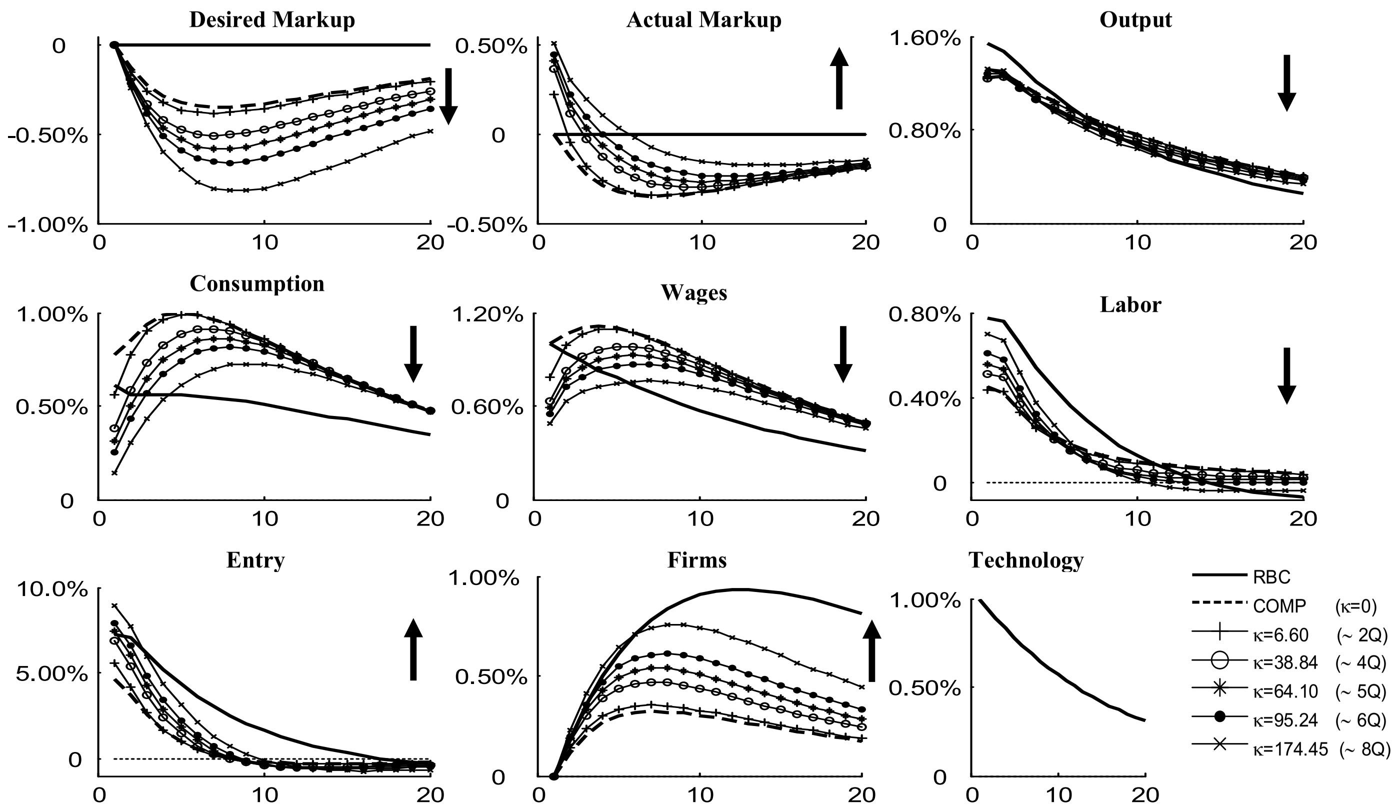
Note: σ_X^2 represents the variance of variable X. The reported moments are the theoretical ones as derived from the different model types. 'RBC' denotes the baseline case with monopolistic markets and flexible prices. 'COMP' is the model variant with oligopolistic competition. The 'κ'-models introduce nominal rigidity, with degree κ, in the oligopolists' price setting behavior. The quarterly interpretation Q of the adjustment cost parameter κ is based on a standard NKPC obtained under a Calvo pricing scheme. '%Δ RBC' denotes for each model variant the percentage change in TFP volatility relative to the RBC-case.

Figure 1: Impulse responses to a technology shock in the model featuring frictionless entry



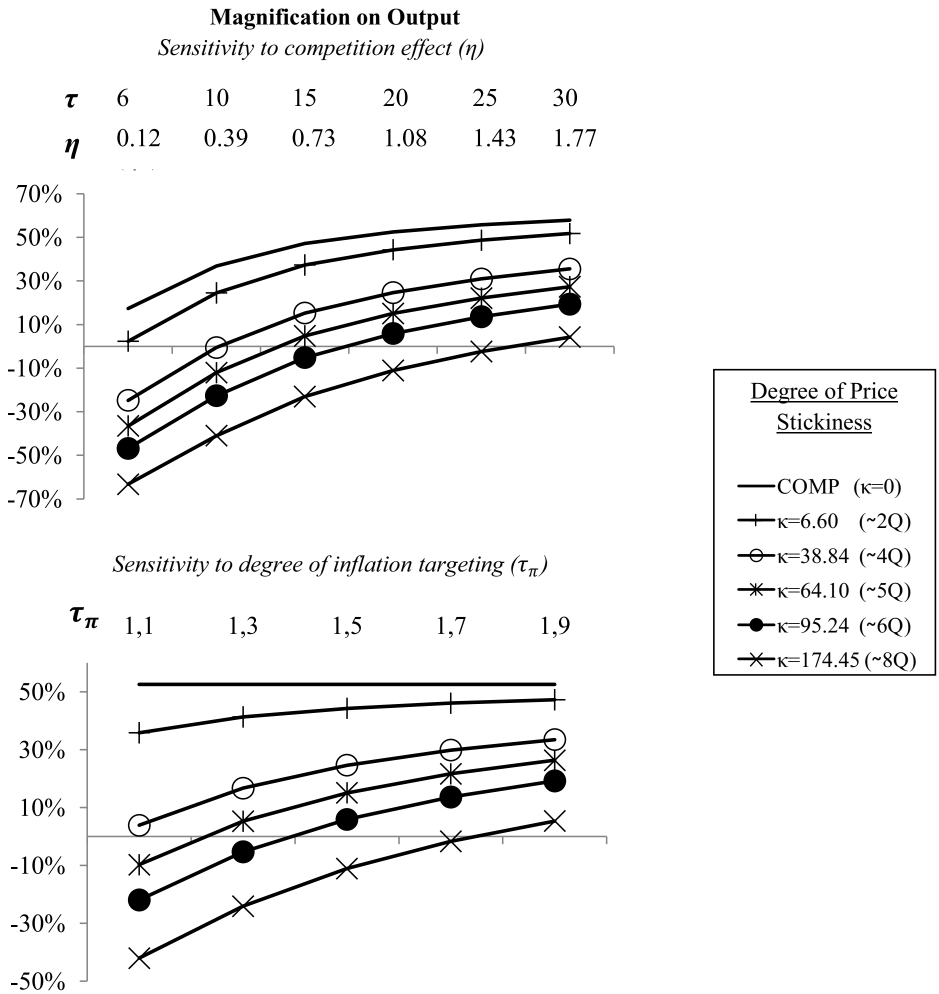
Note: See Table 2 for a brief description of all the model specifications. The quarterly interpretation Q of the price adjustment cost parameter κ is based on a standard NKPC obtained under a Calvo pricing scheme. Arrows present the effect of increasingly price stickiness on the competition channel of shock magnification.

Figure 2: Impulse responses to a technology shock in the model featuring sunk startup costs



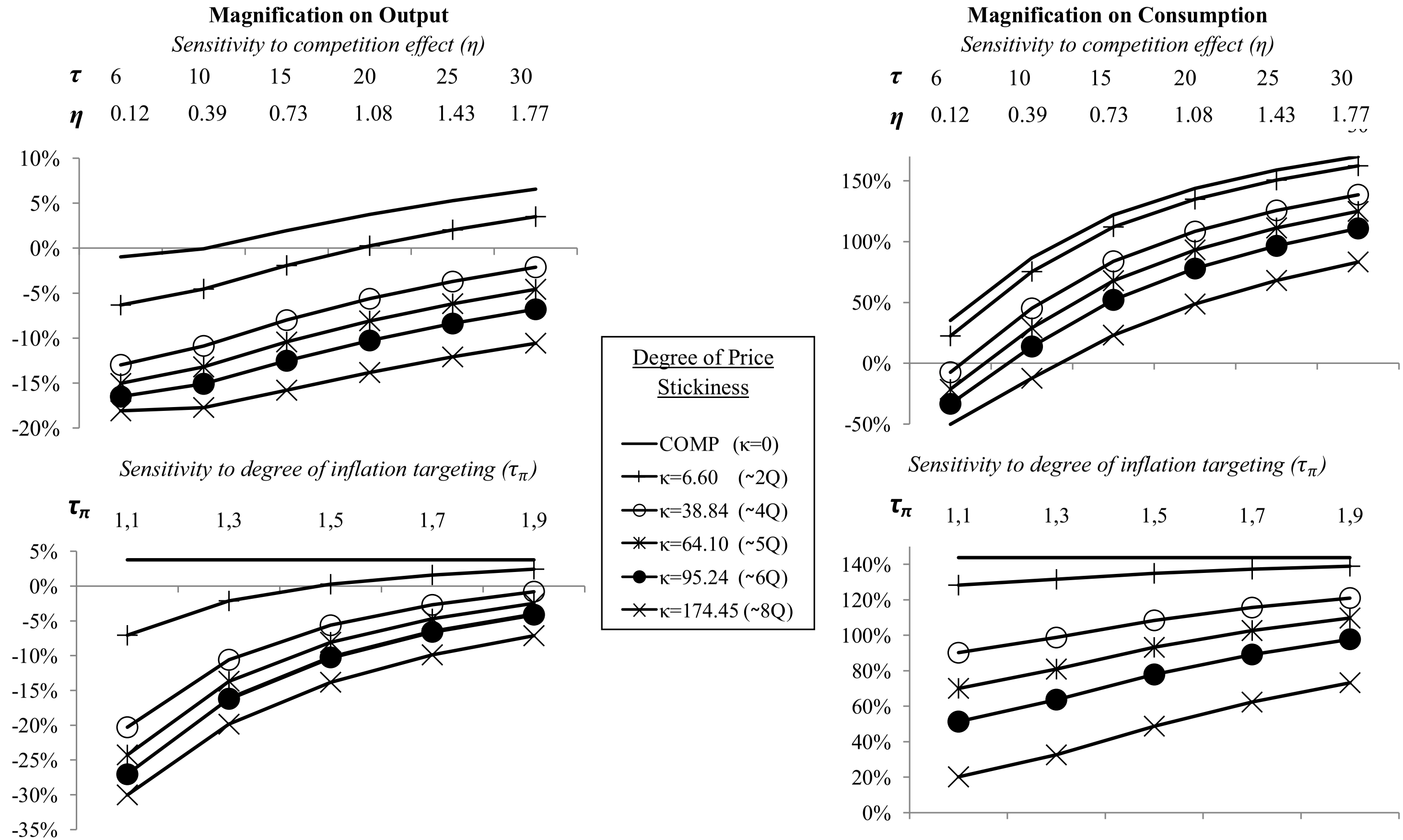
Note: See Table 2 for a brief description of all the model specifications. The quarterly interpretation Q of the price adjustment cost parameter κ is based on a standard NKPC obtained under a Calvo pricing scheme. Arrows present the effect of increasingly price stickiness on the competition channel of shock magnification.

Figure 3a: Sensitivity of the magnification mechanism to alternative parameter specifications – frictionless-entry case



Note: Figures present for each parameterization of each model variant the percentage change in output and consumption volatility relative to the RBC-case. Model variants are as follows: 'COMP' is the oligopolistic model featuring flexible prices. The 'κ'-models introduce nominal rigidity, with degree κ, in the oligopolists' price setting behavior. The quarterly interpretation Q of the adjustment cost parameter κ is based on a standard NKPC obtained under a Calvo pricing scheme.

Figure 3b: Sensitivity of the magnification mechanism to alternative parameter specifications – sunk-entry-cost case



Note: See Figure 3a.

Chapter 4

The Competition Effect in Business Cycles

The Competition Effect in Business Cycles*

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Abstract

How do changes in market structure affect the US business cycle? We estimate a monetary DSGE model with endogenous firm/product entry and a translog expenditure function by Bayesian methods. The dynamics of net business formation allow us to identify the 'competition effect', by which desired price markups and inflation decrease when entry rises. We find that a 1 percent increase in the number of competitors lowers desired markups by 0.15 percent. While markup fluctuations due to sticky prices or exogenous shocks account for a large proportion of US inflation variability, endogenous changes in desired markups also play a non-negligible role.

JEL classification: C11, E23, E32.
Keywords: Bayesian estimation, business cycles, competition, entry, markups.

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Monetary business cycle models typically feature monopolistic competition; this is to justify price setting power and sticky prices. At the same time, such models tend to depart from Dixit and Stiglitz (1977) by assuming a fixed range of products and firms, an assumption which in the presence of positive profits is difficult to uphold. In response to this, a largely theoretical literature has emerged that investigates the role of firm and product entry for aggregate fluctuations. In particular, the 'competition effect', by which an increase in the number of competitors reduces desired markups and inflation, acts as an endogenous propagation and amplification mechanism. Floetotto and Jaimovich (2008) present a business cycle model with oligopolistic competition, where firm entry has a negative effect on markups. Colciago and Etro (2010) show that such a model outperforms the standard real business cycle (RBC) model in terms of matching second moments of certain variables in the data. Bilbiie, Ghironi and Melitz (2012) show that an RBC model with translog consumption preferences generates a competition effect and countercyclical markups. Under this preference structure, the price-elasticity of demand is increasing in the number of available products.

This paper provides an empirical model validation exercise which is so far missing in the literature. It uses Bayesian techniques to estimate the competition effect in a dynamic stochastic general equilibrium (DSGE) model with endogenous entry. We seek to answer two questions. First, how does the competition effect influence the cyclical behavior of markups? Second, is this effect important in explaining US inflation fluctuations?

Our first question relates to the dynamics of price-cost markups, which are key in business cycle transmission. Consider the standard New Keynesian model. On the one hand, an expansionary demand shock raises marginal costs. If prices do not adjust fully, markups fall. On the other hand, an expansionary supply shock lowers marginal costs. If prices do not adjust fully, markups rise. When entry and exit dynamics are taken into account, markups may additionally depend on the degree of competition, i.e., on the number of firms or products.[1] The response of entry to a shock determines how the competition effect works. If an expansionary shock (i.e., one that raises output) leads to profit opportunities over and above entry costs, new firms and products enter. Then, desired markups and inflation are reduced through the competition effect. In contrast, if an expansionary shock crowds out entry, desired markups and inflation rise through the competition effect. Therefore, the competition effect may amplify or dampen propagation in the New Keynesian model. This paper characterizes the conditional dynamics of entry (or the 'extensive margin') and markups in response to an array of shocks.

[1] Campbell and Hopenhayn (2005) present empirical evidence that markups are negatively related to the number of competitors in an industry.

Markups of prices over marginal cost are unobserved and therefore hard to measure. There is no agreement on the conditional properties of markups in the data, or even on their unconditional cyclicality. The influential work by Rotemberg and Woodford (1999) finds evidence of countercyclical markups, while the more recent contribution by Nekarda and Ramey (2010) presents evidence supporting procyclical markups. We circumvent the measurement problem by excluding markups from the estimation and focussing instead on directly observable variables. Using our parameter estimates, we then describe the cyclical behavior of the markup implied by the model. In addition, we quantify the contribution of the competition effect and desired markup shocks to the markup-output correlation.

Our second question concerns the contribution of entry and the competition effect to movements in inflation. The answer to this question has implications for monetary policy. Optimal monetary policy aims at eliminating inefficiencies arising from price setting distortions; i.e., it tries to replicate the equilibrium allocations that would arise under perfect price flexibility. If the competition effect accounts for a large fraction of inflation variability, the central bank runs the risk of reacting to changes in inflation that do not reflect price rigidities but instead endogenous changes in market structure. In order to assess this risk, we wish to quantify the relevance of the competition effect for US inflation.

Firm and product turnover has been neglected in empirical business cycle research, e.g., in the influential studies by Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007). Two exceptions are worth noting, however. Cecioni (2010) estimates a New Keynesian Phillips Curve augmented with firm entry. She finds that the pass-through of real marginal costs to inflation becomes stronger when entry and the competition effect are taken into account. Lewis and Poilly (2012) estimate two variants of the endogenous-entry model by minimizing the distance between the model-based impulse responses to a monetary policy shock and their empirical counterparts. The first model variant features translog preferences and a demand-driven competition effect, while the second assumes strategic interactions between oligopolists and a supply-driven competition effect. They find that the first model generates a significant competition effect in the monetary transmission mechanism, while the second model does not. This paper estimates a DSGE model with endogenous entry using Bayesian methods as in Smets and Wouters (2007). The model features sunk-cost driven entry dynamics and a translog expenditure function for intermediate goods, as well as a host of nominal and real frictions. Assuming a range of exogenous shocks and using a Bayesian approach allows us to address the two research questions posed above, which is not possible in the limited information estimation exercise in Lewis and Poilly (2012) or with the single-equation method of Cecioni (2010).

Our contribution is twofold. First, we show that the way the competition effect influences business cycle transmission is shock-dependent. Supply shocks and monetary policy shocks entail a procyclical movement of entry, thereby inducing a countercyclical desired markup response. Demand shocks, in contrast, lead to a countercyclical response of entry and procyclical desired markups. Our analysis of transmission channels extends Bilbiie, Ghironi and Melitz (2007) and Bilbiie, Ghironi and Melitz (2012), who consider fewer shocks and a smaller set of frictions. The model-implied markup is countercyclical once the competition effect and shocks to desired markups are taken into account. Second, we carry out a counterfactual analysis of US inflation, showing how the historical inflation path was altered by the competition effect. Empirically, the competition effect of entry has at times posed some risk of monetary policy mistakenly reacting to efficient markup fluctuations.

One potential limitation of our exercise is that we measure entry as *firm* entry, i.e., net business formation, new incorporations and establishment births, rather than *product* entry. Bilbiie, Ghironi and Melitz (2012), as well as a number of trade-related studies referenced therein, emphasize the importance of product turnover for output dynamics. Although it would be desirable to estimate the model using product data, we are constrained by the lack of a long enough time series, covering the universe of products, to carry out such an analysis. To the extent that product-level dynamics matter more for markup and inflation fluctuations than firm entry and exit, our results may understate the importance of the competition effect.

The paper proceeds as follows. In Section 1, we present an outline of the baseline model. Section 2 contains details on the estimation method, the data, our choice of priors, and posterior distribution statistics. In Section 3, we characterize the transmission channels of various shocks through the competition effect and the overall cyclicality of the model-implied markup. We perform a counterfactual decomposition of US inflation in Section 4. Section 5 discusses a number of robustness exercises. Section 6 concludes.

1 Model

Our model combines the entry mechanism and the translog expenditure function proposed by Bilbiie, Ghironi and Melitz (2012) with a set of real and nominal frictions as in Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007). We include habit formation and investment adjustment costs / variable capital utilization. These model features are deemed necessary to replicate the dynamics of consumption and investment, respectively. Entry, which constitutes investment along the extensive margin, can only be captured adequately if the model accounts well for the other components of aggregate demand.

In the first subsection, we derive the part of the model related to the translog expenditure function, desired markups and the competition effect. The remaining model equations are presented in linearized form.[2] Hatted variables denote deviations from the deterministic steady state. Variables without a hat or time subscript refer to the steady state level. The equilibrium we consider is symmetric: all households, firms and entrants are identical.

1.1 Translog Expenditure Function, Desired Markups and Competition Effect

We assume that aggregation over intermediate goods varieties takes the translog form, such that the elasticity of demand for an individual good is increasing in the number of competing goods. Consumers choose the cost-minimizing combination of goods to obtain one unit of Y_t^C, the aggregate goods bundle, at price P_t, the aggregate (welfare-based) price index. As in Feenstra (2003), we postulate that the optimal expenditure function is given by

$$\begin{aligned} \ln P_t \quad &= \quad \frac{1}{2}\frac{\tilde{N}-N_t}{\gamma_t \tilde{N} N_t} + \frac{1}{N_t}\sum_{f=1}^{N_t} \ln p_t^f + \frac{\gamma_t}{2}\sum_{f=1}^{N_t}\sum_{j=1}^{N_t} b_{fj} \ln p_t^f \ln p_t^j, \qquad (1) \\ &\text{where } f,j = 1,\ldots,N_t \text{ and } \left\{ \begin{array}{ll} b_{fj} = -\frac{N_t-1}{N_t}, & \text{for } f=j \\ b_{fj} = \frac{1}{N_t}, & \text{for } f \neq j \end{array} \right. . \end{aligned}$$

N_t is the (time-varying) number of available goods, $\tilde{N} > N_t$ is the (constant) number of all conceivable goods, and γ_t measures the (exogenous) price-elasticity of the expenditure share on an individual good f, which is defined as $s_t^f \equiv \frac{p_t^f y_t^f}{P_t Y_t^C}$.[3] We can derive the price-elasticity of demand as

$$\varepsilon_t^f = 1 - \frac{\partial s_t^f}{\partial \ln p_t^f}\frac{1}{s_t^f} = 1 + \frac{\gamma_t}{s_t^f}. \qquad (2)$$

We impose $\gamma_t > 0$ to ensure that the demand elasticity exceeds unity.

Imposing symmetry ($p_t^f = p_t^j = p_t$) and defining the real product price ρ_t as the ratio of the nominal product price p_t to the aggregate price index P_t, i.e., $\rho_t \equiv p_t/P_t$, we can

[2] For a full model derivation, see the appendix available at http://sites.google.com/site/vivienjlewis.

[3] We use the terms 'goods' and 'firms' interchangeably throughout, assuming that each firm produces exactly one differentiated variety. For expositional purposes, we treat N_t as a natural number in this subsection. In the remainder of the model outline, $N_t \in \mathbb{R}^+$.

rewrite (1) as

$$\rho_t(N_t) = \exp\left(-\frac{1}{2}\frac{\tilde{N} - N_t}{\gamma_t \tilde{N} N_t}\right).$$

The real product price is a positive function of the number of firms and products, N_t. In linearized form, this is

$$\hat{\rho}_t = \nu \hat{N}_t + \left(1 - \tfrac{N}{\tilde{N}}\right)\nu\hat{\gamma}_t, \text{ where } \nu = \frac{1}{2\gamma N}.$$

The elasticity of the real product price to the number of firms/products is $\nu \geq 0$. This parameter captures 'love of variety', which measures the degree to which consumers can increase their utility by spreading their consumption expenditure across more differentiated goods. Under the translog expenditure function assumed above, love of variety is inversely related to the steady state number of firms N and to the price-elasticity of the spending share in steady state, γ.[4] Under price symmetry ($\overline{\ln p_t} = \ln p_t^f$), the expenditure share equals the inverse of the number of goods,

$$s_t(N_t) = \frac{1}{N_t}. \tag{3}$$

The demand for a single variety is then found by rearranging the definition of the expenditure share $s_t = \frac{\rho_t y_t}{Y_t^C}$ and substituting out s_t using (3), $y_t = \frac{Y_t^C}{\rho_t N_t}$. In linearized form, this is

$$\hat{y}_t = \hat{Y}_t^C - \hat{\rho}_t - \hat{N}_t.$$

Furthermore, using (3) in (2), the demand elasticity simplifies to

$$\varepsilon_t(N_t) = 1 + \gamma_t N_t. \tag{4}$$

Intuitively, more product diversity makes demand more elastic, as products become more substitutable with entry. With a time-varying demand elasticity, the desired markup defined as $\mu_t^d(N_t) \equiv \frac{\varepsilon_t(N_t)}{\varepsilon_t(N_t)-1}$ is also time-varying. In particular,

$$\mu_t^d(N_t) = \frac{1 + \gamma_t N_t}{\gamma_t N_t}.$$

The desired markup μ_t^d is distinct from the actual markup μ_t which is also affected by price setting frictions. In linearized form, the desired markup is

$$\hat{\mu}_t^d = -\eta(\hat{\gamma}_t + \hat{N}_t), \text{ where } \eta = \frac{1}{1 + \gamma N}. \tag{5}$$

[4] In Dixit and Stiglitz (1977) preferences, love of variety is $\nu = \frac{1}{\varepsilon - 1}$, where ε denotes both the substitution elasticity between goods as well as the price-elasticity of demand. Floetotto and Jaimovich (2008) assume zero love of variety ($\nu = 0$), such that no utility gain arises from additional product diversity.

The desired markup (5) has an endogenous component ($-\eta\hat{N}_t$) and an exogenous component ($-\eta\hat{\gamma}_t$). The elasticity of the desired markup to the number of firms captures the 'competition effect'. For $\eta > 0$, desired markups are eroded by the arrival of new entrants. Assuming a translog expenditure function, the competition effect equals the inverse steady state demand elasticity, $\eta = \frac{1}{\varepsilon}$.

1.2 Firms

We consider a two-sector economy where capital and labor are employed to produce goods and new firms. Let the subscript C denote the goods-producing (manufacturing) sector and let subscript E denote the entry sector. The aggregate production function for goods states that output is produced under a Cobb-Douglas technology with capital services $\hat{K}^s_{C,t}$ and labor $\hat{L}_{C,t}$, weighted by α_C and $1-\alpha_C$, respectively, where $\alpha_C \in (0,1)$,

$$\hat{Y}^C_t = \hat{\rho}_t + \alpha_C \hat{K}^s_{C,t} + (1-\alpha_C)\,\hat{L}_{C,t} + \hat{\eta}^Z_t.$$

The variable $\hat{\eta}^Z_t$ denotes exogenous total factor productivity (TFP). New firms $\hat{N}_{E,t}$ are produced with an analogous technology,

$$\hat{N}_{E,t} + \hat{\eta}^E_t = \alpha_E \hat{K}^s_{E,t} + (1-\alpha_E)\,\hat{L}_{E,t} + \hat{\eta}^Z_t. \tag{6}$$

The exogenous variable $\hat{\eta}^E_t$ captures entry costs per firm, measured in terms of a composite of labor and capital services. The production structure is symmetric such that the capital share is the same in the two sectors, $\alpha_C = \alpha_E = \alpha$.[5] Marginal costs $\widehat{mc}_t$ for producing both goods and firms are a weighted average of the rental rate of capital $\hat{r}^k_t$ and the real wage $\hat{w}_t$, less TFP,

$$\widehat{mc}_t = \alpha \hat{r}^k_t + (1-\alpha)\,\hat{w}_t - \hat{\eta}^Z_t.$$

Cost minimization by firms implies that the rental bill and the wage bill are proportional to each other,

$$\hat{r}^k_t + \hat{K}^s_{C,t} = \hat{w}_t + \hat{L}_{C,t}.$$

Perfect factor mobility equates the capital-labor ratio across the two sectors,

$$\hat{K}^s_{C,t} - \hat{L}_{C,t} = \hat{K}^s_{E,t} - \hat{L}_{E,t}.$$

Firm-level profits are denoted d_t, while aggregate profits are given by

$$\hat{d}_t + \hat{N}_t = (\varepsilon - 1)\,\hat{\mu}_t + \hat{Y}^C_t, \tag{7}$$

[5] In an additional exercise, we set $\alpha_C = \alpha$ and $\alpha_E = 0$. See the sensitivity analysis in Section 5.

where $\varepsilon = 1 + \gamma N$ is the steady state price-elasticity of demand, see (4). Monopolistic firms set prices as a markup $\hat{\mu}_t$ over marginal costs,

$$\hat{\rho}_t = \hat{\mu}_t + \hat{m}c_t.$$

Price setters are subject to a quadratic price adjustment cost of the Rotemberg (1982)-type.[6] Non-adjusted prices are indexed to lagged inflation. The New Keynesian Phillips Curve (NKPC) relates the change in product prices $\hat{\pi}_{p,t}$ to its lagged and expected future value, and to the difference between the desired and the actual markup,

$$\hat{\pi}_{p,t} - \lambda_p \hat{\pi}_{p,t-1} = \frac{\varepsilon - 1}{\kappa_p}(\hat{\mu}_t^d - \hat{\mu}_t) + \beta\,(1 - \delta_N)\,E_t\{\hat{\pi}_{p,t+1} - \lambda_p \hat{\pi}_{p,t}\}, \tag{8}$$

where $\kappa_p > 0$ is the degree of price stickiness, $\lambda_p \in (0,1)$ is the rate of indexation, $\beta \in (0,1)$ is the representative agent's subjective discount factor and E_t denotes the expectations operator conditional on the information set at the beginning of period t. We substitute the desired markup (5) in (8) to obtain an alternative formulation of the NKPC,

$$\hat{\pi}_{p,t} - \lambda_p \hat{\pi}_{p,t-1} = \frac{\varepsilon - 1}{\kappa_p}(-\eta \hat{N}_t - \hat{\mu}_t) + \beta\,(1 - \delta_N)\,E_t\{\hat{\pi}_{p,t+1} - \lambda_p \hat{\pi}_{p,t}\} + \hat{\eta}_t^P, \tag{9}$$

where $\hat{\eta}_t^P$, often referred to as a 'cost-push shock', is a transformation of the price-elasticity of the spending share,

$$\hat{\eta}_t^P = -\frac{\varepsilon - 1}{\kappa_p}\eta \hat{\gamma}_t. \tag{10}$$

The variable $\hat{\eta}_t^P$ thus represents an exogenous shock to desired price markups, i.e., a change in desired markups that is unrelated to the arrival of new entrants, see (5).[7] We multiply the exogenous component of the desired markup in (5) by $\frac{\varepsilon-1}{\kappa_p}$ in order to have the desired markup shock enter the NKPC with a unit coefficient. Through the competition effect ($\eta > 0$), an increase in the number of firms and goods has a direct negative effect on inflation.

[6] To facilitate aggregation, we assume that first-time price setters face adjustment costs just like incumbent firms. As Bilbiie, Ghironi and Melitz (2007) show, adopting the alternative assumption, i.e., that price setting is costless for entrants, does not greatly alter model predictions.

[7] We introduce the desired markup shock as an empirical device to capture variations in inflation that remain unexplained by the model. Using our estimation results below, we carry out a variance decomposition whereby we quantify the part of inflation variability that is accounted for by price stickiness, by the competition effect and by exogenous factors.

1.3 Households

Households derive utility from consuming $\hat{C}_t$ and disutility from working $\hat{L}_t$. The respective marginal utilities are given by

$$\hat{U}_{C,t} = -\frac{\sigma_C}{1-b}(\hat{C}_t - b\hat{C}_{t-1}) \quad \text{and} \quad \hat{U}_{L,t} = \sigma_L \hat{L}_t,$$

where $\sigma_C > 0$ is the degree of risk aversion, $b \in (0,1)$ captures external habit formation in consumption and $\sigma_L > 0$ is the inverse Frisch elasticity of labor supply with respect to the real wage. The household has access to a risk-free one-period nominal bond that pays interest $\hat{R}_t$; the optimal choice of bonds leads to the Euler equation

$$\hat{U}_{C,t} = E_t\{(\hat{R}_t - \hat{\pi}^C_{p,t+1}) + \hat{U}_{C,t+1}\} + \hat{\eta}^T_t, \tag{11}$$

where $\hat{\pi}^C_{p,t}$ is the change in the welfare-based price index P_t. The 'time preference' shock $\hat{\eta}^T_t$ reflects a disturbance to the growth rate of the marginal utility of consumption. Capital services are the sum of the capital stock $\hat{K}_t$ and its utilization $\hat{u}_t$,

$$\hat{K}^s_t = \hat{u}_t + \hat{K}_t.$$

The optimal choice of capital utilization results in a utilization rate that is adjusted to the rental rate of capital with elasticity σ_a,

$$\hat{u}_t = \sigma_a \hat{r}^k_t,$$

where $\sigma_a = \frac{1-\tilde{\sigma}_a}{\tilde{\sigma}_a}$ and $\tilde{\sigma}_a \in (0,1)$ measures utilization adjustment costs. Accumulation of physical capital takes the form

$$\hat{K}_{t+1} = (1-\delta_K)\hat{K}_t + \delta_K \hat{I}_t + \delta_K (1+\beta)\varphi_K \hat{\eta}^I_t,$$

where $\hat{I}_t$ is intensive margin investment, i.e., investment in physical capital, and $\delta_K \in (0,1)$ is the capital depreciation rate. The term $\hat{\eta}^I_t$ represents an exogenous shock to investment-specific technology. The optimal choice of physical capital gives rise to a q-equation,

$$\hat{q}_t = E_t\{-(\hat{R}_t - \hat{\pi}^C_{p,t+1}) + [1-\beta(1-\delta_K)]\hat{r}^k_{t+1} + \beta(1-\delta_K)\hat{q}_{t+1}\}, \tag{12}$$

where the real value of capital $\hat{q}_t$ depends positively on its expected future value and on the expected future rental rate, and negatively on the real interest rate. Physical investment is subject to flow adjustment costs of the type introduced in Christiano, Eichenbaum and Evans (2005). As a result, current investment is a function of its lagged and expected future value, as well as the current value of capital,

$$\hat{I}_t = \frac{1}{(1+\beta)\varphi_K}\hat{q}_t + \frac{\beta}{1+\beta}E_t\{\hat{I}_{t+1}\} + \frac{1}{1+\beta}\hat{I}_{t-1} + \hat{\eta}^I_t,$$

where φ_K captures investment adjustment costs at the intensive margin. Extensive margin investment is determined analogously. The number of firms and goods evolves according to the following law of motion,

$$\hat{N}_{t+1} = (1-\delta_N)\,\hat{N}_t + \delta_N \hat{N}_{E,t}, \tag{13}$$

where δ_N is the firm exit rate. The value of a firm $\hat{v}_t$ depends positively on its expected future value, on expected future dividends, and negatively on the real interest rate,

$$\hat{v}_t = E_t\{-(\hat{R}_t - \hat{\pi}^C_{p,t+1}) + [1-\beta(1-\delta_N)]\,\hat{d}_{t+1} + \beta(1-\delta_N)\,\hat{v}_{t+1}\}. \tag{14}$$

The number of entrants depends on its lagged and expected future value, and on the difference between firm value and the entry cost $\widehat{mc}_t + \hat{\eta}^E_t$,

$$\hat{N}_{E,t} = \frac{1}{(1+\beta)\,\varphi_N}[\hat{v}_t - (\widehat{mc}_t + \hat{\eta}^E_t)] + \frac{\beta}{1+\beta}E_t\{\hat{N}_{E,t+1}\} + \frac{1}{1+\beta}\hat{N}_{E,t-1}, \tag{15}$$

where φ_N captures investment adjustment costs at the extensive margin.[8] Total investment is the sum of intensive and extensive margin investment,

$$\widehat{TI}_t = \frac{I}{TI}\hat{I}_t + \frac{vN_E}{TI}(\widehat{mc}_t + \hat{N}_{E,t} + \hat{\eta}^E_t).$$

We assume monopolistic wage setters and sticky wages as in Erceg, Henderson and Levin (2000). In addition, we stipulate that non-adjusted wages are indexed to price inflation with coefficient λ_w. Wage inflation $\hat{\pi}_{w,t}$ is thus determined as follows,

$$\hat{\pi}_{w,t} - \lambda_w\hat{\pi}_{p,t-1} = \frac{\theta_w - 1}{\kappa_w}[(\hat{U}_{L,t} - \hat{U}_{C,t}) - \hat{w}_t] + \beta E_t\left\{\hat{\pi}_{w,t+1} - \lambda_w\hat{\pi}_{p,t}\right\} + \hat{\eta}^W_t,$$

where $\kappa_w > 0$ is the degree of wage stickiness, $\theta_w > 1$ is the elasticity of substitution between labor types, and $\hat{\eta}^W_t$ denotes an exogenous shock to wage inflation.

1.4 Market Clearing

The aggregate goods bundle $\hat{Y}^C_t$ is a weighted average of private consumption $\hat{C}_t$, physical capital investment $\hat{I}_t$, the costs of adjusting the utilization rate $\hat{u}_t$ and exogenous government consumption $\hat{\eta}^G_t$,

$$\hat{Y}^C_t = \frac{C}{Y^C}\hat{C}_t + \frac{I}{Y^C}\hat{I}_t + \frac{r^k K}{Y^C}\hat{u}_t + \hat{\eta}^G_t.$$

[8] For a more detailed derivation of the dynamic entry equation (15), see Lewis and Poilly (2012).

Let $\hat{Y}_t$ denote total expenditure, which equals goods output and investment at the extensive margin,

$$\hat{Y}_t = \frac{Y^C}{Y}\hat{Y}_t^C + \frac{vN_E}{Y}(\hat{mc}_t + \hat{N}_{E,t} + \hat{\eta}_t^E).$$

The market clearing conditions for labor and capital services are, respectively,

$$\hat{L}_t = \frac{L_C}{L}\hat{L}_{C,t} + \frac{L_E}{L}\hat{L}_{E,t}, \quad \text{and} \quad \hat{K}_t^s = \frac{K_C}{K}\hat{K}_{C,t}^s + \frac{K_E}{K}\hat{K}_{E,t}^s.$$

1.5 Monetary Policy

Monetary policy follows a Taylor-type rule with interest rate smoothing. The interest rate is adjusted in response to the level and the growth rate of the output gap, to product price inflation and to the lagged interest rate,

$$\hat{R}_t = \tau_R \hat{R}_{t-1} + (1-\tau_R)\left(\tau_\pi \hat{\pi}_{p,t} + \tau_Y \hat{Y}_t^{gap}\right) + \tau_{dy}\Delta\hat{Y}_t^{gap} + \hat{\eta}_t^R \tag{16}$$

where Δ is the first difference operator and $\hat{Y}_t^{gap}$ is the output gap as measured by the central bank. An exact definition of the output gap is deferred to Section 2.1. The term $\hat{\eta}_t^R$ represents an exogenous monetary policy shock. We estimate the model on data up to the start of the Great Recession. During a period where the economy is at the zero lower bound on nominal interest rates, the postulated monetary policy rule is no longer applicable. Including the most recent period would distort our estimates.

1.6 Exogenous Shock Processes

Table 1 summarizes the functional forms assumed for the eight exogenous shocks. These are shocks to TFP and to investment-specific technology; time-preference and government spending shocks; price and wage markup shocks; monetary policy shocks and entry cost shocks.

[insert Table 1 here]

Except for the government spending and markup shocks, all disturbances follow $AR(1)$ processes in logarithmic terms. Following Smets and Wouters (2007), disturbances to price and wage markups follow $ARMA(1,1)$ processes; the moving average terms pick up high-frequency movements in inflation. Government spending is also affected by the innovation in the TFP-process. This specification is designed to capture the unmodeled variations in net exports, which may be affected by domestic productivity developments.

2 Estimation

We apply Bayesian estimation techniques as in Fernandez-Villaverde and Rubio-Ramirez (2004) and Smets and Wouters (2003, 2007). For a detailed description, we refer to the original papers. In a nutshell, using the Bayesian paradigm prior information is combined with the data to obtain posterior distributions for the parameters.[9] In the following, we describe the data sources and transformations, before turning to our choice of priors and to the posterior distributions of the model parameters.

2.1 Data

In the model, real variables are deflated by the welfare-based price index P_t, which is unobserved. Empirical measures of the price index correspond rather to the product price p_t, given that consumption baskets are not updated frequently enough to fully take into account the welfare effects from product turnover. Moreover, even if the composition of the consumption basket were adjusted at an adequate frequency, the price index computed by the Bureau of Labor Statistics (BLS) would nevertheless be inconsistent with the translog expenditure function proposed here. Thus, to link the model with the data, we strip out the variety effect on the price index by multiplying each real variable by P_t and dividing by p_t. For any real variable z_t in the model, the linearized data-consistent counterpart then reads $\hat{z}_t^R = \hat{z}_t - \hat{\rho}_t$. In the monetary policy rule (16), the output gap is defined as the deviation of data-consistent output from steady state, $\hat{Y}_t^{gap} = \hat{Y}_t^R$.

In our baseline specification, we estimate the model using eight series of US quarterly data. These are output, consumption, investment, hours, net business formation, real wages, inflation and the interest rate. These eight time series are used to identify the eight structural innovations in the theoretical model, see Table 1. Our vector of observables is thus

$$\mathbf{Y}_t = (\hat{Y}_t^R, \hat{C}_t^R, \widehat{TI}_t^R, \hat{N}_{E,t}, \hat{L}_t, \hat{w}_t^R, \hat{\pi}_{p,t}, \hat{R}_t).$$

Data sources and filtering are as follows. Series for GDP, consumption and investment are obtained from the US Department of Commerce - Bureau of Economic Analysis (BEA). As in Smets and Wouters (2007), personal consumption expenditures include durable goods consumption. Investment is measured as gross fixed private domestic investment,

[9] We use 1,000,000 iterations of the Random Walk Metropolis Hastings algorithm to simulate the posterior distributions and achieve acceptance rates of approximately 35% in all our specifications. We discard the initial 4% of the drawings to compute the posterior moments in each case. We monitor the convergence of the marginal posterior distributions using CUMSUM statistics as defined by Bauwens, Lubrano and Richard (1999).

which abstracts from changes in inventories. As our benchmark measure of entry, we use net business formation. New incorporations and establishment births serve as robustness checks. Net business formation is published in the BEA's Survey of Current Business and covers the majority of US businesses. The original data source is the Dun and Bradstreet Corporation. This series has been discontinued; data run from January 1948 to September 1995. New incorporations are obtained from the same source, with an almost identical sample period. This explains why the sample period in our baseline estimation (from 1957Q1 until 1995Q3) ends so early. The number of establishment births is available from the BLS from 1993Q2 onwards. Data for hours and wages are from the US Department of Labor - BLS. Following Chang, Gomes and Schorfheide (2002), who point to the limited coverage of the nonfarm business sector compared to GDP, we multiply the index of average hours for the nonfarm business sector (all persons) by civilian employment (16 years and over). The interest rate is the Effective Federal Funds Rate from the Board of Governors of the Federal Reserve System. Inflation is measured as the first difference of the log implicit price deflator of GDP (from the BEA).

All raw series are seasonally adjusted using the Census X12 method. All nominal variables are deflated with the GDP deflator. The aggregate real variables are expressed in per capita terms, by dividing by the Civilian Noninstitutional Population over 16 (from the BLS), and linearly detrended in logarithmic terms. The inflation rate and the nominal interest rate are demeaned by subtracting their respective sample averages.

2.2 Priors

An overview of our priors can be found in Table 2. Six parameters are fixed. The subjective discount factor is set to $\beta = 0.99$, implying a steady state annualized real interest rate of 4%. Physical capital depreciates at an annual rate of 10%, i.e., $\delta_K = 0.025$. Similarly, the firm/product exit rate is set to $\delta_N = 0.025$, so as to fit the job destruction rate observed in US data. This value is also consistent with an average product drop rate of 9% per year as reported by Bernard, Redding and Schott (2010). The number of conceivable goods $\tilde{N}$ is hard to pin down. We assume that 95% of conceivable goods are actually produced in steady state, such that $N/\tilde{N} = 0.95$. The parameter of the Cobb-Douglas production function capital share is calibrated to $\alpha = 0.24$, which implies a mean labor share in GDP of three quarters. The government consumes roughly one fifth of all goods produced, $G/Y^C = 0.21$. Finally, following Smets and Wouters (2007) the elasticity of substitution between different labor types is set at $\theta_w = 3$, implying a net wage markup of 50%.

[insert Table 2 here]

The prior distributions on the shock parameters are quite diffuse, with beta distributions with mean 0.5 and standard deviation 0.15 for the autoregressive and moving average coefficients, and inverse gamma distributions with mean 0.1 and standard deviation 2 for the standard errors of the innovations. For most of the structural parameters we use priors as imposed by Smets and Wouters (2007). The monetary policy parameters, however, are given gamma distributions, instead of normal distributions, to impose a lower bound of zero. The Rotemberg price and wage adjustment cost parameters, κ_p and κ_w, are assumed to be gamma distributed with mean 50 and a standard deviation of 7.5. The mean lies between the value of $\kappa_p = 77$, estimated by Ireland (2001), and the prior mean of $\kappa_p = \kappa_w = 20$, imposed by Krause, Lopez-Salido and Lubik (2008). Moreover, a Rotemberg parameter of 50 corresponds to an average contract duration of approximately 4.5 quarters in the Calvo model, a value which lies in the ballpark of estimates obtained from the New Keynesian Phillips curve literature. Our results are robust to imposing a smaller prior mean for κ_p. For the demand elasticity ε we impose a diffuse normal distribution with mean 4 and standard deviation 1.5. This suggests an average price markup of 33%, which lies in the middle of the range 15 to 45% that is typically reported for the US average price markup, e.g., Hall (1988), Roeger (1995), Basu and Fernald (1997), Oliveira Martins and Scarpetta (1999) and Christopoulou and Vermeulen (2008).

2.3 Posterior Estimates

In the following, we discuss our posterior estimates and contrast them, where possible, with the existing empirical evidence from the fixed-variety literature. Our baseline estimation results are reported in Table 2, which summarizes the modes, means and the 5^{th} and 95^{th} percentiles of the posterior distributions. We discuss the mean estimates of the standard parameters first, before turning to the entry-related parameters.

While our estimates of the standard parameters are in line with the literature, several observations are worth making. Compared to business cycle models without entry (see, e.g., Christiano, Eichenbaum and Evans 2005 and Smets and Wouters 2007), our estimates of investment adjustment costs and of capital utilization costs are somewhat higher at about $\varphi_K = 9.15$ and $\tilde{\sigma}_a = 0.77$, respectively. Recall that total investment data is matched with the sum of intensive and extensive margin investment in our model, while in the fixed-variety model the investment series proxies physical capital investment only. For the Rotemberg price and wage stickiness parameters κ_p and κ_w, we obtain values of 59 and 56, respectively, which corresponds to an average contract duration of approximately 3.5

quarters for prices and 2.5 quarters for wages in the Calvo analog.[10] These estimates are at the lower end of those obtained in the macro literature, but are in line with the micro evidence on the frequency of price adjustment, e.g., Blinder et al. (1998) and Nakamura and Steinsson (2008). The estimated monetary policy parameters are consistent with existing evidence: we observe substantial interest rate smoothing ($\tau_R = 0.74$) and a response coefficient on inflation that satisfies the Taylor Principle ($\tau_\pi = 1.52$). With $\tau_y = 0.01$, the response to output is barely significant.

Adjustment costs in entry are estimated at 2.70. This is substantially lower than the value above 8 reported in Lewis and Poilly (2012), who estimate a model similar to the one presented above by impulse response matching techniques. These different results can be explained by the different stochastic structures of the two models. In Lewis and Poilly (2012), fluctuations are driven only by monetary policy shocks. Here, however, we consider a range of shocks. To our knowledge, no other empirical evidence on this parameter exists.

In our steady state, entry costs are 9.6% of GDP. Empirical estimates of the share of entry costs in output vary widely, with our figure lying somewhere in the middle. Barseghyan and DiCecio (2011) pin down entry costs using available estimates of the ratio of entry-to-operating cost ratio. For the US, they report a benchmark estimate of entry costs, as a fraction of output per worker, of 20.8%. An alternative calibration in Barseghyan and DiCecio (2011), using the evolution of firms' productivity over time, yields a smaller estimate of 12.15%. A third measure is constructed as follows. The World Bank's Doing Business project (www.doingbusiness.org) reports the number of days needed to register a firm. Dividing this number by 264 (22 working days per month, times 12 months), gives the time in years that represents an entrepreneur's opportunity cost of starting a business. For the US, we have an entry cost of 6/264=0.0227 years per capita, or 2.27% of annual GDP per capita. The World Bank reports that legal fees to register a business amount to 1.4% of per capita income in the US in the year 2011. Fourth, Ebell and Haefke (2009) compute a composite measure of entry costs in the US in 1997 equal to 0.59 months of output. This measure combines information on entry fees as well as entry delays (number of business days needed to fulfill entry requirements, weighted by the number of procedures) which are converted into lost output.

[10] As seen in equation (8), the Rotemberg adjustment scheme delivers a coefficient $\frac{\varepsilon-1}{\kappa}$ on the markup gap in the NKPC. In the Calvo analog of the NKPC, this slope coefficient is $\frac{(1-\beta\xi)(1-\xi)}{\xi}$, where $\frac{1}{1-\xi}$ determines the duration of price stickiness. Therefore, it is possible to compare the slope coefficients given by the two price adjustment schemes, and to interpret the Rotemberg cost in price duration terms. Strictly speaking, however, we cannot compute an average price contract duration in our model, as this requires a constant population of price setters.

Our main parameter of interest is the price-elasticity of demand, which determines the steady state markup, the competition effect, as well as consumers' love of variety. We find a mean estimate of $\varepsilon = 6.68$ in our baseline estimation, which implies that price markups are 18% on average. While this estimate accords well with the results reported in many micro studies of average markups (e.g., Oliveira Martins and Scarpetta, 1999, and Christopoulou and Vermeulen, 2008), it is significantly lower than the 60% steady state markup implied by the Smets and Wouters' (2007) model with fixed costs and no entry. Lewis and Poilly (2012), whose set of observables includes a markup measure, also find a lower demand elasticity ($\varepsilon = 2.5$). In Section 5 we investigate the sensitivity of our results to alternative specifications and sets of observables.

Turning to the derived parameters, the posterior distribution of ε implies that the competition effect η, the inverse of the demand elasticity, has a mean value of $\eta = 0.15$. Hence, desired markups fall by 0.15% in response to a 1% increase in the number of firms. Cecioni (2010) uses single-equation techniques to estimate the New Keynesian Phillips Curve (9). She finds a competition effect of 1.2. In her model, the competition effect is supply-driven and stems from an oligopolistic market structure. In contrast, our model with translog expenditure cannot generate a competition effect above unity given the lower bound on the demand elasticity, $\varepsilon \geq 1$. While our estimate of the competition effect is statistically significant, we investigate below if this effect is also economically important in driving inflation. From the model's steady state, we can compute the steady state number of firms. Given the relation between the demand elasticity ε and the number of firms N (which we compute using the calibrated parameters and the posterior mean of ε) in (4), we derive the price-elasticity of the spending share $\gamma = 0.75$. Thus, in response to a 1% price increase for an individual variety, the spending share drops by 0.75%.

3 Markups and the Competition Effect

This section analyzes markup dynamics in the presence of the competition effect as predicted by the model. First, we highlight how the competition effect works conditional on a specific shock. Second, we examine the unconditional properties of the model-implied markup, in particular its cyclicality.

3.1 Transmission Channels

The eight structural shocks are grouped as follows. TFP shocks $\hat{\eta}_t^Z$, entry cost shocks $\hat{\eta}_t^E$ and shocks to wage inflation $\hat{\eta}_t^W$ constitute 'supply shocks', which affect marginal costs of production in (one of) the two sectors. Government spending shocks $\hat{\eta}_t^G$, investment-specific technology shocks $\hat{\eta}_t^I$ and time preference shocks $\hat{\eta}_t^T$ are classified as 'demand shocks'. Monetary policy shocks $\hat{\eta}_t^R$ and desired markup shocks $\hat{\eta}_t^P$ are treated as separate categories. Note that we consider expansionary shocks throughout; all shocks have been normalized to produce a(n eventual) increase in GDP.

3.1.1 Supply Shocks

Figure 1a depicts the impulse responses of selected variables to the three supply shocks. Consider the first two panels showing the dynamics triggered by shocks to TFP and wage markups. Favorable movements in both shocks, i.e., positive TFP shocks and negative wage markup shocks, lower real marginal costs in both sectors. Prices are sticky and do not fall by the same amount. Therefore, actual markups rise, which increases profits and firm value through (7) and (14), respectively. The fall in entry costs and the rise in profits lead to entry (15) and a gradual decline in desired markups via the competition effect (5). Consequently, in response to 'standard' supply shocks, the competition effect mitigates the procyclical effect of price stickiness on markups. After approximately 6 to 8 quarters, the competition effect dominates and actual markups fall.

[insert Figure 1a here]

The transmission of entry cost shocks deserves special attention since this type of shock is specific to the endogenous-entry framework. An exogenous decrease in startup costs directly raises entry through (15). The number of producers and goods rises too, though only gradually and after a one-period lag, see (13). This leads to an eventual decrease in the desired markup through the competition effect (5). Initially, the rise in investment in new firms induces a reallocation of production factors from the manufacturing sector to new startups, implying a decrease in GDP on impact. However, the economic downturn is short-lived, as the rise in extensive margin investment eventually pushes output above steady state. The ensuing rise in aggregate demand raises marginal costs and prices. Due to price adjustment costs, prices rise less than marginal costs, such that actual markups decrease. Actual markups decline by less than desired markups. Therefore, inflation rises through the New Keynesian Phillips Curve (8).

3.1.2 Demand Shocks

Next, we examine the propagation of demand shocks. We notice from Figure 1b that all three shocks generate strong crowding-out effects at the extensive margin; entry drops.

The monetary policy tightening in reaction to expansionary demand shocks implies an increase in the real interest rate, which, in turn, lowers firm value through (14). Combined with an increase in entry costs (marginal costs increase together with aggregate demand), this effect leads to a fall in entry through (15) and puts upward pressures on desired markups via the competition effect (5). The dominant effect on markups, however, stems from price stickiness. An exogenous increase in demand raises marginal production costs more than prices, inducing actual markups to fall. The competition effect thus mitigates the countercyclical response of markups to demand shocks.

[insert Figure 1b here]

Expansionary shocks to government spending and investment-specific technology are followed by an (eventual) increase in profits. This is explained by the rise in output that dominates the decline in the actual markup in (7). In contrast, in response to time preference shocks, profits fall. Relative to the previous two demand shocks, the output increase induced by the time preference shock is smaller. Therefore, the negative effect of falling markups prevails and profits fall. Notice also that the effects of the time preference shock are short-lived due to the low shock persistence ($\rho_T = 0.16$, see Table 2).

3.1.3 Monetary Policy Shocks

Concerning the monetary policy shock (displayed in the top panel of Figure 1c), two model predictions stand out. First, the model predicts that aggregate profits decrease following an expansionary monetary policy shock. This result is in contrast to evidence reported in Lewis (2009) and Lewis and Poilly (2012). However, it is in line with Bilbiie, Ghironi and Melitz (2007). A decline in the interest rate leads to an increase in marginal costs and, given that prices do not adjust fully, to a decrease in actual markups, which, in turn, depresses profits. The greater the price-elasticity of demand ε, the greater this effect of markups on profits, see (7). At the same time, a decline in the interest rate has expansionary effects on aggregate demand $\hat{Y}_t^C$, which raises profits. Our estimates imply that the first effect dominates the second effect, such that profits decrease on net.

Notice the difference with Lewis and Poilly (2012), who find that profits rise in response to a monetary expansion. There are two reasons for this difference. First, our demand elasticity ε is larger, which makes the first effect more important. Second, the model in Lewis and Poilly (2012) includes working capital. Within that framework, an interest rate decline puts downward pressures on marginal costs. Therefore, relative to our model economy, if $\hat{R}_t$ falls marginal costs do not rise as much.

Second, the model predicts that despite the decrease in profits, entry rises in reaction to a loosening of monetary policy. This is in line with the evidence reported in Bergin and Corsetti (2008), Lewis (2009) and Lewis and Poilly (2012). The explanation is that the interest rate decline entails a decrease in the expected return on shares to eliminate arbitrage across assets. The expected return on shares falls through a rise in the current relative to the future share price. This rise in firm value exceeds the rise in marginal costs (i.e., entry costs).[11] On balance, therefore, entry expands and the desired markup falls through (5). As a result, the competition effect augments the countercyclical effect of price stickiness on markups in the case of monetary policy shocks.

[insert Figure 1c here]

3.1.4 Desired Markup Shocks

The bottom panel in Figure 1c shows the effects of an exogenous drop in desired markups (a decrease in $\hat{\eta}_t^P$). By (10), the spending share becomes more price-elastic and via (5) the desired markup decreases. This lowers inflation through the New Keynesian Phillips Curve (8) and boosts demand. The ensuing boom drives up real marginal costs; because of price stickiness, actual markups fall. Aggregate profits decrease, as the decrease in the actual markup $\hat{\mu}_t$ dominates the rise in demand $\hat{Y}_t^C$ in the profit expression (7). Entry costs rise by more than firm value, such that entry contracts.

To sum up, the model predicts a procyclical entry response to supply shocks and to monetary policy shocks, but a countercyclical response to demand shocks. As a result, through the competition effect, desired markups are countercyclical in response to supply shocks and monetary policy shocks, but procyclical following demand shocks. The competition effect, therefore, augments the countercyclical effect of price stickiness on markups in the case of monetary policy shocks, whereas it counteracts the sticky price effects on markups in response to supply and demand shocks. Exogenous disturbances to the desired markup eventually lead to countercyclical entry.

3.2 The Cyclicality of the Markup

Here we study the unconditional cyclicality of the markup implied by the model. There are three reasons for the markup to vary. These are the competition effect, sticky prices,

[11] This is in contrast with Bilbiie, Ghironi and Melitz (2007), where entry costs are very responsive to shocks due to full wage flexibility. In that model, entry drops after a monetary policy expansion.

and shocks to desired markups. We conduct 300 stochastic simulations based on random draws from the posterior distribution and back out, for each of these simulations, first, the model-implied markup $\hat{\mu}_t$, second, the component driven by sticky prices and desired markup shocks $\hat{\mu}_t^{noCE}$ (i.e., the counterfactual markup series obtained in the absence of the competition effect), and, third, the 'sticky-price' component $\hat{\mu}_t^{SP}$. To compute $\hat{\mu}_t^{noCE}$ we shut of firm entry and exit dynamics in the stochastic simulation. In practice, we set $\hat{N}_{E,t} = 0$ and simulate the model using our benchmark parameter estimates, that is, without re-estimation. This counterfactual exercise corresponds to considering an arbitrarily large entry adjustment cost parameter φ_N. Finally, to compute the sticky-price component, we set $\hat{N}_{E,t} = 0$ and perform the stochastic simulation, excluding the desired markup shock ($\hat{\eta}_t^P = 0$). The resulting markup series, denoted $\hat{\mu}_t^{SP}$, reflects variations in the *model-implied* markup under constant *desired* markups.

Similar to Bilbiie, Ghironi and Melitz (2012), we then compute for each of the model simulations the correlation of the three markup series with output at various leads and lags. Since our model includes a whole array of structural shocks, this exercise should provide a realistic description of what a DSGE model with endogenous entry implies for (unconditional) markup variations. Figure 2 plots the mean and the 5th and 95th percentile correlations $corr(\hat{Y}_{t+s}^R, \hat{\mu}_t)$, $corr(\hat{Y}_{t+s}^R, \hat{\mu}_t^{noCE})$ and $corr(\hat{Y}_{t+s}^R, \hat{\mu}_t^{SP})$ for $s = -5, -4, \ldots, 0, \ldots, 5$.

[insert Figure 2 here]

The model-implied markup is countercyclical at all leads and lags. If we switch off the competition effect, the correlation between the markup and output rises; the contemporaneous correlation $corr(\hat{Y}_t^R, \hat{\mu}_t^{noCE})$ is not significantly different from zero. If, in addition, we eliminate desired markup shocks, the cyclicality turns positive: the sticky-price component is significantly procyclical. Thus, it is the combination of the competition effect and desired markup shocks that reverses the sign of the markup-output correlation. Recall from Figures 1a-c that entry is procyclical in response to supply shocks and monetary policy shocks (such that the competition effect leads to countercyclical markups), but countercyclical in response to demand shocks (such that the competition effect leads to procyclical markups). The result that $\hat{\mu}_t$ is countercyclical reflects the importance of supply shocks in driving aggregate fluctuations.

Figure 3 presents a forecast error variance decomposition for output $\hat{Y}_t^R$, inflation $\hat{\pi}_{p,t}$ and markups $\hat{\mu}_t$. For these three variables, TFP and wage markup shocks are an important source of volatility, while entry cost shocks hardly matter.[12]

[insert Figure 3 here]

Long run output variability is explained almost entirely by two supply shocks: wage markup shocks and TFP shocks (each 45%). In the short run, the sources of output fluctuations are more mixed: government spending shocks and TFP each account for around one fifth, investment-specific technology for one third. The variation in the markup is mainly accounted for by a combination of TFP and price markup shocks (each 30% in the long run); entry cost shocks and wage markup shocks each explain 15% of markup fluctuations.

To conclude, we find a major role for supply-type shocks in driving output and markup fluctuations. Since, through the competition effect, supply shocks are a source of markup countercyclicality, the model-implied correlation between markups and output is negative overall.

4 A Counterfactual Analysis of US Inflation Dynamics

This section examines in greater detail the sources of inflation dynamics in US data. We aim to assess the risk of misguided cyclical monetary policy when inflation fluctuations result from endogenous market structure changes.[13] To this end, we decompose US inflation, into a sticky-price component plus two components reflecting endogenous and exogenous variations in the desired markup.

Our premise here is that the objective of monetary policy is to close gaps, i.e., to stabilize inflation which fluctuates in response to markup variations induced, in turn, by nominal rigidities. This is the optimal prescription for monetary policy in the New Keynesian tradition, see Woodford (2003) and Galí (2008). Bergin and Corsetti (2008) and Bilbiie, Ghironi and Melitz (2007) show that this optimal policy prescription carries over to the more recent business cycle literature on endogenous entry, provided that fiscal instruments are used to address inefficiencies at the steady state. The consensus here is that the central bank should let number of firms fluctuate freely and should not respond to changes in inflation arising from entry and exit. In fact, optimal cyclical monetary

[12] Most of the variability in entry is explained by its own shock $\hat{\eta}_t^E$. More detailed results are available from the authors upon request.

[13] Note that we abstract from the implications of entry for the optimal long run inflation rate, which are analyzed in Bilbiie, Fujiwara and Ghironi (2011). That paper also shows that the cyclical Ramsey policy comes close to inflation targeting in terms of welfare.

policy in the presence of endogenous entry is somewhat more complicated. There are two opposing effects on welfare: a positive variety effect (through increased product diversity) and a negative 'business stealing effect' (through decreased profits). While these two externalities exactly offset each other in the case of Dixit-Stiglitz preferences, they do not under translog preferences. However, a thorough analysis of the Ramsey-optimal conduct of monetary policy is beyond the scope of this paper. We want to provide some first empirical insights into the importance of changes in competition for macroeconomic dynamics. Therefore, we abstract from possible net externalities at the business cycle frequency by assuming that the central bank wishes not to target inflation changes due to the competition effect, which it regards as efficient.

Suppose the central bank observes a fall in inflation. It may face a signal extraction problem in that it cannot tell whether (part of) this fall is due to stronger competition from a larger number of producers that compresses desired markups. In response to receding inflationary pressures the central bank is set to loosen its monetary policy stance. In times of weakening aggregate demand, such a policy response is warranted. In this case, sticky-price firms are unable to fully adjust prices downward as they would under perfect price flexibility, such that actual markups increase and inflation drops. However, loosening monetary policy is not the right response if firm entry has risen, e.g., because certain supply-side measures (such as market deregulation) have lowered entry costs, decreasing desired markups and inflation through the competition effect. Thus, we wish to gauge the economic importance of the competition effect, in order to assess the likelihood of such mistaken policy actions.

In the following, we perform a counterfactual analysis of US inflation. The approach is similar to the markup decomposition of Section 3.2. We filter out the contribution of *exogenous* desired markup shocks to inflation. To this end, we feed the price markup shock series $\hat{\eta}_t^P$ into the model, setting all other shocks to zero, and denote the resulting inflation series $\hat{\pi}_{p,t}^P$. In addition, we are interested in two types of *endogenous* driving forces of inflation. The first $\hat{\pi}_{p,t}^{SP}$ captures the endogenous sticky-price channel of inflation fluctuations that characterizes the (hybrid) New Keynesian model. Through this channel, current inflation is driven by marginal costs and expected future inflation (through price stickiness) and by lagged inflation (through indexation to past inflation). We set all parameter values to their baseline estimates in Table 2. Then, we feed the shocks into the model, excluding entry dynamics and the desired markup shock, $\hat{N}_{E,t} = \hat{\eta}_t^P = 0$.[14] The resulting inflation path is what we call 'sticky-price inflation', determined through

[14] Again, a no-entry equilibrium arises for arbitrarily high values of the entry adjustment cost parameter φ_N.

the modified New Keynesian Phillips Curve,

$$\hat{\pi}_{p,t}^{SP} - \lambda_p \hat{\pi}_{p,t-1}^{SP} = \frac{\varepsilon - 1}{\kappa_p} (-\hat{\mu}_t^{SP}) + \beta (1 - \delta_N) E_t \{\hat{\pi}_{p,t+1}^{SP} - \lambda_p \hat{\pi}_{p,t}^{SP}\}.$$

The 'sticky-price component' $\hat{\mu}_t^{SP}$ is the counterfactual markup series that we obtain under constant desired markups, that is, in the absence of a competition effect and desired markup shocks. The second endogenous component $\hat{\pi}_{p,t}^{CE}$ denotes the competition effect of entry on inflation, and is computed as the actual inflation rate, less sticky-price inflation, less the contribution of desired markup shocks,

$$\hat{\pi}_{p,t}^{CE} = \hat{\pi}_{p,t} - \hat{\pi}_{p,t}^{SP} - \hat{\pi}_{p,t}^{P}.$$

Figure 4a plots the quarterly inflation rate in the US from 1957q1 to 1995q2 and its three components $\hat{\pi}_{p,t}^{SP}$, $\hat{\pi}_{p,t}^{CE}$ and $\hat{\pi}_{p,t}^{P}$.

[insert Figure 4a here]

Compared with the sticky-price component and the exogenous component, the competition effect plays a smaller, but nevertheless noticeable role in driving US inflation. In the late 1960s and between 1985 and 1995, inflation was reduced through the competition effect. From the mid 1970s to the mid '80s, inflation rose as a result of changes in competition. Therefore, there is some danger that monetary policy reacts unwittingly to inflation changes unrelated to (endogenous or exogenous) price distortions. In the first case, there is a risk of monetary policy being too loose; in the second case, disregarding competitive pressures resulted in monetary policy being too tight.

Figure 3 confirms the importance of desired price markup shocks for inflation. In the short run, such shocks account for over half of inflation fluctuations.

As a robustness check, we estimated the model for the period 1993q2-2007q4 where entry $N_{E,t}$ is measured as the number of establishment births, see Section 5. Our previous finding is confirmed in the later sample: the competition effect is less important then the other two driving forces. Since it explains at most 0.1 percentage points of quarterly US inflation, the risk of misplaced policy actions by the central bank appears to have been small in recent times. See Figure 4b.

[insert Figure 4b here]

5 Sensitivity Analysis

This section focuses on the sensitivity of our demand elasticity estimate ε to five alternative model specifications. First, we replace the time preference shock with a risk premium shock that affects the real interest rate. Second, we treat profits as an additional observable variable and extend the model by adding a white-noise measurement error to the profit function (7). Third, we estimate the Dixit-Stiglitz (1977) model with a constant elasticity of substitution (CES) aggregator on our original set of observables. Fourth, we consider the asymmetric production structure favored by Bilbiie, Ghironi and Melitz (2012), where new firms are set up using labor services only. Finally, we consider different mappings between entry in the model and business formation in the data.

[insert Table 3 here]

The results of these robustness exercises are displayed in Table 3. We discuss them in turn.

5.1 Risk Premium Shock

Smets and Wouters (2007) propose a demand-type shock that generates co-movement between consumption and investment. Following this idea, we stipulate that the return to one-period nominal bonds is multiplied by a random variable η_t^{RP}, which in logarithmic terms follows a first-order autoregressive process with persistence ρ_{RP} and standard deviation σ_{RP}. We call this variable a 'risk premium shock'. It reflects an exogenous risk premium on bond holdings, which drives a wedge between the bond return and the risk-free rate set by the central bank. While the time preference shock of the baseline model affected only the Euler equation for bonds, the risk premium shock enters all three asset pricing equations. In the optimality condition for bonds (11), $\hat{\eta}_t^T$ is replaced with $\hat{\eta}_t^{RP}$. In the first order conditions for capital (12) and equity (14), the shock $\hat{\eta}_t^{RP}$ enters the right hand side with a negative sign.

Figure 5 shows the impulse responses of some key variables to an expansionary risk premium shock. As output and inflation move in the same direction, we consider this as a demand-type shock. However, in contrast with the three demand shocks in Figure 1b, the risk premium shock generates a procyclical response of entry and, therefore, a countercyclical competition effect, which dampens inflation.

[insert Figure 5 here]

The estimation results of this alternative model are shown in Table 3 in the column entitled 'Risk-P'. The parameter estimates are similar to the baseline estimates; all confidence intervals overlap. The only noteworthy difference between the two sets of estimates is that the risk premium shock itself is more persistent and significantly bigger than the time preference shock.

5.2 Using Profit Data in Estimation

In a second exercise, we investigate whether considering profit data in our estimation greatly changes the results. In particular, we add data-consistent aggregate profits $\hat{D}_t^R = \hat{d}_t + \hat{N}_t - \hat{\rho}_t$ to the set of observables $\mathbf{Y}_t$. To avoid stochastic singularity—a problem that arises when having more variables than shocks—we include an exogenous iid normal error term $\hat{\varepsilon}_t^D$ with mean zero and standard deviation σ_D in the measurement equation of firm profits, such that (7) becomes

$$\hat{D}_t^R = (\varepsilon - 1)\,\hat{\mu}_t + \hat{Y}_t^C - \hat{\rho}_t + \hat{\varepsilon}_t^D.$$

Quarterly data for corporate profits after taxes are taken from the NIPA tables. The parameter estimates are summarized in column 'P' of Table 3. The mean demand elasticity increases to about $\varepsilon = 8.7$ when we include profits, which lowers the competition effect.[15] This can be explained by the large volatility of profits in the data and confirms the 'profit volatility puzzle'. Small changes in the markup can generate large profit movements only if the corresponding elasticity, $\varepsilon - 1$, is large, see (7). From existing research we know that neither the fixed-variety DSGE model (see Christiano, Eichenbaum and Evans, 2005), nor the endogenous-entry model (see Colciago and Etro, 2010; Lewis and Poilly, 2012) succeeds in explaining well the observed profit dynamics.

5.3 CES Aggregator

It is instructive to compare our baseline model featuring a translog expenditure function with the Dixit-Stiglitz (1977) model assuming CES aggregator. In the latter model, the demand elasticity ε is constant and equal to the elasticity of substitution between varieties. Consequently, desired markups are also constant, such that $\hat{\mu}_t^d = 0$. Another model feature is that the love of variety is equal to the net steady state markup $\mu - 1 = \frac{1}{\varepsilon - 1}$. The results are reported in column 'CES' of Table 3. None of our parameter estimates change significantly relative to our baseline model. Thus, allowing for competition effects and a variable demand elasticity does not change our conclusions about the short-run dynamics of macroeconomic variables, including net business formation.

[15] The value $\varepsilon = 8.7$ lies in the upper tail of the prior distribution. The cumulative probability at this value equals 0.999. Therefore, our prior distribution might be too restrictive relative to the information contained in the data. In an additional robustness check available upon request, we impose a looser prior on ε, namely a gamma distribution with mean 4 and standard deviation 2.5. In this case, ε increases to 9.16, which lies within the 92% confidence interval of the prior distribution.

5.4 Asymmetric Sectors

As a fourth robustness check, we consider an alternative specification for entry costs consisting only of labor costs. Concretely, in the technology with which new firms are produced (6), α_E is set to zero. Bilbiie, Ghironi and Melitz (2012) remove capital from the production of new firms because their model has a unique non-explosive solution only for very high rates of capital depreciation.[16] We circumvent this problem by introducing adjustment costs in both intensive and extensive margin investment.[17]

The last column of Table 3 reports the parameter estimates under the heading 'AsymPF'. Two observations stand out. First, the demand elasticity increases relative to the baseline estimate. Second, as ε increases, the price indexation parameter λ_p also increases. A possible explanation is that, as noted by Bilbiie, Ghironi and Melitz (2007), the endogenous-entry NKPC entails more inflation persistence because the number of varieties N_t is a state variable. Hence, the higher is the demand elasticity, the smaller is the competition effect and the less important is the endogenous persistence generated by entry, necessitating a higher degree of indexation.[18]

5.5 Mapping between Model and Data

Finally, we investigate whether the mapping of entry in the model and business formation in the data is important. We do this in order to address the concern that our net business formation index is a measure of *net* entry, while the model variable $N_{E,t}$ corresponds to *gross* entry.

First, we match net business formation in the data with net entry in the model, which we define as $N_{NE,t}$. Net entry equals entry $N_{E,t}$ minus exit $\delta(N_t + N_{E,t})$. Net entry in steady state is zero. Therefore, we express net entry in deviations from the steady state number of entrants,

$$\hat{N}_{NE,t} = (1-\delta)\,(\hat{N}_{E,t} - \hat{N}_t).$$

The estimation results are not strongly affected by this alternative mapping, see Table 3, column 'NE'. This is not surprising since exit is exogenous in the model.

[16] See the working paper version of Bilbiie, Ghironi and Melitz (2012).

[17] The model solution is indeterminate if the adjustment of *both* intensive and extensive margin investment is costless. Assuming adjustment costs along one of the two margins restores determinacy.

[18] Note that love of variety also generates some additional persistence. Even after transforming the model as explained in Section 3.1, the variety effect does not vanish in the case where risk aversion σ_C is greater than 1 and/or habits b are greater than 0. See also Lewis and Poilly (2012).

Second, we match $N_{E,t}$ in the model with the number of 'New Incorporations', a data series provided by the BEA's Survey of Current Business, together with net business formation. The sample period is almost the same as in the baseline estimation. We do not observe a large impact on estimation results (Table 3, column 'NI') other than a drop in the entry adjustment cost parameter φ_N.

Third, we use an alternative measure of firm entry based on establishment data. The column 'Births' shows the estimation results when $N_{E,t}$ is measured as 'Establishment Births'. Data are obtained from the BLS and span the period 1993q2-2007q4. Also here, the entry adjustment cost drops significantly. In addition, the monetary policy response to output and the properties of some of the shock processes are changed. Importantly, the estimates of the key parameters of interest, ε and η, do not change significantly when we use establishment entry instead of firm entry.

In sum, our estimates of the demand elasticity and the competition effect are robust to alternative ways of mapping entry in the model to the data.

6 Conclusion

This paper analyzes the empirical importance of changes in market structure and competition for business cycle dynamics in the US. By 'competition effect' we mean an inverse relationship between markups and entry rates as observed in the industrial organization literature. In response to expanding profit opportunities, more firms and products enter, which heightens competitive pressures and reduces desired markups and inflation. To quantify the relevance of this mechanism for cyclical fluctuations, we estimate—using Bayesian methods—a sticky-price business cycle model with sunk-cost driven entry dynamics and a translog expenditure function. We obtain two main results. Our first finding is that the impact of the competition effect on markups and inflation is shock-dependent. In the case of supply shocks and monetary policy shocks, entry is procyclical. Thus, the competition effect generates countercyclical markups and dampens inflation. The opposite is true for demand shocks. Overall, the model-implied markup is countercyclical, due to a combination of desired markup shocks and the competition effect. In a counterfactual exercise where sticky prices are the only source of markup variations, the model-implied markup is, in contrast, procyclical. Second, the estimated competition effect equals 0.15. A one percent increase in the number of firms and goods decreases desired markups by 0.15 percent. While a substantial part of US inflation is driven by a combination of sticky prices and exogenous markup shocks, the contribution of the competition effect to inflation fluctuations is non-negligible. An interesting question for future research is to what extent the observed interest rate path was consistent with the optimal monetary policy prescription.

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Table 1: Exogenous Shock Processes

Total factor productivity shock	$\hat{\eta}_t^Z = \rho_Z \hat{\eta}_{t-1}^Z + \hat{\varepsilon}_t^Z$
Investment-specific technology shock	$\hat{\eta}_t^I = \rho_I \hat{\eta}_{t-1}^I + \hat{\varepsilon}_t^I$
Time preference shock	$\hat{\eta}_t^T = \rho_T \hat{\eta}_{t-1}^T + \hat{\varepsilon}_t^T$
Government spending shock	$\hat{\eta}_t^G = \rho_G \hat{\eta}_{t-1}^G + \hat{\varepsilon}_t^G + \rho_{GZ} \hat{\varepsilon}_t^Z$
Price markup shock	$\hat{\eta}_t^P = \rho_P \hat{\eta}_{t-1}^P + \hat{\varepsilon}_t^P - \mu_P \hat{\varepsilon}_{t-1}^P$
Wage markup shock	$\hat{\eta}_t^W = \rho_W \hat{\eta}_{t-1}^W + \hat{\varepsilon}_t^W - \mu_W \hat{\varepsilon}_{t-1}^W$
Monetary policy shock	$\hat{\eta}_t^R = \rho_R \hat{\eta}_{t-1}^R + \hat{\varepsilon}_t^R$
Entry cost shock	$\hat{\eta}_t^E = \rho_E \hat{\eta}_{t-1}^E + \hat{\varepsilon}_t^E$

Note: In each shock process i, the innovations $\widehat{\varepsilon}_t^i$ are independently and identically distributed random variables following a normal distribution with mean zero and variance σ_i^2.

Table 2: Estimation Results: Baseline

ESTIMATED STRUCTURAL PARAMETERS			Posterior		SHOCKS AR(1), MA(1)		Posterior	
Symbol	Description	Prior (P1,P2)	Mode	Mean [5th; 95th %ile]	Symbol	Prior (P1,P2)	Mode	Mean [5th; 95th %ile]
b	Consumption habit	B (0.70, 0.10)	0.69	0.70 [0.64; 0.77]	ρ_Z	B (0.50, 0.15)	0.98	0.98 [0.97;0.99]
σ_c	Consumption utility	N (1.5, 0.375)	1.57	1.42 [0.96; 1.86]	ρ_T	B (0.50, 0.15)	0.13	0.16 [0.06; 0.25]
σ_l	Consumption labor	N (2.00, 0.75)	1.88	1.80 [0.84; 2.73]	ρ_I	B (0.50, 0.15)	0.42	0.41 [0.31; 0.50]
					ρ_G	B (0.50, 0.15)	0.90	0.89 [0.87; 0.92]
φ_K	Investment adj. cost	N (4.00, 1.50)	8.99	9.15 [7.11; 11.20]	ρ_P	B (0.50, 0.15)	0.78	0.77 [0.70; 0.84]
φ_N	Entry adj. cost	N (4.00, 1.50)	2.39	2.70 [1.92; 3.46]	ρ_W	B (0.50, 0.15)	0.97	0.94 [0.88; 0.99]
$\tilde{\sigma}_a$	Capacity util. cost	B (0.50, 0.15)	0.77	0.77 [0.65; 0.90]	ρ_R	B (0.50, 0.15)	0.17	0.18 [0.09; 0.26]
					ρ_E	B (0.50, 0.15)	0.85	0.85 [0.81; 0.89]
λ_p	Indexation prices	B (0.50, 0.15)	0.31	0.36 [0.18; 0.55]	ρ_{GZ}	B (0.50, 0.15)	0.79	0.75 [0.60; 0.91]
κ_p	Price rigidity	G (50.0, 7.50)	59.37	59.01 [47.41; 70.06]	μ_w	B (0.50, 0.15)	0.61	0.60 [0.46; 0.74]
λ_w	Indexation wages	B (0.50, 0.15)	0.56	0.54 [0.35; 0.73]	μ_p	B (0.50, 0.15)	0.43	0.41 [0.25; 0.57]
κ_w	Wage rigidity	G (50.0, 7.50)	52.73	56.37 [43.81; 68.29]				
$\boldsymbol{\varepsilon}$	**Demand elasticity**	**N (4.00, 1.50)**	**6.37**	**6.68 [5.34; 8.00]**				
$\boldsymbol{\eta}$	**Competition effect**		**0.15**	**0.15 [0.12; 0.18]**				
					SHOCK INNOVATIONS			
τ_R	Interest smoothing	B (0.75, 0.10)	0.74	0.74 [0.69; 0.78]				
τ_π	Policy inflation	G (1.50, 0.25)	1.48	1.52 [1.34; 1.70]	σ_Z	IG (0.10, 2)	0.82	0.82 [0.74; 0.90]
τ_y	Policy output	G (0.50, 0.25)	0.01	0.01 [0.002; 0.02]	σ_T	IG (0.10, 2)	0.28	0.29 [0.25; 0.32]
τ_{dy}	Policy lagged output	G (0.50, 0.25)	0.11	0.11 [0.08; 0.14]	σ_I	IG (0.10, 2)	1.35	1.38 [1.12; 1.63]
					σ_G	IG (0.10, 2)	3.04	3.07 [2.75; 3.38]
CALIBRATED STRUCTURAL PARAMETERS					σ_P	IG (0.10, 2)	0.23	0.25 [0.19; 0.31]
					σ_W	IG (0.10, 2)	0.44	0.43 [0.36; 0.50]
β	Discount factor			0.99	σ_R	IG (0.10, 2)	0.25	0.25 [0.23; 0.28]
α	Capital share in production			0.24	σ_E	IG (0.10, 2)	3.35	3.54 [2.98; 4.10]
δ_N	Firm exit rate			0.025				
δ_K	Capital depreciation rate			0.025				
θ_w	Elasticity of substitution labor types			3				
G/Y^c	Exogenous spending share			0.21				
$N/\tilde{N}$	Ratio of available to conceivable goods			0.95				

Note: B = Beta, G = Gamma, IG = Inverse Gamma and N = Normal distributions. P1 = Mean and P2 = Standard deviation for all distributions. Posterior moments are computed using 960,000 draws from the distribution simulated by the Random Walk Metropolis Hastings algorithm.

Table 3: Sensitivity Analysis

Symbol	Description	PRIOR (P1,P2)	POSTERIOR DISTRIBUTION: Mean [5th; 95th %ile] Risk-P	P	CES	Asym-PF
STRUCTURAL PARAMETERS						
b	Consumption habit	B (0.70, 0.10)	0.64 [0.55; 0.73]	0.70 [0.64; 0.77]	0.68 [0.62; 0.74]	0.68 [0.61; 0.74]
σ_c	Consumption utility	N (1.5, 0.375)	1.32 [0.98; 1.65]	1.40 [0.95; 1.86]	1.69 [1.23; 2.12]	1.96 [1.58; 2.33]
σ_l	Consumption labor	N (2.00, 0.75)	1.55 [0.66; 2.40]	1.78 [0.82; 2.71]	2.37 [1.43; 3.26]	2.46 [1.51; 3.37]
φ_K	Investment adj. cost	N (4.00, 1.50)	7.00 [4.90; 9.09]	8.92 [6.77; 11.12]	8.74 [6.68; 10.72]	7.76 [5.79; 9.80]
φ_N	Entry adj. cost	N (4.00, 1.50)	2.79 [2.08; 3.47]	3.31 [2.50; 4.12]	2.44 [1.61; 3.22]	1.66 [1.30; 2.02]
$\tilde{\sigma}_a$	Capacity util. cost	B (0.50, 0.15)	0.67 [0.51; 0.83]	0.77 [0.65; 0.90]	0.72 [0.58; 0.87]	0.88 [0.81; 0.96]
λ_p	Indexation prices	B (0.50, 0.15)	0.43 [0.23; 0.62]	0.42 [0.23; 0.62]	0.39 [0.20; 0.58]	0.87 [0.79; 0.96]
κ_p	Price rigidity	G (50.0, 7.50)	57.89 [46.2; 69.1]	63.20 [51.2; 75.1]	63.29 [50.8; 75.2]	63.60 [52.1; 75.2]
λ_w	Indexation wages	B (0.50, 0.15)	0.51 [0.32; 0.71]	0.55 [0.36; 0.74]	0.51 [0.32; 0.70]	0.62 [0.43; 0.80]
κ_w	Wage rigidity	G (50.0, 7.50)	55.29 [43.4; 67.3]	56.33 [43.6; 68.6]	57.74 [45.5; 69.8]	56.94 [44.9; 70.0]
$\boldsymbol{\varepsilon}$	**Demand elasticity**	**N (4.00, 1.50)**	**7.18 [5.81; 8.55]**	**8.69 [7.77; 9.60]**	**5.72 [4.42; 7.07]**	**10.01 [8.61; 11.4]**
$\boldsymbol{\eta}$	**Competition effect**		**0.14 [0.12; 0.17]**	**0.12 [0.10; 0.13]**		**0.10 [0.09; 0.12]**
τ_R	Interest smoothing	B (0.75, 0.10)	0.75 [0.71; 0.80]	0.74 [0.70; 0.79]	0.73 [0.69; 0.78]	0.77 [0.73; 0.80]
τ_π	Policy inflation	G (1.50, 0.25)	1.64 [1.41; 1.87]	1.55 [1.36; 1.74]	1.75 [1.47; 2.02]	1.42 [1.27; 1.56]
τ_y	Policy output	G (0.50, 0.25)	0.02 [0.01; 0.03]	0.01 [0.01; 0.02]	0.01 [0.01; 0.02]	0.06 [0.04; 0.08]
τ_{dy}	Policy lagged output	G (0.50, 0.25)	0.13 [0.09; 0.16]	0.11 [0.08; 0.14]	0.12 [0.08; 0.15]	0.14 [0.10; 0.17]
AR(1), MA(1)						
ρ_Z	TFP	B (0.50, 0.15)	0.98 [0.98; 0.99]	0.98 [0.98;0.99]	0.98 [0.98;0.99]	0.98 [0.98;0.99]
ρ_T	Time Preference	B (0.50, 0.15)		0.16 [0.06; 0.25]	0.18 [0.07; 0.28]	0.15 [0.06; 0.24]
ρ_{RP}	Risk Premium	B (0.50, 0.15)	0.29 [0.12; 0.46]			
ρ_I	Inv. Spec. Tech.	B (0.50, 0.15)	0.52 [0.42; 0.62]	0.43 [0.34; 0.52]	0.41 [0.32; 0.50]	0.48 [0.40; 0.56]
ρ_G	Gov. Spending	B (0.50, 0.15)	0.89 [0.86; 0.92]	0.89 [0.86; 0.92]	0.90 [0.87; 0.93]	0.89 [0.86; 0.92]
ρ_P	Price Markup AR(1)	B (0.50, 0.15)	0.77 [0.71; 0.85]	0.75 [0.68; 0.83]	0.77 [0.69; 0.85]	0.54 [0.45; 0.64]
ρ_W	Wage Markup AR(1)	B (0.50, 0.15)	0.95 [0.91; 0.99]	0.93 [0.87; 0.99]	0.97 [0.94; 0.99]	0.98 [0.98; 0.99]
ρ_R	Monetary Policy	B (0.50, 0.15)	0.20 [0.10; 0.30]	0.19 [0.10; 0.28]	0.17 [0.08; 0.25]	0.10 [0.04; 0.15]
ρ_E	Entry Cost	B (0.50, 0.15)	0.87 [0.84; 0.90]	0.86 [0.82; 0.89]	0.84 [0.80; 0.88]	0.85 [0.82; 0.87]
ρ_{GZ}	Corr. TFP – Gov.	B (0.50, 0.15)	0.76 [0.61; 0.92]	0.77 [0.62; 0.92]	0.74 [0.58; 0.91]	0.79 [0.66; 0.92]
μ_w	Wage Markup MA(1)	B (0.50, 0.15)	0.67 [0.55; 0.79]	0.61 [0.48; 0.75]	0.58 [0.44; 0.72]	0.53 [0.37; 0.69]
μ_p	Price Markup MA(1)	B (0.50, 0.15)	0.42 [0.37; 0.58]	0.40 [0.24; 0.56]	0.48 [0.32; 0.65]	0.29 [0.14; 0.43]
INNOVATIONS						
σ_Z	TFP	IG (0.10, 2)	0.80 [0.72; 0.88]	0.80 [0.72; 0.87]	0.84 [0.75; 0.92]	0.92 [0.83; 1.01]
σ_T	Time Preference	IG (0.10, 2)		0.29 [0.25; 0.33]	0.27 [0.23; 0.31]	0.31 [0.27; 0.36]
σ_{RP}	Risk Premium	IG (0.10, 2)	1.63 [1.04; 2.20]			
σ_I	Inv. Spec. Tech.	IG (0.10, 2)	1.14 [0.91; 1.35]	1.24 [1.03; 1.45]	1.46 [1.19; 1.72]	1.15 [0.96; 1.34]
σ_G	Gov. Spending	IG (0.10, 2)	3.01 [2.70; 3.31]	2.92 [2.63; 3.19]	3.19 [2.85; 3.54]	2.80 [2.53; 3.06]
σ_P	Price Markup	IG (0.10, 2)	0.27 [0.21; 0.33]	0.28 [0.22; 0.35]	0.25 [0.20; 0.31]	0.53 [0.46; 0.61]
σ_W	Wage Markup	IG (0.10, 2)	0.44 [0.37; 0.52]	0.44 [0.37; 0.51]	0.43 [0.36; 0.50]	0.42 [0.34; 0.49]
σ_R	Monetary Policy	IG (0.10, 2)	0.25 [0.23; 0.28]	0.25 [0.23; 0.28]	0.25 [0.23; 0.28]	0.25 [0.23; 0.28]
σ_E	Entry Cost	IG (0.10, 2)	3.27 [2.71; 3.80]	3.89 [3.29; 4.46]	3.32 [2.78; 3.86]	3.12 [2.68; 3.55]
σ_D	Profit Meas. Error	IG (0.10, 2)		12.41 [11.2; 13.6]		

Note: 'Risk-P' replaces the time-impatience shock by the Smets and Wouters (2007) risk-premium shock which generates comovement between consumption and investment. 'P' uses profit data in the estimation and introduces a measurement error in equation (8). 'CES' is a model with constant elasticity of substitution between goods as in Dixit and Stiglitz (1977). 'Asym-PF' is a model with an asymmetric production structure for the entry and goods producing sector. B = Beta, G = Gamma, IG = Inverse Gamma and N = Normal distributions. P1 = Mean and P2 = Standard deviation for all distributions. Posterior moments are computed using 576,000 draws from the distribution simulated by the Random Walk Metropolis Hastings algorithm.

Table 3 (Contd): Sensitivity Analysis

Symbol	Description	PRIOR (P1,P2)	POSTERIOR DISTRIBUTION: Mean [5th; 95th %ile] NE	NI	Births
STRUCTURAL PARAMETERS					
b	Consumption habit	B (0.70, 0.10)	0.71 [0.65; 0.78]	0.72 [0.67; 0.77]	0.64 [0.49; 0.80]
σ_c	Consumption utility	N (1.5, 0.375)	1.34 [0.91; 1.78]	1.51 [1.10; 1.90]	1.76 [1.29; 2.21]
σ_l	Consumption labor	N (2.00, 0.75)	1.70 [0.74; 2.66]	2.02 [1.10; 2.94]	2.41 [1.26; 3.49]
φ_K	Investment adj. cost	N (4.00, 1.50)	9.25 [7.20; 11.20]	7.69 [5.73; 9.68]	5.07 [2.90; 7.24]
φ_N	Entry adj. cost	N (4.00, 1.50)	2.62 [1.84; 3.35]	0.93 [0.72; 1.13]	0.53 [0.40; 0.67]
$\tilde{\sigma}_a$	Capacity util. cost	B (0.50, 0.15)	0.79 [0.68; 0.91]	0.72 [0.58; 0.87]	0.69 [0.52; 0.87]
λ_p	Indexation prices	B (0.50, 0.15)	0.35 [0.17; 0.52]	0.29 [0.14; 0.44]	0.35 [0.14; 0.55]
κ_p	Price rigidity	G (50.0, 7.50)	58.86 [47.3; 70.3]	58.37 [49.8; 69.4]	60.22 [48.1; 72.3]
λ_w	Indexation wages	B (0.50, 0.15)	0.54 [0.35; 0.73]	0.56 [0.37; 0.75]	0.47 [0.23; 0.71]
κ_w	Wage rigidity	G (50.0, 7.50)	56.55 [44.2; 69.0]	55.96 [44.1; 67.8]	52.34 [40.1; 64.2]
$\boldsymbol{\varepsilon}$	**Demand elasticity**	**N (4.00, 1.50)**	**6.44 [5.16; 7.69]**	**5.80 [4.90; 6.68]**	**4.84 [3.82; 5.84]**
$\boldsymbol{\eta}$	**Competition effect**		**0.16 [0.13; 0.19]**	**0.17 [0.15; 0.20]**	**0.21 [0.17; 0.26]**
τ_R	Interest smoothing	B (0.75, 0.10)	0.73 [0.69; 0.78]	0.75 [0.71; 0.79]	0.86 [0.82; 0.90]
τ_π	Policy inflation	G (1.50, 0.25)	1.51[1.33; 1.67]	1.58 [1.38; 1.78]	1.95 [1.52; 2.38]
τ_y	Policy output	G (0.50, 0.25)	0.01 [0.01; 0.02]	0.01 [0.01; 0.03]	0.18 [0.07; 0.29]
τ_{dy}	Policy lagged output	G (0.50, 0.25)	0.11 [0.07; 0.14]	0.11 [0.08; 0.15]	0.07 [0.03; 0.10]
AR(1), MA(1)					
ρ_Z	TFP	B (0.50, 0.15)	0.98 [0.98; 0.99]	0.98 [0.98;0.99]	0.58 [0.45;0.72]
ρ_T	Time Impatience	B (0.50, 0.15)	0.16 [0.06; 0.25]	0.14 [0.05; 0.22]	0.69 [0.54; 0.84]
ρ_{RP}	Risk Premium	B (0.50, 0.15)			
ρ_I	Inv. Spec. Tech.	B (0.50, 0.15)	0.38 [0.28; 0.48]	0.50 [0.42; 0.59]	0.44 [0.31; 0.58]
ρ_G	Gov. Spending	B (0.50, 0.15)	0.89 [0.86; 0.92]	0.89 [0.86; 0.92]	0.87 [0.79; 0.95]
ρ_P	Price Markup AR(1)	B (0.50, 0.15)	0.77 [0.69; 0.84]	0.77 [0.69; 0.85]	0.76 [0.65; 0.87]
ρ_W	Wage Markup AR(1)	B (0.50, 0.15)	0.93 [0.86; 0.98]	0.96 [0.93; 0.98]	0.52 [0.33; 0.72]
ρ_R	Monetary Policy	B (0.50, 0.15)	0.18 [0.09; 0.26]	0.15 [0.07; 0.23]	0.44 [0.29; 0.59]
ρ_E	Entry Cost	B (0.50, 0.15)	0.85 [0.82; 0.89]	0.81 [0.77; 0.85]	0.55 [0.43; 0.67]
ρ_{GZ}	Corr. TFP – Gov.	B (0.50, 0.15)	0.76 [0.60; 0.92]	0.74 [0.57; 0.90]	0.58 [0.35; 0.80]
μ_w	Wage Markup MA(1)	B (0.50, 0.15)	0.60 [0.46; 0.73]	0.51 [0.35; 0.67]	0.47 [0.28; 0.66]
μ_p	Price Markup MA(1)	B (0.50, 0.15)	0.41 [0.25; 0.58]	0.41 [0.25; 0.57]	0.41 [0.22; 0.61]
INNOVATIONS					
σ_Z	TFP	IG (0.10, 2)	0.83 [0.74; 0.91]	0.84 [0.76; 0.92]	0.63 [0.53; 0.74]
σ_T	Time Impatience	IG (0.10, 2)	0.29 [0.25; 0.33]	0.29 [0.25; 0.32]	0.09 [0.05; 0.12]
σ_{RP}	Risk Premium	IG (0.10, 2)			
σ_I	Inv. Spec. Tech.	IG (0.10, 2)	1.41 [1.14; 1.66]	1.16 [0.97; 1.35]	1.31 [0.97; 1.65]
σ_G	Gov. Spending	IG (0.10, 2)	3.08 [2.77; 3.40]	3.16 [2.84; 3.48]	2.38 [1.98; 2.77]
σ_P	Price Markup	IG (0.10, 2)	0.25 [0.18; 0.30]	0.23 [0.18; 0.28]	0.15 [0.10; 0.19]
σ_W	Wage Markup	IG (0.10, 2)	0.43 [0.36; 0.50]	0.42 [0.35; 0.49]	0.83 [0.66; 0.99]
σ_R	Monetary Policy	IG (0.10, 2)	0.25 [0.23; 0.28]	0.25 [0.22; 0.27]	0.09 [0.08; 0.11]
σ_E	Entry Cost	IG (0.10, 2)	2.51 [2.96; 4.05]	3.41 [2.93; 3.90]	3.31 [2.63; 3.97]
σ_D	Profit Meas. Error	IG (0.10, 2)			

Note: 'NE' matches the series of net business formation with net entry in the model. 'NI' denotes the use of data on New Incorporations instead of data on net business formation. 'Births' estimates the model on a later sample using establishment data. B = Beta, G = Gamma, IG = Inverse Gamma and N = Normal distributions. P1 = Mean and P2 = Standard deviation for all distributions. Posterior moments are computed using 576,000 draws from the distribution simulated by the Random Walk Metropolis Hastings algorithm.

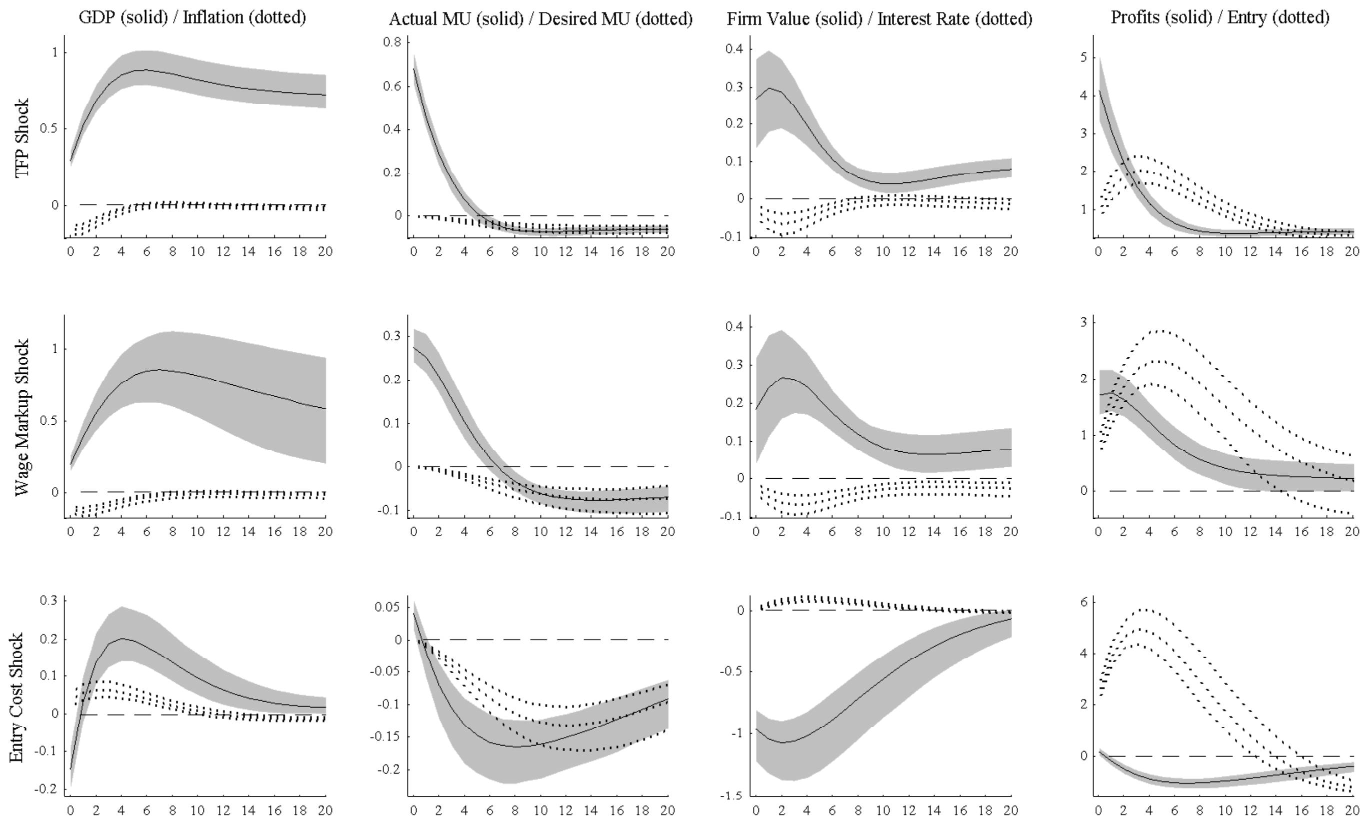

Figure 1a: Impulse Responses to Supply Shocks

Note: Impulse responses functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in GDP.

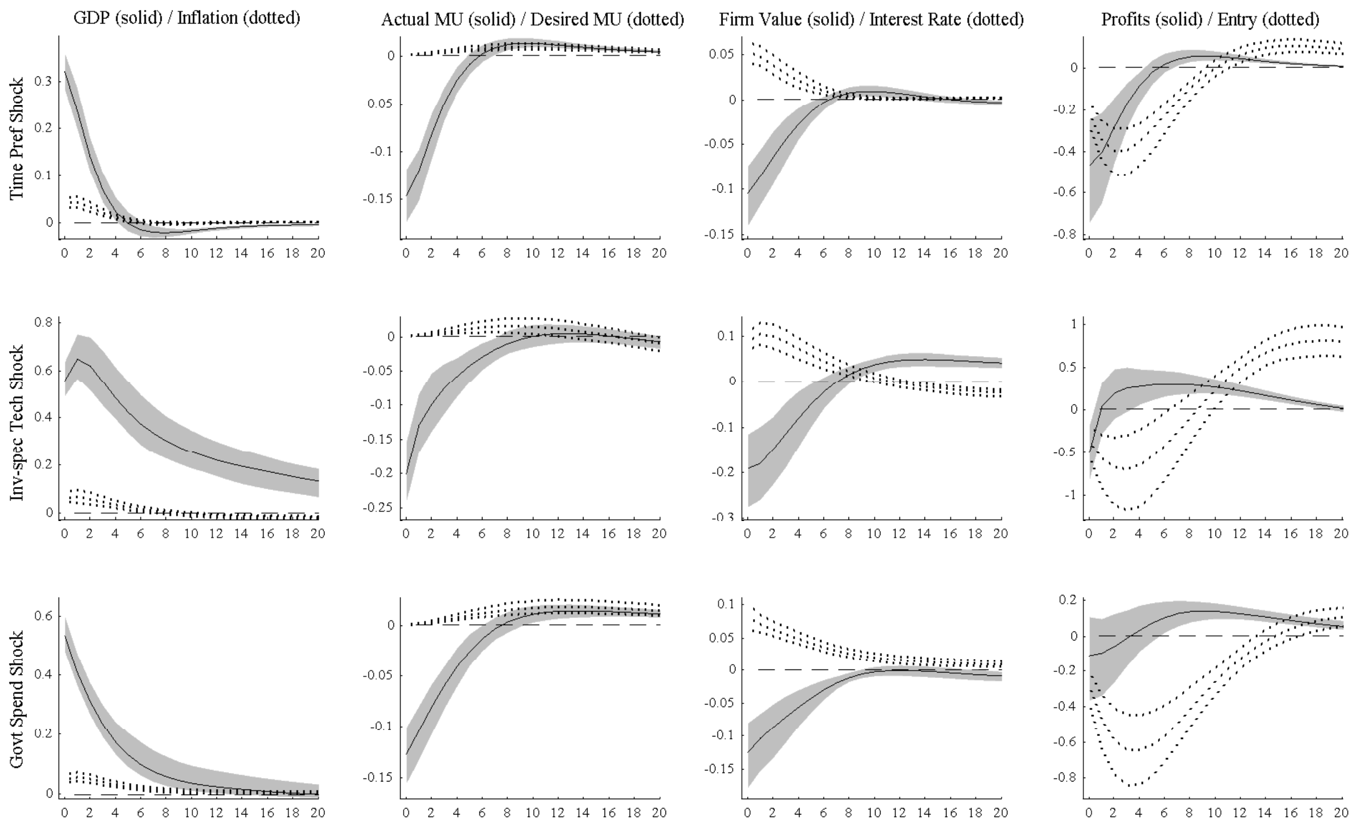

Figure 1b: Impulse Response to Demand Shocks

Note: Impulse responses functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in GDP.

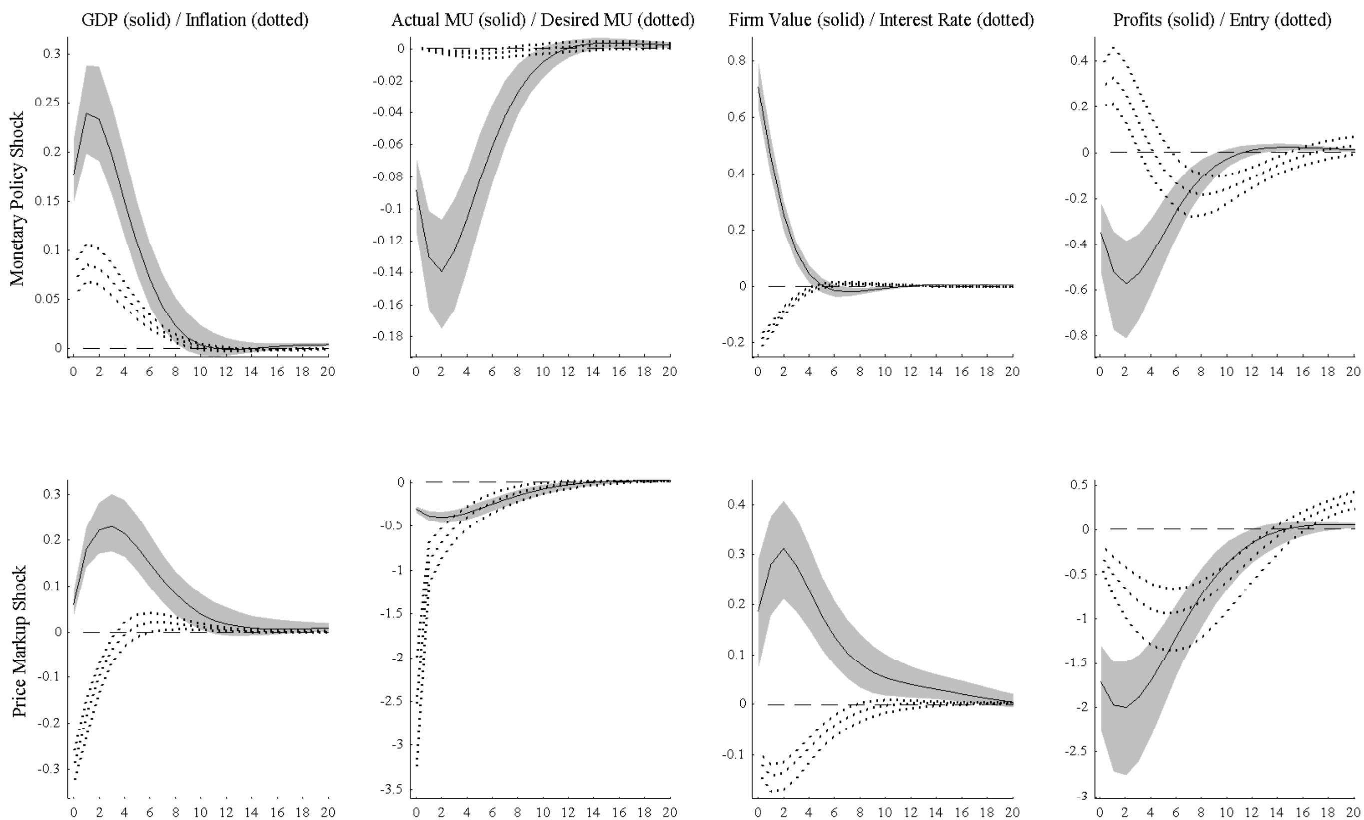

Figure 1c: Impulse Responses to Monetary Policy and Price Markup Shocks

Note: Impulse responses functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in GDP.

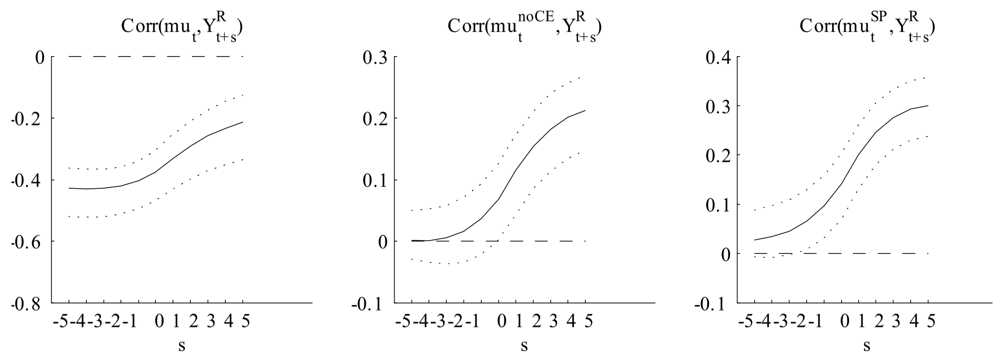

Figure 2: The Cyclicality of the Markup

Note: The figure shows the cyclicality of the model-implied markup at different leads and lags. The left panel depicts the actual markup $\hat{\mu}_t$ as implied by the model, the center panel shows the counterfactual markup in the absence of the competition effect $\hat{\mu}_t^{noCE}$, and the right panel depicts the 'sticky price' component $\hat{\mu}_t^{SP}$, which we would obtain in the absence of both the competition effect and desired markup shocks.

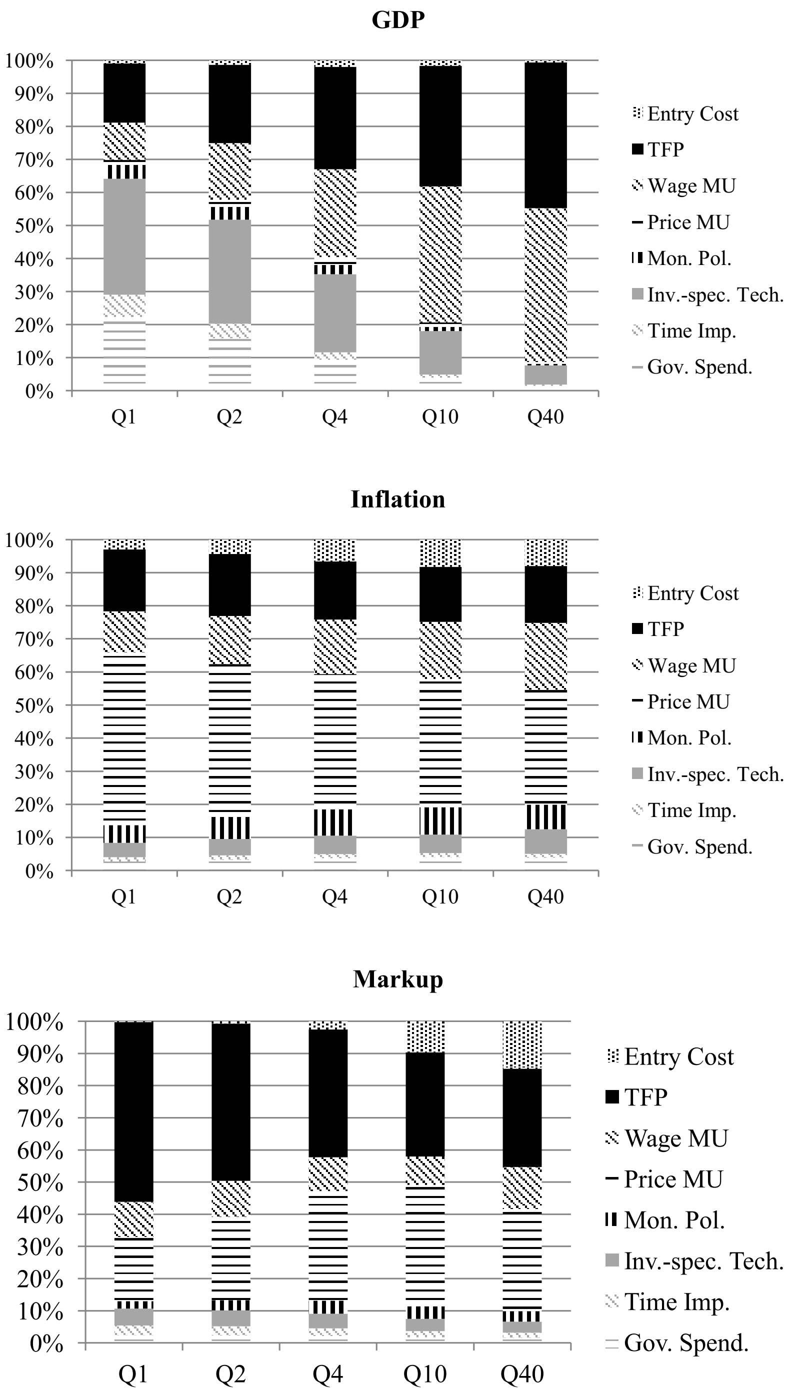

Figure 3: Forecast Error Variance Decomposition (at posterior mode)

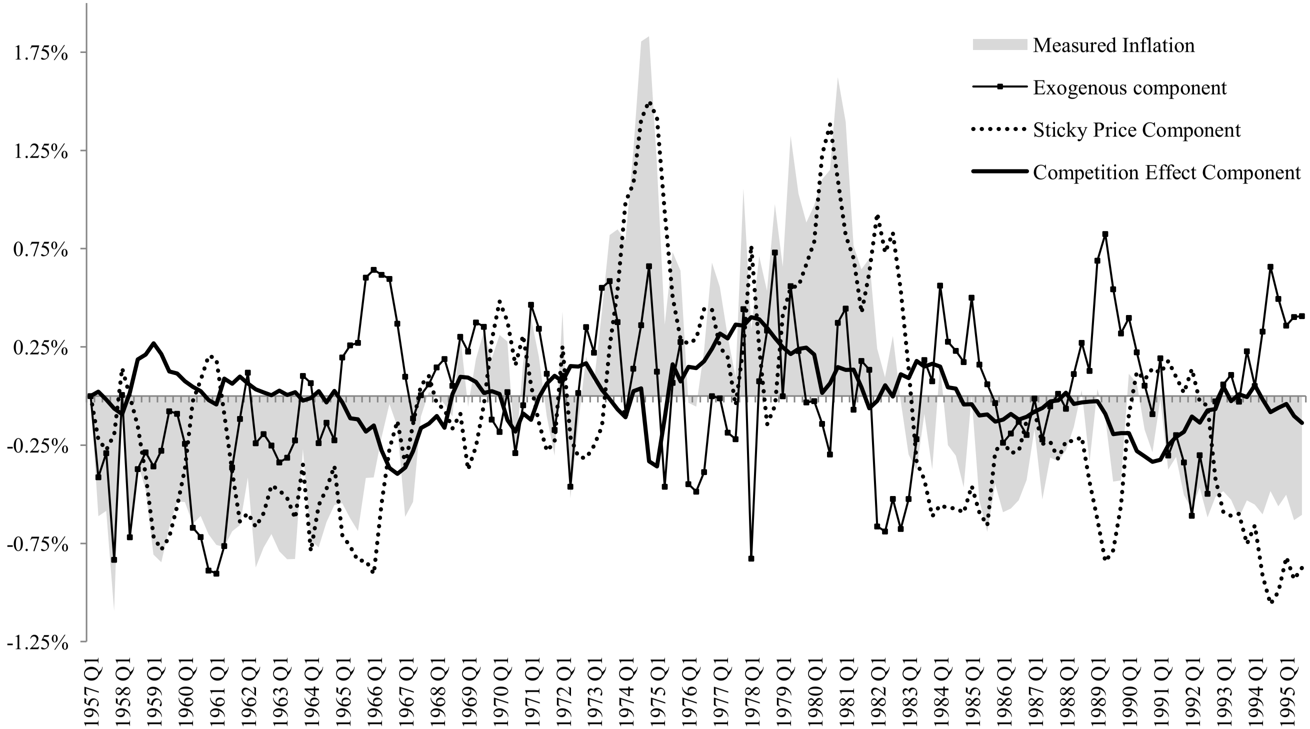

Figure 4a: Counterfactual Decomposition of US Inflation: Earlier Sample

Note: Entry is measured as net business formation. The inflation rate and its components have been constructed by feeding the smoothed shocks into the model. The ‘Exogenous component’ represents the contribution of desired price markup shocks to inflation. The ‘Sticky Price Component’ captures the counterfactual inflation path when desired markups are constant. The ‘Competition Effect Component’ is the residual of the actual inflation rate less the two other components.

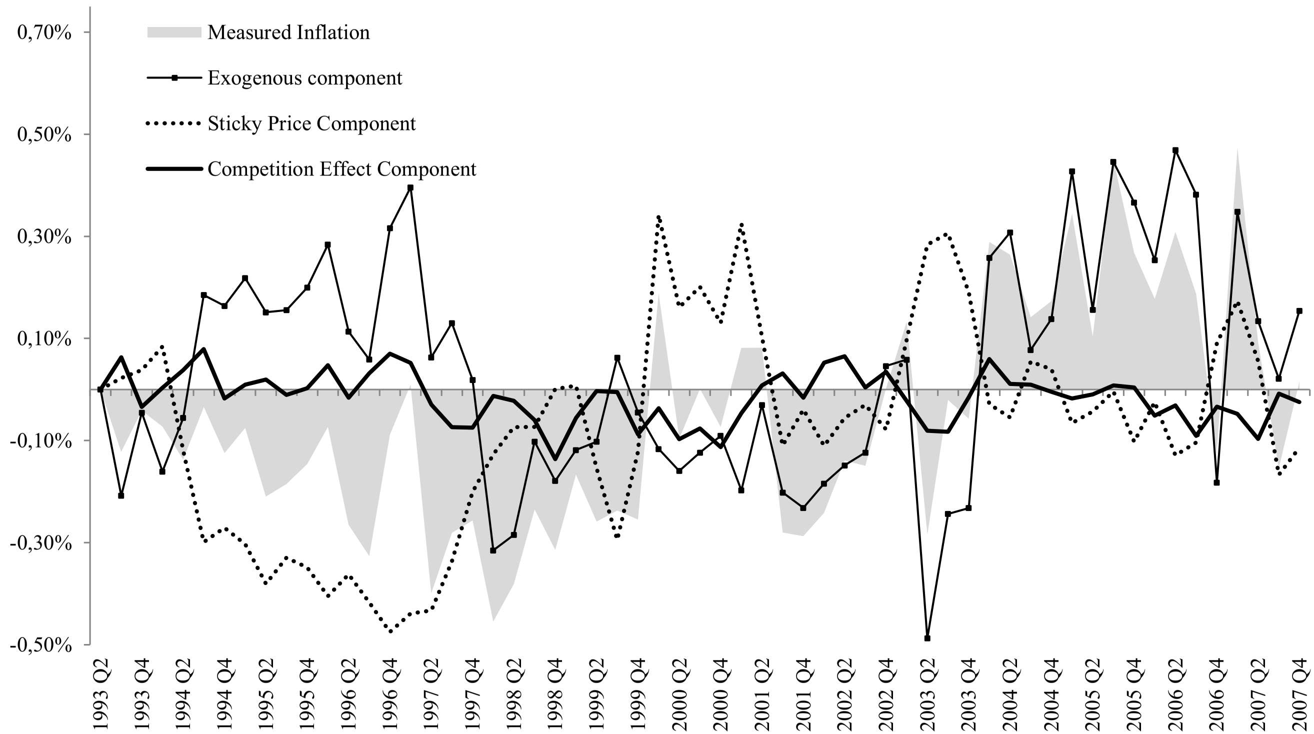

Figure 4b: Counterfactual Decomposition of US Inflation: Later Sample

Note: Entry is measured as establishment births. The inflation rate and its components have been constructed by feeding the smoothed shocks into the model. The ‘Exogenous component’ represents the contribution of desired price markup shocks to inflation. The ‘Sticky Price Component’ captures the counterfactual inflation path when desired markups are constant. The ‘Competition Effect Component’ is the residual of the actual inflation rate less the two other components.

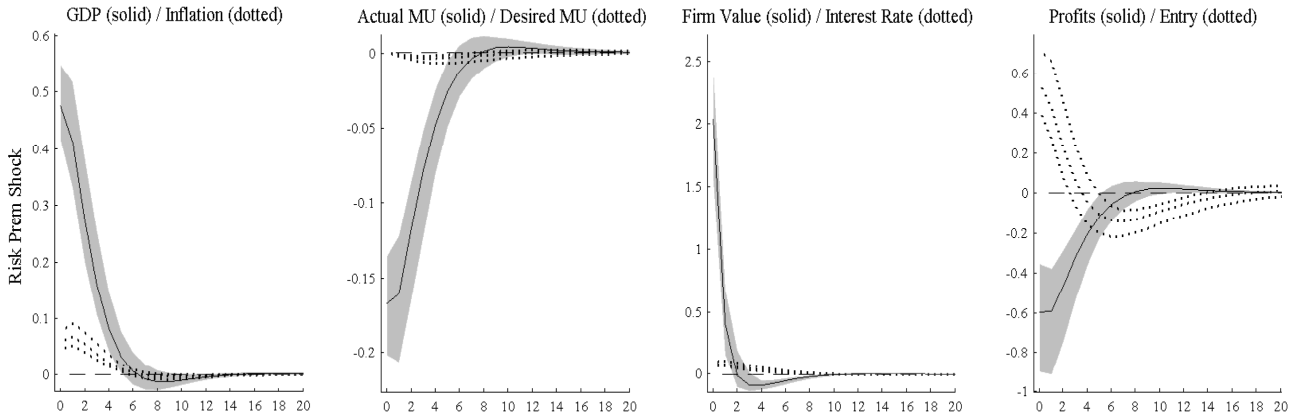

Figure 5: Sensitivity Analysis. Impulse Responses to Risk Premium Shock

Note: Impulse responses functions (IRFs) to a one standard deviation shock, measured in percentage deviations from steady state. Median IRF and 5th and 95th percentiles are based on 300 random draws from the posterior distribution. All shocks have been normalized to produce an increase in GDP.

Chapter 5

Can Stronger Competition Explain the Flattening of the Phillips Curve?

Can Stronger Competition Explain the Flattening of the Phillips Curve?*

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Abstract

Many observers suggest that the flattening of the Phillips curve, which is observed in industrial countries, is explained by stronger competition. The empirical literature is highly inconclusive with respect to this topic. What can we learn from the micro-founded new-Keynesian Phillips curve (NKPC)? This paper argues that to answer this question, we must relax the standard Dixit-Stiglitz monopolistic competition assumption for market structure. I consider oligopolistic competition and demonstrate that stronger competition unambiguously increases the slope of the Phillips curve. The standard NKPC, therefore, does not support the argument that higher competition flattens the Phillips curve.

JEL classification: E31, E39
Keywords: Competition, Phillips Curve Slope, Oligopoly.

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1 Introduction

There is widespread evidence that the response of inflation to output, the slope of the Phillips curve, has declined in recent years. Since the mid-1980s, almost all advanced countries have experienced a flattening of the Phillips curve, e.g., Borio and Filardo (2007) and Ihrig et al. (2007).[1] This decline in the output-inflation trade-off has important consequences for monetary policy because it implies that the sacrifice ratio is now larger than it was two decades ago; in other words, output must decrease by a greater extent to achieve a given reduction in inflation. Therefore, it is important to understand the factors that drive the flattening of the Phillips curve. One recent and popular argument ascribes the decline in the slope of the Phillips curve to increased goods market competition, which is generated by deregulation and globalization.[2] However, studies that evaluate this argument report mixed results. Duca and VanHoose (2000) find that increased overall competition flattened the Phillips curve in the US during the 1990s. In an assessment that focuses specifically on the competitive effects of globalization, the IMF (2006) estimates that a negative interaction term exists between the slope of the Phillips curve and the degree of trade openness among the group of advanced countries as a whole. By contrast, Ball (2006) and Gaiotti (2010) fail to uncover any significant relationship between openness indicators and the output-inflation trade-off for the US and Italy, respectively.

Given the disagreement in the empirical literature with respect to the role of competition in the flattening of the Phillips curve, Gali (2010) proposes extending the analysis beyond the investigation of reduced form relationships. In particular, he suggests analyzing the competition effects on inflation dynamics in the context of microfounded new-Keynesian Phillips curves (NKPCs). However, similar to the empirical literature, theoretical contributions that address this suggestion, such as Kahn (2005) and Sbordone (2009), reach ambiguous conclusions. Khan (2005) notes the importance of price-setting behavior in understanding the effects of stronger competition on the NKPC slope. He demonstrates that higher competition increases the slope of the NKPC in the Rotemberg model, whereas in the Calvo model, the slope of the NKPC is either reduced or left unchanged by increases in competition. Sbordone (2009) extends the standard Calvo pricing-model by allowing

[1] See also Roberts (2006), Williams (2006), IMF (2006) and Guilloux and Kharroubi (2008).

[2] A more traditional argument links the flattening of the Phillips curve to the vigorous monetary policy that has been conducted in many countries during the last two decades. From this perspective, there are two possible explanations for the flattening of the Phillips curve. First, according to Ball et al. (1989), lower trend inflation reduces the frequency at which firms engage in nominal price adjustments, which flattens the Phillips curve. Second, Bayoumi and Sgherri (2004) argue that increasing policy credibility anchors inflation expectations and thereby dampens movements in actual inflation.

for a time-varying demand elasticity using Kimball (1995) preferences. She finds that an increase in competition flattens the NKPC only under certain parameter specifications of the Kimball aggregator.

An important feature of the afore-mentioned theoretical contributions is that they all consider monopolistic competition among many small firms à la Dixit and Stiglitz (1977). However, the appropriateness of the monopolistic competition framework for investigating the effects of increasing market competition is theoretically questionable. Monopolistic markets are characterized by a continuum of many small firms, each of which supplies only a small portion of aggregate output. As a result, firms do not engage in strategic pricing competition, and each firm's actions have a negligible impact on the market. Within this framework, increasing competition cannot generate any significant effect on the overall economy. Khan (2005) and Sbordone (2009) circumvent this issue by assuming that the long-run (i.e., steady state) equilibrium of the economy is characterized by a finite number of firms. However, two objections can be raised with respect to this approach. First, this perspective creates an inconsistency problem between the long- and short-run dynamics of the model economy; i.e., the steady state demand elasticity becomes a function of the structural degree of competition, whereas cycle variations in demand elasticity remain unaffected by competitive pressures. Second, monopolistic competition can be interpreted as an extreme case of oligopolistic competition that features an unlimited number of competitors. Therefore, in considerations involving a finite number of firms, the market structure is essentially oligopolistic rather than monopolistic. Pricing behavior should then be modeled accordingly, accounting for the strategic interactions between the oligopolists.

In this paper, I overcome these issues by considering price-setting behavior under conditions of oligopolistic instead of monopolistic competition. Within oligopolistic markets, each firm supplies a sizable portion of aggregate output; therefore, each firm's price decisions have a non-negligible impact on the market. This approach induces a time-varying price-elasticity of demand that increases in the number of competitors. After establishing this transmission channel, I investigate the impact of a structural increase in competition on the slope of the NKPC. Throughout the analysis, a structural increase in competition is defined in terms of a one-off increase in the steady state number of firms or goods. Oligopolistic markets are modeled in accordance with the reasoning of Floetotto and Jaimovich (2008). More specifically, I consider an economy that includes a continuum of industries, each of which consists of a small number of large firms that engage in price competition. To assess the robustness of the analysis, I employ two commonly used approaches to model firms' price-setting behavior: the Calvo (1983) random price adjustment signal and the Rotemberg (1982) quadratic cost of price adjustment.

I demonstrate that a structural increase in the degree of oligopolistic competition unambiguously increases the slope of the NKPC in both the Rotemberg and the Calvo pricing models. This result contradicts the argument that observed increases in competition have reduced the slope of the Phillips curve. With respect to the slope of the Calvo NKPC, this result also significantly differs from the ambiguous competition effects that were reported in the original contributions to the literature considering monopolistic competition.

The key to understanding the different results that are implied by oligopolistic and monopolistic markets is the interaction between the degree of competition and firms' fears of losing market share. The latter induces a 'real rigidity' in price setting, as explained by Ball and Romer (1990). Within oligopolistic markets, competition occurs between a small number of firms. Therefore, the actions of one firm influence the price decisions of its competitors. These strategic interactions lead to a demand elasticity that depends positively on relative prices. Firms, therefore, maintain their prices at rigid levels to avoid losing market share. Increases in competition lower the relative importance of each firm in the aggregate market and alleviate firms' concerns about their market share. This, in turn, promotes greater price flexibility and increases the slope of the Phillips curve. Within monopolistic markets, market share concerns prevail only under certain conditions, and the relationship between these concerns and competition is not well characterized. Kimball (1995) preferences induce strategic pricing behavior and a variable demand elasticity that increases in relative prices. However, whereas in the oligopolistic market structure strategic pricing behavior is related to the degree of competition, Kimball preferences assume the existence of strategic pricing without discussing the sources of this behavior. Therefore, the effects of competition on market share concerns and on the slope of the Phillips curve are critically dependent on the parameterization of the Kimball aggregator.

It is important to note that my analysis should be treated with caution in considerations of the overall effects of globalization. Similarly to Sbordone (2009), I interpret globalization in terms of increasing market competition, which is induced by an increase in the number of goods traded. However, globalization may also affect the short-run inflation dynamics through an increase in the degree of openness of the economy. It has been shown, e.g., Benigno and Faia (2010) and Guerrieri et al. (2010), that increasing openness lowers the impact of domestic economic activity on inflation and renders domestic inflation more sensitive to global factors (i.e., 'global slack'), such as relative import prices. In this study, I do not explore this so-called 'global slack hypothesis'. Instead, I focus on the effects of increased goods market competition for a given level of trade openness.[3]

[3] The discussion about the 'global slack hypothesis' was initiated by Borio and Filardo (2007). Specifically, these authors find a shrinking role for the domestic outputgap in estimated inflation equations,

The paper proceeds as follows. In Section (2), I derive the NKPC under the assumption that product markets are oligopolistic competitive. Section (3) investigates the impact of a structural increase in competition on the slope of the NKPC. Finally, Section (4) draws the main conclusions.

2 The Oligopolistic New-Keynesian Phillips Curve

In this section I derive the NKPC within a model of oligopolistic competition. The analytical framework can be regarded as part of a general equilibrium model that also includes household behavior and endogenously determined cycle variations in the number of firms in the market. I consider two commonly used approaches to model price stickiness. First, I assume that firms set their prices following a staggered pricing mechanism à la Calvo (1983). Second, I derive the NKPC under the assumption that price decisions are subject to Rotemberg (1982)-type quadratic price adjustment costs. Oligopolistic markets are modeled in the spirit of Floetotto and Jaimovich (2008). In particular, the economy is assumed to consist of a fixed range of industries, each one characterized by a small number of large firms, taking strategic interactions into account and competing in prices. I proceed to the log-linearized versions of the model equations, except in cases that are less standard in the literature.[4] Hatted variables denote deviations from the deterministic steady state. Variables without a hat or time subscript refer to the steady state level.

2.1 Oligopolistic Goods Markets

Production in the economy occurs in two layers, as described by Floetotto and Jaimovich (2008). The economy is characterized by a fixed range of industries of measure 1, indexed by $j \in (0, 1)$. The final consumption good Y_t is a constant elasticity of substitution (CES) composite of the industry goods $Y_t(j)$,

$$Y_t = \left[\int_0^1 Y_t(j)^{\omega} dj \right]^{\frac{1}{\omega}}, \tag{1}$$

combined with the increasing importance of measures of global outputgaps, 'global slack', as determinants of domestic inflation. Subsequent studies, however, have questioned the 'global slack hypothesis'. For instance, Ihrig et al. (2007) and Calza (2008) show that the findings of Borio and Filardo (2007) are not robust to different specifications for the measurement of global slack.

[4] An appendix with the full derivation of the model (Appendix A) and an appendix that closes the model by accounting for household and firm entry behavior (Appendix B) are available at http://users.ugent.be/∼ansteven.

where $\omega \in (0,1)$, and $\frac{1}{1-\omega} > 1$ defines the elasticity of substitution between any two different industry goods. Within each industry j, there is a finite number N_t of firms, indexed by $i \in (1, N_t)$, with each producing differentiated intermediate goods $y_t(j,i)$. An industry good $Y_t(j)$ bundles intermediate goods according to a CES aggregator, as follows,

$$Y_t(j) = N_t^{1-\frac{1}{\tau}} \left[\sum_{i=1}^{N_t} y_t(j,i)^{\tau} \right]^{\frac{1}{\tau}}, \tag{2}$$

where $\tau \in (0,1)$, and $\frac{1}{1-\tau} > 1$ is the elasticity of substitution among the goods in an industry.[5] Importantly, goods are less substitutable across industries than within an industry; thus, $\frac{1}{1-\omega} < \frac{1}{1-\tau}$.[6] The demand schedules for industry and intermediate goods are, respectively,

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{\frac{1}{\omega-1}} Y_t \ , \quad \text{and} \quad y_t(j,i) = \left(\frac{p_t(j,i)}{P_t(j)} \right)^{\frac{1}{\tau-1}} \frac{Y_t(j)}{N_t}, \tag{3}$$

where $p_t(j,i)$ is the price of good i in industry j, $P_t(j) = N_t^{\frac{1}{\tau}-1} \left[\sum_{i=1}^{N_t} p_t(j,i)^{\frac{\tau}{\tau-1}} \right]^{\frac{\tau-1}{\tau}}$ is the price index of industry j, and $P_t = \left[\int_0^1 P_t(j)^{\frac{\omega}{\omega-1}} dj \right]^{\frac{\omega-1}{\omega}}$ represents the aggregate price index.

Intermediate goods firms in each industry operate in a regime of oligopolistic competition. Oligopolistic behavior entails two types of strategic interactions with respect to a firm's pricing decisions, and these interactions create a variable price-elasticity of demand. First, within oligopolistic markets, competition takes place between a small number of firms; therefore, the actions of one firm influence the price decisions of its competitors. This strategic pricing behavior implies that a firm's demand elasticity depends on its own relative price $\frac{p_t(j,i)}{P_t(j)} \equiv P_t^r\,(j,i)$. Second, each oligopolistic competitor supplies a large portion of industry output and therefore takes into account that its price decisions have a non-negligible weight in the market. In other words, a firm's price-setting decision internalizes the effect of this decision on industry prices and output. As shown in detail in Floetotto and Jaimovich (2008), these strategic interactions in turn imply that the price-elasticity of demand varies in the number of operating firms. In summary, the relevant

[5] The term $N_t^{1-\frac{1}{\tau}}$ in the CES aggregator of intermediate goods eliminates the 'love of variety' effect in the model; i.e., I eliminate the channel by which consumers can increase their utility by spreading their consumption expenditure across more differentiated goods.

[6] Evidence for this assertion is provided by Broda and Weinstein (2006).

conditional demand function for intermediate good i in industry j reads as

$$y_t(j,i) = (p_t(j,i))^{\frac{1}{\tau-1}} \left(N_t^{\frac{1-\tau}{\tau}} \left[\sum_{i=1}^{N_t} p_t(j,i)^{\frac{\tau}{\tau-1}} \right]^{\frac{\tau-1}{\tau}} \right)^{\frac{1}{\omega-1}-\frac{1}{\tau-1}} \left(\frac{1}{P_t} \right)^{\frac{1}{\omega-1}} \frac{Y_t}{N_t}, \tag{4}$$

which implies that the price-elasticity of demand faced by a single firm $\varepsilon_t(j,i)$ is given by

$$\varepsilon_t(j,i) = \frac{1}{1-\tau} + \left(\frac{1}{1-\omega} - \frac{1}{1-\tau} \right) (P_t^r(j,i))^{\frac{\tau}{\tau-1}} N_t^{-1}. \tag{5}$$

Because $\frac{1}{1-\omega} < \frac{1}{1-\tau}$, the demand elasticity increases in the number of firms N_t. Furthermore, the price-elasticity of demand is lower for goods with a lower relative price. This result implies that the price-elasticity of demand is on average higher for price increases than for price decreases. Oligopolistic competition, therefore, generates a concave or 'quasi-kinked' demand curve in logarithmic terms as in Kimball (1995).

With a time-varying demand elasticity, the desired markup, which is defined as $M_t(j,i) \equiv \frac{\varepsilon_t(j,i)}{\varepsilon_t(j,i)-1}$, is also time varying. In the aggregate, the linearized form of the desired markup is given by

$$\hat{M}_t = -\eta \hat{N}_t, \text{ where} \tag{6}$$

$$\eta = \frac{\frac{1}{1-\tau} - \varepsilon}{\varepsilon(\varepsilon-1)} \geqslant 0. \tag{7}$$

η captures the so-called 'competition effect' in oligopolistic markets, by which a cyclical increase in the number of competitors reduces desired markups. The parameter ε represents the long-run (i.e., steady state) price-elasticity of demand, which increases as the number of firms N rises. The elasticity of demand and the desired markup reduce to their expressions under monopolistic competition if there are an infinite number of firms in the economy, i.e., as $N \to \infty$. More specifically, as N approaches infinity, the price-elasticity of demand approaches $\varepsilon = \frac{1}{1-\tau}$, and the desired markup becomes constant, i.e., $\eta = 0$.

2.2 Price Setting

Intermediate goods $y_t(j,i)$ are produced with the technology $y_t(j,i) = A_t l_t(j,i) - \phi$, where $l_t(j,i)$ represents firm-specific labor input and A_t denotes total factor productivity (TFP). The term $\phi > 0$ denotes fixed production costs.[7] Real marginal costs mc_t are equal across

[7] To obtain a well-defined steady state in the oligopolistic market structure, the number of firms must be finite in the long run. One way to bound the number of operating firms is by considering fixed production costs, because these costs imply zero profits in the long run. Alternatively, we could assume that firms face a sunk startup cost prior to entry as in Bilbiie et al. (2007).

firms and are equal to the real wage rate w_t divided by TFP, i.e., $mc_t = \frac{w_t}{A_t}$. In linearized form, this is

$$\widehat{mc}_t = \hat{w}_t - \hat{A}_t. \tag{8}$$

Oligopolistic firms set prices P_t as a markup μ_t over nominal marginal costs, i.e., $P_t = \mu_t \left(P_t mc_t\right)$, which implies that $\frac{1}{\mu_t} = mc_t$. Therefore, in linearized form, the actual markup reads as

$$\hat{\mu}_t = -\widehat{mc}_t. \tag{9}$$

Price setters are subject to nominal rigidities. I employ two widely used approaches to model price stickiness, namely, the random price adjustment signal suggested by Calvo (1983) and the quadratic cost of price adjustment proposed by Rotemberg (1982).

Calvo Price Staggering The Calvo model assumes that during each period, there is a fixed probability $(1 - \xi_C) \in (0, 1)$ that a firm can re-optimize its nominal price. Given the conditional demand schedule (4), a firm chooses its price $\widetilde{p}_t\left(j, i\right)$ to maximize its expected sum of future discounted profits,

$$\max_{\widetilde{p}_t(j,i)} E_t \sum_{l=0}^{+\infty} \left(\beta \xi_C\right)^l \varphi_{t,t+l} v_{t,t+l} \left[\left(\widetilde{p}_t\left(j, i\right) - mc_{t+l} P_{t+l}\right) y_{t+l}(j, i)\right],$$

where $v_{t,t+l} \equiv \beta^l \frac{U_{c,t+l} P_t}{U_{c,t} P_{t+l}}$ represents the nominal discount factor for firms, which is dependent on households' subjective discount factor β and households' marginal utility of consumption $U_{c,t}$. The variable $\varphi_{t,t+l}$ represents the firm's expected survival rate over l periods at time t.[8]

Rotemberg Price Adjustment Costs Under the Rotemberg pricing structure, an oligopolistic firm faces a quadratic cost $PAC_t\left(j, i\right)$ of adjusting nominal prices. This cost is proportional to the firm's revenues and is given by

$$PAC_t\left(j, i\right) = \frac{\xi_R}{2} \left(\frac{p_t\left(j, i\right)}{p_{t-1}\left(j, i\right)} - 1\right)^2 P_t\left(j, i\right) y_t\left(j, i\right), \tag{10}$$

where $\xi_R > 0$ measures the degree of nominal price rigidity. Price adjustment costs are higher, the more the change in the firm's price $p_t\left(j, i\right) / p_{t-1}\left(j, i\right)$ diverges from the gross steady state inflation rate π, which is assumed to be one (i.e., I consider a long-run

[8] See Appendix A for details.

equilibrium involving zero inflation). The price-setting problem of firm i in industry j can then be expressed as follows,

$$\max_{p_t(j,i)} E_t \sum_{l=0}^{+\infty} \varphi_{t,t+l} v_{t,t+l} \left[\left((p_{t+l}(j,i) - mc_{t+l} P_{t+l}) - \frac{\xi_R}{2} \left(\frac{p_{t+l}(j,i)}{p_{t+l-1}(j,i)} - 1 \right)^2 p_{t+l}(j,i) \right) y_{t+l}(j,i) \right].$$

A firm chooses its price $p_t(j,i)$ to maximize its current and discounted future profits. Through this process, the firm internalizes its conditional demand schedule (4).

The New-Keynesian Phillips Curve As shown in Appendix A, the two pricing models deliver equivalent inflation dynamics if they are log-linearized around the zero-inflation steady state. Specifically, both models imply the same reduced-form NKPC specification,

$$\hat{\pi}_t = \beta E_t \pi_{t+1} - \kappa_i \left[\hat{\mu}_t - \hat{M}_t \right], \text{ where } i \in (C, R). \tag{11}$$

Inflation $\hat{\pi}_t$ depends positively on expected future inflation and negatively on $\hat{\mu}_t - \hat{M}_t$, the gap between the actual and desired price markup. Recall that oligopolistic behavior entails a competition effect by which cyclical increases in competition reduce desired markups, as expressed by equation (6). Therefore, in contrast to the traditional NKPC, the oligopolistic competitive NKPC (11) identifies the effects of cyclical competitive pressures on inflation dynamics.[9] If the number of firms N approaches infinity (i.e., if markets are monopolistic competitive), then equation (11) reduces to the traditional NKPC, where $\hat{M}_t = 0$. Notably, to derive the NKPC under Calvo price staggering, two conditions need to be satisfied which deserve special attention in cases of oligopolistic product markets. First, because Calvo pricing contracts involve renegotiation probabilities, aggregation in the Calvo model requires that the number of firms is large enough so that the law of large numbers prevails. As a result, linear approximations of the Calvo Phillips curve are flowed if sector markets only feature a limited number of competitors. To overcome this issue, this paper considers oligopolistic markets that in size lie close to monopolistic competitive markets. Second, the distribution of prices among firms that do not adjust their prices during period t must correspond to the distribution of effective prices in the previous period $t-1$. I make several simplifying assumptions that guarantee that this condition holds true under time-varying competitive pressures. Specifically, I assume that all of the incumbent firms face the same probability of exiting the market. Furthermore, I assume that the prices of firms that are entering the market have the same distribution as the prices of the incumbent firms.

[9] For empirical investigations of cyclical competition effects on markups and inflation dynamics, see, e.g., Cecioni (2010), Lewis and Poilly (2012) and Lewis and Stevens (2012).

Although the reduced-form NKPC specifications for the Rotemberg and the Calvo models can be written in the same manner, these specifications are not identical. In particular, the slope κ_i of the markup gap differs between the two models. Under the Calvo price-setting mechanism, the slope reads as

$$\kappa_C = \frac{(1-\beta\xi_C)(1-\xi_C)}{\xi_C}\frac{1}{1+(M-1)E_{\varepsilon}^{P^r}}, \text{ where} \tag{12}$$

$$E_{\varepsilon}^{P^r} = \frac{\vartheta\varepsilon}{\vartheta P^r}\frac{P^r}{\varepsilon}. \tag{13}$$

Relative to the monopolistic market structure, oligopolistic behavior changes the slope of the Calvo Phillips curve. More specifically, in addition to the nominal rigidity component $\frac{(1-\xi)(1-\beta\xi)}{\xi}$, the slope coefficient contains a real rigidity (or strategic complementarity) term, which is given by $\frac{1}{1+(M-1)E_{\varepsilon}^{P^r}}$. The variable $(M-1)$ denotes firms' desired net price markup in steady state. The variable $E_{\varepsilon}^{P^r}$ is the steady state elasticity of the demand elasticity with respect to relative price, the so-called 'curvature' of kinked demand curves. An increase in the curvature of demand produces real rigidities in price-setting behavior and decreases the slope of the Phillips curve. To understand these relationships, consider a negative gap between the actual and desired markup. If markets are monopolistic, then the price-elasticity of demand is constant, i.e., $E_{\varepsilon}^{P^r} = 0$. Under these conditions, if a firm were free to alter its price, it would raise its prices. Conversely, in the case of oligopolistic markets, strategic pricing competition entails quasi kinked demand curves, implying that an increase in the firm's price above the price levels of its competitors increases the demand elasticity for the firm's product, i.e., $E_{\varepsilon}^{P^r} > 0$. Therefore, the firm will optimally choose a smaller price increase than it would have selected in the monopolistic environment (for which $E_{\varepsilon}^{P^r} = 0$) because the firm wishes to avoid a loss of market share. Consequently, relative prices are rigid within oligopolistic markets. The larger the curvature of demand, the greater the fears of losing market share and the more rigid prices are.

In the Rotemberg model the slope of the oligopolistic NKPC is given by

$$\kappa_R = \frac{\varepsilon-1}{\xi_R}, \tag{14}$$

which is identical to the slope coefficient that is obtained under monopolistic competition. In contrast to the Calvo model, which implies relative-price dispersion among firms, the Rotemberg model is consistent with a symmetric equilibrium. Thus, relative prices are equal across firms. This result eliminates the oligopolists' concern about market share and consequently eliminates the real rigidity in price-setting behavior that is observed in the Calvo price-setting model. As a result, the slope of the Rotemberg NKPC does not depend on whether markets are monopolistic or oligopolistic competitive. Price flexibility increases (i.e., the slope κ_R of the Rotemberg NKPC steepens) as the degree of nominal price rigidity ξ_R decreases and as the demand elasticity ε increases. The intuitive reasoning underlying the latter result is as follows. As the price-elasticity of demand increases and the economy moves closer to perfect competition, the size of optimal price adjustment falls. Then, under the assumption of a quadratic cost of price adjustment, see equation (10), price adjustments become relatively cheaper which promotes greater price flexibility.

3 Competition and the Oligopolistic NKPC Slope

I now raise N, the steady state number of competitors in the market, to investigate how a structural increase in the degree of oligopolistic competition affects the slope of the oligopolistic NKPC. Within a general equilibrium framework, the steady state number of firms depends on the structural parameters of the model. In particular, this number of firms depends on the entry cost parameters that serve to bound the number of operating firms, such as fixed production costs ϕ.[10] Therefore, a one-off increase in N can be interpreted in terms of deregulatory measures that lower the entry cost for firms.

A structural increase in competition (i.e., a greater value of N) raises the price-elasticity of demand ε, as stated in equation (5). This result is in accordance with the general intuition that as more goods are traded in a market, demand is likely to decrease by a greater amount in response to small price increases. The upward shift in the demand elasticity, in turn, affects the slope coefficients of both the Rotemberg and Calvo Phillip curves (i.e., κ_R and κ_C, respectively).

In the Rotemberg pricing model, an increase in the price-elasticity of demand ε has a direct and positive effect on the NKPC slope κ_R, as specified by equation (14). Therefore, higher competition raises the slope of the Rotemberg NKPC through the positive effects that is produces on ε. Rotemberg's model implies that the cost of price adjustment decreases as the optimal size of the price adjustment is reduced. A structural increase in competition lowers desired price markups and depresses the size of optimal price adjustments. Therefore, in this pricing model, higher competition promotes greater price flexibility and increases the slope of the Phillips curve.

[10] In Appendix B, I close the model by adding households, monetary policy and firm entry/exit behavior. Entry is considered to be frictionless, as discussed by Floetotto and Jaimovich (2008); i.e., there are no startup costs prior to entry, and firms enter instantaneously in each period until all profit opportunities are exploited. In this instance, the number of steady state firms is determined by the share of fixed costs in production, i.e., by $\frac{\phi}{Y}$. See Appendix B for details.

In the Calvo model, an increase in the price-elasticity of demand ε affects the oligopolistic NKPC slope κ_C by altering the real rigidity term $\frac{1}{1+(M-1)E_{\varepsilon}^{P^r}}$. By the definition of the desired markup ($M_t \equiv \varepsilon_t / (\varepsilon_t - 1)$) and by the expression for the demand elasticity (see equation (5)), the net markup $(M-1)$ and the curvature of demand $E_{\varepsilon}^{P^r}$, respectively, read as

$$(M-1) = \frac{1}{\varepsilon - 1}, \tag{15}$$

$$E_{\varepsilon}^{P^r} = \frac{\partial \log(\varepsilon)}{\partial \log(P^r)} = \frac{\tau}{1-\tau}\left(\frac{\frac{1}{1-\tau} - \varepsilon}{\varepsilon}\right), \tag{16}$$

which both depend on the price-elasticity of demand ε. Taking the derivatives of equations (15) and (16) with respect to ε yields the following expressions,

$$\frac{\partial E_M^{\varepsilon}}{\partial \varepsilon} = -\frac{1}{(\varepsilon - 1)^2} < 0, \tag{17}$$

$$\frac{\partial E_{\varepsilon}^{P^r}}{\partial \varepsilon} = -\frac{\tau}{(1-\tau)^2 \varepsilon^2} < 0, \tag{18}$$

which reveal that both the markup and the curvature of demand decrease as ε increases. Consequently, an increase in the price-elasticity of demand lowers real rigidities in price setting and increases the Phillips curve slope κ_C. Because ε is an increasing function of N, it follows that higher competition raises the slope of the Calvo NKPC. Intuitively, higher competition reduces the relative importance of each oligopolistic competitor in the aggregate market. Therefore, as competition increases, the importance of strategic interactions in firms' pricing decisions declines, and the sensitivity of a firm's market share to its own relative price decreases (i.e., the curvature of demand $E_{\varepsilon}^{P^r}$ decreases). This result implies that as competition increases, firms are less concerned about aligning their price level to average prices, resulting in greater price flexibility. In brief, stronger competition lowers the risk of losing market share and decreases real price rigidities.

We conclude that a structural increase in the degree of oligopolistic competition unambiguously increases the slope of the NKPC in both the Rotemberg and the Calvo pricing models. This contradicts the argument that the observed increases in competition that have recently been induced by deregulation and globalization have reduced the slope of the Phillips curve.

A few remarks, however, are worthwhile making. First, the policy relevant trade-off is that between inflation and the output gap, rather than that between inflation and the markup gap. Therefore, to assess the impact of increased competition on the short-run inflation dynamics, we should account for not only the effects on the pass-through from the markup gap on inflation (as captured by the slope κ_i of equation (11)), but also the effects on the relationship between the markup gap and output. In Appendix B, I close the model by adding households and firm entry behavior, and I derive the elasticity of inflation with respect to the natural output gap. This exercise indicates that a structural increase in competition produces a greater positive effect on the inflation pass-through of output than on the inflation pass-through of marginal costs. This result strengthens the conclusion that higher competition raises the slope of the Phillips curve. Second, in terms of globalization, my analysis focuses solely on the effects that run through an increase in competition that is generated by an increase in the number of goods traded in the economy. A complete analysis of all of the effects of a more integrated economy on short run inflation dynamics should extend beyond the current analysis and incorporate other dimensions of globalization, such as the degree of openness of the economy (see, e.g., Benigno and Faia, 2010 and Guerrieri et al., 2010). Therefore, the results of this paper should not be interpreted to imply that globalization has no effects on the flattening of the Phillips curve. However, if such an effect exists, it is very unlikely that it propagates through increases in goods market competition.

4 Conclusion

This paper employs the microfounded new-Keynesian Phillips curve to examine whether stronger competition can explain the flattening of the Phillips curve that has been observed in many advanced countries over the previous two decades. To identify the effects of a structural increase in competition, we must relax the standard Dixit-Stiglitz monopolistic competition assumptions regarding market structure. Monopolistic markets are characterized by a continuum of many small firms. Within this framework, each firm supplies only a small portion of aggregate output, and each firm's actions produce a negligible impact on the market. Given these assumptions, increases in competition do not generate any significant effect on the overall economy. In this paper, instead of examining monopolistic markets, I consider an oligopolistic market, in which each firm in the market possesses increased relative importance. I demonstrate that a structural increase in the degree of oligopolistic competition unambiguously increases the slope of the Phillips curve. This finding contradicts the argument that the observed increases in competition that have been induced by deregulation and globalization have reduced the slope of the Phillips curve.

A Appendix

A model appendix with the full derivation (Appendix A) and an appendix that closes the model by adding household and firm entry behavior (Appendix B) are available at http://users.ugent.be/∼ansteven.

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