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Comovement of oil prices with US economic indicators over the business cycle: facts and explanations*

Yazid Dissou† and Lilia Karnizova‡

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† Department of Economics, University of Ottawa, 120 University Private, Ottawa, Ontario, Canada, K1N 6N5. E-mail addresses: Yazid.Dissou@uOttawa.ca,
‡ Department of Economics, University of Ottawa, 9053-120 University Private, Ottawa, Ontario, Canada, K1N 6N5. E-mail addresses: Lilia.Karnizova@uOttawa.ca.

Abstract

Empirical industry-level studies find a systematic pattern of output and price responses to variations in oil prices. This pattern depends on the energy-intensity of production and on the origin of oil price shocks. We build a multisector business cycle model that features endogenous production of oil, multiple sources of oil price movements and intersectoral input-output linkages. The model explains the observed sectoral heterogeneity in output and price responses to oil prices changes, previously emphasized by empirical studies. In addition, we show that accounting for the sectoral linkages helps amplify the predicted effects of oil price changes at the aggregate level.

Key words: *oil price; multiple sectors; business cycle; industry effects*

JEL Classification: E32, Q43, E37, D57.

Résumé

Plusieurs études empiriques ont trouvé une relation systématique entre les réactions du prix et de la production suite aux changements du prix du pétrole. Cette relation dépend de l'intensité énergétique de la production et de l'origine du choc du prix du pétrole. Nous construisons un modèle multisectoriel de cycle économique caractérisé par une production endogène du pétrole, plusieurs sources de variations de prix du pétrole, et par la présence de relations intersectorielles. Le modèle explique l'hétérogénéité observée dans les réponses de la production et des prix, suite aux variations du prix du pétrole, qui a été mentionnée dans les études empiriques. Nous montrons aussi que la prise en compte des relations interindustrielles permet d'amplifier les effets agrégés des changements du prix du pétrole.

Mots clés : *le prix du pétrole; les modèles multisectoriels; le cycle économique; les effets industriels*

Classification JEL : E32, Q43, E37, D57.

1. Introduction

This paper aims to document and explain comovement of oil prices with US economic indicators. To this end, we build a multisector dynamic stochastic general equilibrium (DSGE) model that features endogenous production of oil and multiple sources of oil price movements. In each sector, output is allowed to be used as an intermediate input or as a final good for investment or consumption. Our main objective is to assess whether the model, calibrated to the historical input-output structure of the US economy, can explain the observed comovement of oil prices with aggregate and sectoral variables.

Oil price changes have been traditionally viewed as exogenous supply shocks. Since oil is an intermediate input of production, increasing the price of this input will push production costs up and decrease output.[1] Over the last decade, however, the view of oil price shocks as a pure supply-side phenomenon has been challenged. A particular attention has been drawn to demand effects from changing patterns of consumers' and firms' expenditures on energy-sensitive products (Hamilton, 1988 and 2003), precautionary demand shocks and shocks to global aggregate demand (Kilian, 2009). The current consensus in the empirical literature is that "not all oil price shocks are alike" (Kilian, 2009, p. 1053), as oil shocks with different origins trigger distinct aggregate output and price responses in the US economy.

At the industry level, the effects of oil price shocks are even more complex. Lee and Ni (2002) show that an exogenous oil price increase reduces industrial production in most US industries. Despite the same pattern of output responses, the price responses are surprisingly different, and dependent on the oil share in total costs. In particular, following an exogenous increase in the price of oil, manufacturing prices tend to rise in oil-intensive industries, such as petroleum refinery and industrial chemicals. However, prices tend to fall in many other industries, most notably in the automobile industry. Thus, adverse oil supply shocks

[1] Jones, Leiby and Paik (2004), Barsky and Kilian (2004), Kilian (2008), Hamilton (2008) provide excellent surveys on the traditional analysis of oil price shocks.

act like supply shocks in oil-intensive industries, but like demand shocks in many others. Furthermore, output and price responses to oil price shocks at the industry level vary not only with the oil-intensity of production, but also with the origin of the shock (Fukunaga, Hirakata and Sudo, 2011).

Industry-level responses to oil price shocks are useful for understanding how these shocks are transmitted through the macroeconomy. For example, the similarity in output responses across industries, documented in a time-series analysis by Lee and Ni (2002) and Fukunaga, Hirakata and Sudo (2011), seems to suggest that an oil shock can induce an economy-wide recession. Furthermore, the similarity of output responses across the industries does not appear to support the hypothesis of Hamilton (1988) that labour reallocation is the main transmission mechanism of oil shocks at the industry level.[2]

Linn (2009) finds that input-output linkages amplify the effects of oil price shocks in the cross-sectional US data. Quantitative effects of oil price shocks through the traditional direct input cost channel are limited by the oil share in production costs (e.g. Rotemberg and Woodford, 1996). Since this share is small, a predicted theoretical impact of oil price shocks on the US economy is typically much weaker than estimates from econometric studies suggest. The input-output linkages provide additional supply and demand channels of oil shock transmission. In particular, an increase in the price of oil will push up prices of materials produced by oil-intensive industries. These higher material costs will increase production costs of downstream industries further, thereby amplifying the negative supply effects on production.[3] Demand effects on an industry can stem from a contraction of energy-intensive users of its output. In Linn's baseline econometric specification, the estimated

[2] Using the data on job creation and destruction, Davis and Haltiwanger (2001) find that oil price shocks do have important reallocation consequences. The results of Lee and Ni (2002) and Fukunaga, Hirakata and Sudo (2011) do not exclude the possible importance of labour reallocation at the higher level of disaggregation.

[3] For example, production of paper is energy-intensive. An oil price increase will increase the price of paper. The higher price of paper will in turn raise the production costs and lower output in the publishing industry that uses paper.

impact of oil price increases on value-added is "about four times larger than the average energy cost share" (p. 588).

Overall, empirical research provides compelling arguments for analyzing not only supply, but also demand effects of oil price changes. Industry-level studies argue that "the use of industry-level data in addition to aggregate data is crucial in revealing the effects of oil price shocks" (Lee and Ni, 2002, p. 825). Yet, there has been no evaluation to what extent the pattern of industry responses to oil price shocks is consistent with optimizing behaviour of rational agents. Our study aims at filling this gap.

There are two main contributions in the paper. First, a multisector business cycle model, calibrated to the input-output structure of the US economy, explains the observed sectoral heterogeneity in output and price responses to oil prices changes, emphasized by empirical studies. Second, the intersectoral linkages help amplify the predicted effects of oil price changes at the aggregate level. These results would be of limited value, however, if the model had grossly counterfactual predictions for traditional business cycle statistics. We show that this is not the case. The predicted statistics for volatility and comovement with aggregate output are comparable with those of other business cycle models.

In our model, oil is one of the production sectors. The price and the supply of oil vary in response to sector-specific productivity shocks. This modelling approach allows us to evaluate comovement of economic variables with the price of oil, conditional on different shocks. By contrast, a traditional assumption of the oil price exogeneity does not differentiate between fundamental sources of oil price movements. Theoretical studies that adopt this assumption, such as Kim and Loungani (1992), Rotemberg and Woodford (1996), Finn (2000), Blanchard and Gali (2007), are unable to address the fact, documented by empirical studies, that not oil price shocks are alike.

Several recent studies endogenize oil prices and production, and incorporate multiple causes of oil price movements. They demonstrate that these modelling strategies can significantly change model predictions. For example, relaxing the assumption of the oil price exogeneity in the model of Leduc and Sill (2004) yields a different prescription for the optimal monetary policy (Nakov and Pescatori, 2010). Multiple origins of oil price shocks can help explain a weak empirical relation between the price of oil and the US trade balance (Bodenstein, Erceg and Guerrieri, 2011).[4] The existing studies, however, abstract from the realistic sectoral heterogeneity and input-output linkages.

Computable general equilibrium (CGE) models are renown for a rich sectoral characterization of the economy. However, CGE models usually abstract from intertemporal saving and consumption decisions and from endogenous variation in aggregate employment (e.g. Hanson, Robinson and Schluter, 1993). Even more macro-oriented models, such as the G-Cubed model of McKibbin and Wilcoxen (1999), are set in a deterministic environment. They are silent about the importance of oil price shocks over the business cycle. CGE modelers often analyze sectoral effects of a single realization of an oil price shock. Yet, to the best of our knowledge, no attempt has been made to relate predictions of CGE models to empirical patterns of industry responses to oil price shocks.

Our multisector model is a real business cycle model with sectoral productivity shocks. Horvath (2000) and Kim and Kim (2006) find that such models can help explain comovement of industry inputs and outputs over the business cycle. The novelty of our work lies in isolating oil and energy inputs from other intermediate inputs. This innovation allows us to study the predicted comovement of aggregate and sectoral variables with the price of oil. We are not aware of another paper that evaluates the sectoral impacts of oil shocks in a DSGE framework.

We adopt a closed economy specification, in line with Kim and Loungani (1992), Rotemberg and Woodford (1996) and Finn (2000). While the US is a net importer of crude oil, most households and firms do not buy crude oil directly. Instead, they purchase refined

[4] Other studies with endogenous oil prices include Leduc and Sill (2007), Balke, Brown and Yücel (2010), Arora and Gomis-Porqueras (2011), Unalmis, Unalmis and Unsal (2012) and Peersman and Stevens (2013).

petroleum products, processed domestically. The large differences between the world price of crude oil and US gasoline prices following hurricanes Rita and Katrina in 2005 indicate that production shocks to US oil refineries could be an important source of energy cost shocks faced by households and firms.[5] In our model, the price and the production of oil are determined domestically. Our empirical series for the price oil is constructed from the industry-level US data. This series is responsive to shocks originated within the US economy, similar to its theoretical counterpart.

In this paper, we want to highlight supply and demand effects of oil price changes in the simplest setting. We assume perfect competition in production of all goods, including oil. We intentionally abstract from several features that have been found helpful for understanding the effects of oil-related shocks: monopolistic competition (Rotemberg and Woodford, 1996; Nakov and Pescatori, 2010), variable capacity utilization (Finn, 2000), production externalities (Aguiar-Conraria and Wen, 2007), oil inventories[6] and speculative behaviour of investors (Kilian and Murphy, 2010; Peersman and Stevens, 2013; Unalmis et al. 2012). In addition, we abstract from monetary policy and nominal rigidities. We view our real business cycle model with perfect competition as a useful benchmark for exploring the role of input-output linkages in explaining the observed patterns of comovement of the price of oil with aggregate and sectoral variables.

More generally, our paper contributes to a growing body of research that emphasizes production linkages across industries. For example, industry interactions help explain industry comovement of output and inputs,[7] cross-country correlations of output and consumption (Ambler, Cardia and Zimmermann, 2002), and the propagation of monetary policy shocks

[5]Despite a decline in crude oil prices, gasoline prices skyrocketed after the hurricanes because refineries in the Gulf area were shut down. According to Edelstein and Kilian (2007) and (2009), these spikes in gasoline prices led to the largest decline in purchasing power that US households experienced between 1970 and 2006.

[6]While we do not model inventories explicitly, we do allow oil to be used for investment. In the annual data, less than 0.05 percent of all oil is used for investment.

[7]Long and Plosser (1983), Hornstein and Praschnik (1997), Horvath (2000) and Kim and Kim (2006).

(Bouakez, Cardia and Ruge-Murcia, 2009). Accounting for sectoral interactions overturns the famous result of Gali (1999) that aggregate hours fall in response to a positive technology shock (Holly and Petrella, 2012). Input-output linkages provide a mechanism to amplify the effects of sectoral productivity shocks (Long and Plosser, 1983 and Horvath, 2000) and monetary policy shocks (Bouakez, Cardia and Ruge-Murcia, 2009). They magnify the effects of factor misallocations on GDP in a growth model of Jones (2011). Acemoglu et al. (2012) show analytically how industry interactions can overcome a diversification argument of Lucas (1977) and the irrelevance theorems of Dupor (1999).[8] Econometric results of Shea (2002), Conley and Dupor (2003), Foerster, Sarte and Watson (2011), Holly and Petrella (2012) suggest that input-output linkages play a prominent role in explaining aggregate volatility.

The rest of the paper is organized as follows. Section 2. establishes business cycle facts related to oil prices that our theoretical model seeks to explain. Section 3. describes the model and its solution. Section 4. focuses on quantitative predictions for business cycle statistics. Section 5. compares the observed and predicted patterns of sectoral output and price responses, conditional on different shocks. Section 6. highlights the role of intersectoral interactions in explaining the results. Section 7. concludes.

2. Business cycle facts related to oil prices

This section describes five business cycle facts that our theoretical model will try to explain. We first quantify the degree of comovement of oil prices with macroeconomic aggregates. We then expand the analysis to sectoral data and document heterogeneity in comovement patterns across the US sectors. We draw on the existing evidence to argue that intersectoral linkages can amplify the effects of oil price changes. Before presenting the facts, we describe our data and discuss our measure of oil prices.

[8] According to Lucas and Dupor, independent sectoral shocks will tend to average out and, by the law of large numbers, have negligible aggregate effects.

2.1. Data sources

The dataset of Jorgenson (2007), described in Jorgenson, Gollop and Fraumeni (1987), provides annual series for industry prices and quantities for gross output, primary and intermediate inputs. The dataset breaks the entire US economy into 35 industries at roughly the 2-digit SIC level from 1960 to 2005.[9] We aggregate industry data into economy-wide aggregates of value added, labour input and labour input cost (wage rate). We also compute empirical analogues of the theoretical sectors. The aggregation procedure follows Jorgenson, Gollop and Fraumeni (1987) and Horvath (2000).

Appendix A reports our aggregation of the US industries into five sectors. The OIL sector includes petroleum refining, oil and gas extraction and gas utilities. Electricity and coal industries comprise the other energy sector, OEN. Jointly, output of the energy sectors defines the energy input in the Jorgenson's dataset. An industry is classified as a service industry using the characterization of the Bureau of Economic Analysis (BEA). We use a list of energy-intensive industries from the US Department of Energy to form the energy-intensive goods producing sector EIN.[10] The remaining 15 industries are combined into the non-energy intensive goods producing sector NEIN.

Our measures of aggregate consumption and investment are real personal consumption expenditures (PCE) and real gross private domestic investment from the BEA. We use the BEA's price index for PCE to express prices and labour input costs in real terms.

Oil price measure. The price of oil is the output price index for the OIL sector, deflated by the BEA's price index for PCE. The series is plotted on Figure 1. For comparison, Figure 1 also plots the annual average price of West Texas Intermediate crude oil from Hamilton (2009),[11] deflated by the BEA's price index for PCE. The two oil price indices are closely related: the correlation coefficient between their growth rates is 0.88. Yet, there

[9] The data set is available at http://scholar.harvard.edu/jorgenson/data.
[10] See http://www1.eere.energy.gov/manufacturing/resources/industries.html.
[11] The nominal price is from http://dss.ucsd.edu/~jhamilto/software.htm.

are significant differences in terms of their volatility.

Our oil price index has two advantages relative to the price of crude oil. First, most households and firms buy refined petroleum products rather than crude oil. Consequently, our oil price index represents better energy costs experienced by US firms and households than the price of crude oil. The decisions of these agents determine the price of oil in our model. Second, our oil price index reflects US domestic shocks at the oil refining stage, which may not affect the price of crude oil. The lower variability of our price index relative to the price of crude oil also suggests that some shocks to crude oil prices may have been absorbed at the refining stage, and may have not been passed onto user prices of petroleum products.

2.2. Comovement with the price of oil

To characterize the comovement of the price of oil with different variables, we compute unconditional dynamic correlations.[12] Such reduced form approach has the advantage of being agnostic about the exogeneity of oil price movements or their precise origin. We complement our statistics with the evidence from more structural models.

Oil price volatility. Figure 1 shows that oil prices remained stable through the first quarter of the sample. This stability can be largely attributed to US institutional settings. Hamilton (1985) documents that the nominal US price of oil in the pre-OPEC period was heavily influenced by state regulatory commissions' policy. In particular, the Texas Railroad Commission tended to offset demand fluctuations by regulatory adjustments in the oil production, unless there was a large exogenous shock. Since the oil price is freely determined by the market forces in our model and not subject to regulation, we focus on the period from 1973 to 2005 to establish empirical facts. The bottom panel of Figure 1 plots the cyclical components of the price of oil and aggregate value added. The figure illustrates that the

[12] Prior to computing the statistics, we logged and detrended all empirical series using the Hodrick-Prescott filter with a smoothing parameter 100 using the entire data period from 1960 to 2005.

price of oil is highly volatile (formal statistics are reported in Table 3).

Oil price and aggregate output. Figure 1 also implies that the price of oil is countercyclical. The top left panel of Figure 2, which reports dynamic correlations of the price of oil with aggregate value added, makes this property more clear. In the US data, the price of oil is significantly negatively correlated with contemporaneous and one year lead value of aggregate output. Several analysts have argued that the link between oil prices and GDP weakened some time in the early 1980s. While recognizing this possibility, we have chosen to use the longest feasible sample in computing statistics in this study.[13]

The negative short-run comovement of the oil price with aggregate output echoes the results from more structural empirical studies. For example, Hamilton (1983, 2008) demonstrates that all but one post World War II recessions in the US were preceded by an oil price increase. Jones, Leiby and Paik (2004) report that the best empirical estimates of an oil price-output elasticity, defined as the percent change in output divided by the percent change in the price of oil, are between -0.05 and -0.06. Structural vector autoregression (SVAR) models that impose specific identifying assumptions about exogenous oil price shocks find that an adverse oil supply shock leads to a significant decline in GDP (e.g. Burbidge and Harrison, 1984; Kilian, 2009; Wu and Cavallo, 2012).

Oil price and aggregate variables. The top right panel of Figure 2 reports negative short-run correlations of the price of oil with aggregate consumption, investment and labour input. There is a strong negative relation between the price of oil and the real labour input cost. In the context of a SVAR, Rotemberg and Woodford (1996) find that an exogenous oil price increase leads to a sharp decline in both output and real wages. They also show that is it hard to explain a simultaneous decline in both variables using standard models. Consequently, the negative comovement between the price of oil and the real wage provides

[13] A debate on instability of oil price-GDP and its possible causes is still ongoing. The reader is referred to the surveys by Jones, Leiby and Paik (2004), Hamilton (2003), Kilian (2008) and Lescaroux (2011) for a discussion.

an important evaluation criteria for our theoretical model.

Oil price and sectoral variables. Comovement of the price of oil with sectoral output and prices can indicate the strengths of supply and demand effects of oil price changes in a specific sector. The bottom row of Figure 2 plots the dynamic correlations of the price of oil with sectoral value added and output prices. The price of oil has a negative correlation with contemporaneous value added and leads sectoral output by one or two years. There is a difference across sectors in the comovement with output prices. Higher oil prices are associated with lower prices in the service sector, but with higher prices in the other sectors. The differences in the observed comovement at the sectoral level suggest that increases in oil costs may induce not only traditional supply effects (lower output, higher prices) but also demand effects (lower output, lower prices). A more formal support for this hypothesis comes from the empirical studies of Lee and Ni (2002) and Fukunaga, Hirakata and Sudo (2011).

Lee and Ni (2002) analyze industry reports published in trade journals during oil crises of 1973-74 and 1978-81. These two periods witnessed large oil price hikes, which were arguably exogenous to the US economy. Output of most of manufacturing industries plunged during both episodes. Noteworthy, the severity of output decline was not correlated with the energy intensity of production (Bohi, 1991). Automobile production was the most affected activity. Lee and Ni (2002) provide concrete examples of negative supply and demand effects of oil price hikes on US industries during the oil crises. These effects can be linked to input-output interactions between industries. For instance, shortages of crude oil and natural gas during both oil crises limited the production of energy-intensive industrial chemicals by creating problems with petroleum feedstocks. However, the plummeted consumer demand for large cars was the main trigger for the devastating impact on the US automobile industry. The negative impact on the car manufacturers spread over the other industries. For instance, *Industry Week*, *Ward's Auto World,* and *Chemical Week* attributed a fall in production of steel and aluminum to the automobile industry's reduced demand for these products.

Lee and Ni (2002) also document a systematic pattern of industry responses to an adverse oil supply shock in SVAR models. While depressing production in all industries, such shock tends to increase prices in more oil-intensive industries and decrease prices in less oil-intensive industries. It follows that the negative impacts of oil supply shocks on output are not identical in all industries. In oil-intensive industries, like petroleum refineries and chemical industries, oil supply shocks reduce output mainly through their negative impact on production cost. In contrast, in most of the other industries, like in the automobile industry, oil supply shocks reduce output mainly through their negative impact on demand for industry products. Overall, the dominant type of effects of oil supply shocks on US industries depends on the oil-intensity of production.

Fukunaga, Hirakata and Sudo (2011) establish that industry responses to oil price shocks depend not only on the oil intensity of production, but also on the origin of the oil price change. They incorporate the global oil market of Kilian (2009) into a SVAR with US industry data. The global oil market, and hence the price of oil, are subject to three types of shocks: oil supply shocks, oil-specific demand shocks, and global demand shocks. These shocks have different effects on the US economy. The results of Fukunaga, Hirakata and Sudo (2011) for oil supply shocks largely confirm the findings of Lee and Ni (2002) at both aggregate and industry levels. However, non-oil supply shocks to the global oil market generate different patterns of responses. An unexpected increase in oil specific demand acts mainly as a supply shock in most manufacturing industries. That is, industry output falls while its price rises, when an oil price increase is due to an increase in the demand for oil. However, an increase in global demand acts mainly as a positive demand shock in all industries. It leads to higher output and prices.

2.3. Amplification of oil price shocks through input-output linkages

Empirical studies find that the quantitative impact of oil price changes on the US economy are larger than the oil shares in production costs would imply. There is no commonly acceptable explanation for why oil price changes can have a large effect. Input-output interactions across industries provide one possibility.

Linn (2009) evaluates the role of input-output linkages in amplifying the effects of oil price shocks using plant data for the 427 US manufacturing industries from the Census of Manufacturers. In his sample, the average oil price elasticity of value added is -0.066, which is more than four times larger than the sample average energy cost share of 0.015. Linn finds that the interindustry supply effect explain about one half of the total effect.[14]

2.4. Summary of the facts

The five business cycle facts that our model seeks to explain are as follows:

(1) The price of oil is highly volatile and countercyclical.

(2) The price of oil is negatively correlated with aggregate consumption, investment, labour input and labour input costs.

(3) The price of oil negatively correlated with sectoral value added. The price of oil is negatively correlated with output price in the service sector, but is positively correlated with output prices in the other sectors.

(4) A pattern of comovement of the price of oil with sectoral output and prices depends on the oil-intensity of production and on the origin of the oil price change.

(5) Input-output linkages amplify the effects of oil price shocks on US industries.

The first two facts have received some attention in the theoretical literature. However, we are not aware of a DSGE model that studies the comovement of the price of oil with sectoral variables. In contrast, the empirical evidence "underscores the importance of look-

[14] Linn (2009) finds small demand effects in cross-sectional data. The demand effects appear to be much more important in SVARs models.

ing beyond economy-wide aggregate data in searching for the transmission mechanisms of macroeconomic shocks" (Lee and Ni, 2002, p. 850). It draws attention to demand effects of oil prices shocks on US industries, in addition to the traditional supply effects. Motivated by the empirical evidence, we construct a multisector DSGE model that incorporates both demand and supply effects of oil price changes.

3. The model

We consider a closed-economy model with heterogeneous production sectors, identical households and a government. A key feature of the model is the endogenous determination of the oil supply and the price of oil in a setting characterized by realistic sectoral linkages. Fluctuations in the price of oil and the oil production stem from sector-specific productivity shocks.

3.1. Model description

Production sectors. The economy is disaggregated into $N = 5$ production sectors, indexed by j, each producing a distinct good that can be used for consumption, investment and intermediate purposes. The sectors considered are oil and gas (OIL), other energy (OEN), energy intensive (EIN), non-energy intensive (NEIN) and services (SERV).[15] We believe that this disaggregation is sufficiently large to capture the empirical regularities in the industry-level data. At the same time, the number of sectors is small enough to provide insights on the transmission of oil price changes through the economy.

All markets are perfectly competitive. The type of the production function is assumed to be the same across the sectors. However, the parameters of the production function are sector-specific and calibrated to the actual IO structure of the US economy. A representative firm in sector j produces Y_{jt} units of good j in period t, according to a constant returns to

[15] The other energy good includes coal and electricity.

scale technology, combining capital K_{jt}, labour L_{jt}, the index of energy inputs E_{jt} and the index of non-energy inputs M_{jt}: $Y_{jt} = F_j (Z_{jt}, K_{jt}, L_{jt}, E_{jt}, M_{jt})$. Production is subject to a stochastic productivity shock, Z_{jt}, described further below.

By convention, we will denote by M_{jt}^s the intermediate good produced in sector s that is used by sector j. The energy index E_{jt}, is a constant elasticity of substitution (CES) aggregate of the oil input M_{jt}^{oil} and other energy inputs M_{jt}^{oen}, as shown in (1), with the elasticity of substitution $\sigma_e > 0$. The choice of the CES function is meant to capture the limited substitutability between oil and other energy, such as electricity, documented in a meta-analysis survey by Stern (2012). The index M_{jt} for sector j, in (2), is a CES aggregate of non-energy intermediate inputs M_{jt}^{ein}, M_{jt}^{nein} and M_{jt}^{serv}, with the elasticity of substitution $\sigma_m > 0$. The factor share parameters $\varphi_j \in (0,1)$, $\theta_j^s \in (0,1)$ and $\theta_j^{ein} + \theta_j^{nein} + \theta_j^{serv} = 1$. The scale parameters $A_j^e > 0$ and $A_j^m > 0$.

$$E_{jt} = A_j^e[\varphi_j \left(M_{jt}^{oil}\right)^{(\sigma_e-1)/\sigma_e} + \left(1-\varphi_j\right)(M_{jt}^{oen})^{(\sigma_e-1)/\sigma_e}]^{\sigma_e/(\sigma_e-1)}, \quad (1)$$

$$M_{jt} = A_j^m[\sum_{s\in\{ein,nein,serv\}} \theta_j^s \left(M_{jt}^s\right)^{(\sigma_m-1)/\sigma_m}]^{\sigma_m/(\sigma_m-1)}. \quad (2)$$

Based on the evidence presented in Basu (1996, p. 733-734) for the US manufacturing, we assume that production function $F_j(\cdot)$ is a Leontief composite of a KLE_{jt} aggregate of capital, labour, energy and non-energy intermediate inputs M_{jt}:

$$Y_{jt} = \min\left\{\frac{1}{a_j^{kle}} KLE_{jt}, \frac{1}{a_j^m} M_{jt}\right\}, a_j^{kle} > 0, a_j^m > 0. \quad (3)$$

There is no consensus in the literature on the nature of interactions between capital, labour and energy in production, or on the degree of substitutability between these factors.[16] We assume unitary elasticities of substitution, and use a Cobb–Douglas function of capital,

[16] For example, Kim and Loungani (1992), Leduc and Sill (2004), Carlstrom and Fuerst (2006) and Bodenstein and Guerrieri (2011) combine energy with capital and labour inputs in differently nested CES functions. Van der Werf (2008) discusses recent empirical estimates of the substitution elasticities.

labour and energy, with the capital and labour shares $\alpha_{Kj}, \alpha_{Lj} \in (0, 1)$,

$$KLE_{jt} = KLE(Z_{jt}, K_{jt}, L_{jt}, E_{jt}) = Z_{jt} K_{jt}^{\alpha_{Kj}} L_{jt}^{\alpha_{Lj}} E_{jt}^{1-\alpha_{Kj}-\alpha_{Lj}}. \tag{4}$$

The productivity shock $Z_{jt} = \bar{Z}_j z_{jt}$, with a scale factor $\bar{Z}_j > 0$ and a stochastic component z_{jt}.[17] Similar to Horvath (2000) and Kim and Kim (2006), we assume that z_{jt} in sector j follows a stochastic process

$$\ln z_{jt} = \rho_j \ln z_{j,t-1} + \varepsilon_{jt}, \;\; \rho_j \in (0, 1), \tag{5}$$

where ε_{jt} is serially uncorrelated and normally distributed random variable with zero mean and $E\left(\varepsilon_t \varepsilon_t'\right) = \Omega$. The variance-covariance matrix Ω is not necessarily diagonal, as sector-specific productivity impulses ε_{jt} can be contemporaneously correlated. Such correlations could arise because of possible similarities in technological processes or government regulations simultaneously affecting several sectors. They may also capture the effects of aggregate factors, which are left outside of our model. Note that, as gross output Y_{jt} is produced using a fixed proportion of KLE_{jt}, the dynamics of the TFP shock to gross output would be similar to that of the productivity shock Z_{jt}.

We assume that investment decisions are made by the households, who own the capital stock and rent it out to firms. It follows that the representative firm solves a static optimization problem. The representative firm rents capital at the rental rate R_t, hires sector-specific labour L_{jt} at the wage rate w_{jt} and buys intermediate inputs at the user price p_{st} for good s. All intermediate goods are delivered within the period. In every period t, the firm chooses the quantity of production factors to maximize its profits, defined by $P_{jt}Y_{jt} - R_t K_{jt} - w_{jt} L_{jt} - \sum_{s=1}^{N} p_{st} M_{jt}^{s}$. The producer price P_{jt} for good j differs from the user price p_{jt} because of the producer tax $\tau_j \in (0, 1)$: $P_{jt} = (1 - \tau_j)\, p_{jt}$.

[17] Even though we abstract from productivity growth, our model can be interpreted as a stationary (de-trended) representation of another model that includes sector-specific productivity trends.

Profit maximization requires that each factor is employed up to the point where its marginal product is equal to its price. In a competitive framework, the output price is equal to the marginal cost. The latter, in turn, is negatively related to the sectoral productivity shock Z_{jt} and positively related to intermediate input prices. In particular, an increase in the price of oil will increase the marginal cost in all other sectors. Appendix B provides the expressions for input demands and prices.

Households. The representative household maximizes the expected utility

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\ln C_t + \chi \ln \left(1 - H_t\right)\right], \ \beta \in (0,1), \ \chi > 0, \tag{6}$$

where β is the discount factor. Aggregate consumption C_t is a Cobb-Douglas aggregate over the individual goods c_{jt}: $C_t = A_c \prod_{j \in N} (c_{jt})^{\xi_j}$, $A_c > 0$, $\xi_j \in (0,1)$, $\sum_{j \in N} \xi_j = 1$.[18] The household is endowed with one unit of time in each period t, which is allocated between leisure and work. As in Horvath (2000), we assume that the representative household has preference for diversity of labour, in order to capture sector specificity of labour and cross-sectional heterogeneity of wages within the representative agent framework. The index of aggregate hours H_t is a constant elasticity of transformation aggregate of hours h_{jt} supplied to each sector j, with the elasticity $\zeta > 0$: $H_t = A_h [\sum_{j=1}^{N} \eta_j h_{jt}^{(\zeta+1)/\zeta}]^{\zeta/(\zeta+1)}$, $A_h > 0$, $\eta_j \in (0,1)$, $\sum_{j=1}^{N} \eta_j = 1$. A desirable feature of a limited substitutability of labour across sectors is that it helps generate employment and output comovement in multisector models with divisible labour (Kim and Kim, 2006).

The household makes investment X_t to augment the stock of capital K_t according to

$$K_{t+1} = (1 - \delta) K_t + X_t, \ t \geq 0. \tag{7}$$

[18] The scale parameter A_c as well as the parameters A_h and A_x defined below and the scale parameters in the production functions are included in the aggregators to normalize the index prices to unity in the steady state.

Here $\delta \in (0,1)$ is the rate of capital depreciation. The composite investment good X_t is a Cobb-Douglas aggregate of individual goods x_{jt}, used for investment purpose, $X_t = A_x \prod_{j \in N_x} (x_{jt})^{\gamma_j}, A_x > 0, \gamma_j \in (0,1), \sum_{j \in N_x} \gamma_j = 1$. When good j is not used for investment, it does not appear in the investment aggregator.[19]

The household receives wage and capital incomes, pays labour and capital income taxes, with the tax rates $\tau_h, \tau_k \in (0,1)$, and collects government transfers T_t. The household pays the same user price p_{jt} for good j, irrespective of whether this good is bought for consumption or investment. The household's budget constraint in period t is

$$\sum_{j=1}^{N} p_{jt} c_{jt} + \sum_{j=1}^{N} p_{jt} x_{jt} = (1 - \tau_h) \sum_{j=1}^{N} w_{jt} h_{jt} + (1 - \tau_k) R_t K_t + T_t. \tag{8}$$

The optimal demands for consumption c_{jt} and investment x_{jt} are fractions of aggregate consumption and investment expenditures. Hours h_{jt}, supplied to sector j, are dependent on the sectoral wage differentials and proportional to the hours aggregator H_t. The latter is determined by the intratemporal trade-off between consumption and leisure. Finally, aggregate consumption C_t evolves according to the conventional Euler equation, which describes a trade-off between consumption and saving that must hold in all periods and states of nature. Appendix B provides the optimality conditions.

The government. The government consumes an exogenous amount $G_{jt} \geq 0$ of each good $j = 1, ..., N$ in period t. The government collects taxes on output, labour and capital incomes. We abstract from the government borrowing for simplicity, and define the government balance in every period as follows:

$$T_t = \sum_{j=1}^{N} \tau_j p_{jt} Y_{jt} + \tau_h W_t H_t + \tau_k R_t K_t - \sum_{j=1}^{N} p_{jt} G_{jt}.$$

[19] We restrict the subset of investment goods because coal and electricity are not used for investment in the US data.

The transfer T_t acts as an absorber. A positive value of T_t is considered as a rebate to households, while a negative value acts as an extra lump-sum tax.

Competitive equilibrium. In a perfectly competitive equilibrium, firms and households solve their respective maximization problems, the government respects its budget constraint and all markets clear: (i) $K_t = \sum_{j=1}^{N} K_{jt}$, (ii) $h_{jt} = L_{jt}$ $(j = 1, ..., N)$ and (iii) $Y_{jt} = c_{jt} + x_{jt} + G_{jt} + \sum_{s=1}^{N} M_{st}^{j}$ $(j = 1, ..., N)$. The goods market clearing condition takes into account the fact that output produced in each sector j can be used for household and government consumption, for investment and for intermediate use.

3.2. Solution and calibration

We apply the extended deterministic path method of Fair and Taylor (1983) to solve the model numerically, using GAMS (the General Algebraic Modeling System software). Gagnon (1990) and Taylor and Uhlig (2008) provide excellent discussions of the solution method. Heer and Maussner (2008) and Love (2010) find this method to be accurate and superior to log-linearization solutions.

We calibrate the model to the annual US data. In selecting the parameters, our goal is to match historical decompositions of sectoral output into demand and factor cost components for each sector of the model. To this end, we select the share and the scale parameters in consumption, investment, labour supply aggregators and in the production functions so that the steady state of the model reproduces all entries in Table 1. The rest of the section elaborates on our procedure.

Balanced input-output table. Table 1 summarizes a balanced historical input-output breakdown of the US economy into the five sectors. The table reflects three types of historical shares. The average shares of input costs in total costs are based on the Jorgenson's dataset for the 1960-2005 period. To be consistent with the closed economy framework, we define empirical GDP as the domestic component of output.[20] The average output use for private and public consumption and for investment, by sectors, is based on the Input-Output (IO) accounts published by the BEA. We use the annual IO accounts from 1998 to 2005 and the 2002 benchmark tables.[21] The average producer taxes are based on the value of indirect taxes in GDP in the BEA IO accounts.

We use the computed historical shares to decompose a fictional GDP of the $1,000 value. The IO table based solely on the historical shares does not provide a balanced account, in which the use of output is equal to total factor payments in every sector. We correct this problem with the bi-proportionate RAS method, commonly used in the CGE literature. The method essentially redistributes the use of intermediate inputs keeping the other entries of the IO table untouched. Schneider and Zenios (1990) discuss the rationale behind the RAS method and its mathematical properties.

Table 1 shows substantial heterogeneity across the sectors as well as important input-output linkages. The columns of Table 1 break down total costs of each sector into input costs and producer taxes. For example, the column OIL implies that the two most important intermediate inputs for the OIL sector are *oil* and *ein*. The rows 1 to 5 describe the use of sectoral output. For example, the row for *ein* implies that 90% of gross output of the energy-intensitve sector EIN is used as intermediate inputs, and only 9% of its output is used for private and public consumption. The last two rows of Table 1 report gross and value added outputs. Finally, the table implies that consumption and investment shares in aggregate value added are about 66% and 17%.

We choose the scale factors $\overline{Z}_j$, A_j^e, A_j^m, A_c, A_h and A_x so that the user prices p_j, the aggregate wage and price indices, defined in Appendix B, are equal to one in the steady state. Without affecting the solution dynamics, this normalization implies that Table 1

[20] This assumption is not very restrictive for the U.S. economy, in which net exports have been a relatively small fraction of total GDP historically.

[21] The first year of the sample is limited by the data availability.

defines not only nominal values, but also the quantities of all sectoral variables.

Production parameters. The elasticity of substitution between oil and other energy $\sigma_e = 0.825$ is the value of unweighted mean elasticity of substitution between oil and electricity estimated by Stern (2012). Similar to Horvath (2000) and Kim and Kim (2006), we set the elasticity of substitution between non-energy intermediate inputs to $\sigma_m = 1$.[22] Given the values of σ_e and σ_m, we infer from Table 1 the share parameters of oil and of non-energy intermediate inputs in (1) and (2) from cost shares of the relevant inputs in total expenditures on energy and non-energy intermediate inputs. The cost shares of capital and labour α_{Kj} and α_{Lj} are the ratios of profits and wages to the value of the KLE output in sector j. The latter is equal to the difference between gross output and the cost of non-energy intermediate inputs. We calculate the parameters of the Leontief function in (3) as the ratios of steady state values of the KLE aggregate and the index of non-energy intermediate inputs to gross output.

Table 2 reports two measures related to the oil-intensity of production. The direct share of oil in production costs is substantial in the energy sectors, but rather small in the non-energy sectors (less than three percent of production costs). Lee and Ni (2002) and Linn (2009) emphasize that the oil intensity of production is not limited to the direct cost of oil. One should also take into account the oil-intensity of intermediate inputs. The second row of Table 2 reports such intensity for each sector. This measure is defined as a weighted sum of cost shares of all intermediate inputs of a sector, where the weights are equal to their direct oil intensities. The total oil-related costs in the non-energy sectors in Table 2 are about twice as large as the direct cost of oil.

Productivity shocks. We first construct empirical residuals SR_{jt} for equation (4):

$$\ln SR_{jt} \equiv \ln KLE_{jt} - \alpha_{Kj} \ln K_{jt} - \alpha_{Lj} \ln L_{jt} - (1 - \alpha_{Kj} - \alpha_{Lj}) \ln E_{jt}. \quad (9)$$

[22] We have experimented with a Leontief aggregator ($\sigma_m = 0$), and retained the main results of the paper.

Here K_{jt}, L_{jt} and E_{jt} are the historical series for capital, labour and energy inputs in sector j. The measure of real output KLE_{jt} is the sectoral gross output less materials, computed as the Törnqvist index. The resulting series for the stochastic components of productivity shocks, $\ln z_{jt}$, is set to the cyclical component $\ln SR_{jt}$, detrended with the HP-filter. We rely on TFP series to generate multiple origins of oil price movements, despite commonly known measurement issues, associated with Solow-type residuals. We estimate the persistence coefficients ρ_j in (5) by the ordinary least squares, and use the estimated residuals for each sector to compute the covariance matrix Ω. Table 2 reports our estimates, based on the 1960-2005 period.

Preference parameters. The weights in the consumption and investment composites ξ_j and γ_j are equal to the shares of good j in the aggregate consumption and investment expenditures implied by Table 1. The elasticity of substitution between sectoral hours $\zeta = 1$, consistent with the empirical estimate of Horvath (2000). The steady state value of hours worked $H^* = 0.20$ (King and Rebelo, 1999) is achieved by the choice of the parameter χ, related to the disutility of leisure. The weights η_j are the shares of labour input in sector j in aggregate labour input. The discount factor $\beta = 0.917$, based on the profits information in Table 1. The annual depreciation rate $\delta = 0.10$.

Policy parameters. The tax rates $\tau_h = 0.32$ and $\tau_k = 0.35$ are from McGrattan and Prescott (2010). The output tax rates τ_j are the ratios of the indirect taxes to gross output in Table 1. Government consumption for each sector is set to the values in Table 1.

4. Results: business cycle implications

This section evaluates the ability of the model to explain the first three business cycle facts related to oil prices, documented in section 2.. To this end, we report unconditional second moments implied by the model and compare these moments with the corresponding empirical statistics.[23] Such approach to model evaluation is meaningful, since our calibration procedure targeted the input-structure of the US economy and did not rely on any second moments. In addition, we analyze the model performance related to traditional business cycle statistics of volatility and comovement of aggregate output.

4.1. Cyclical properties of the price of oil and aggregate output

The model generates a countercyclical and highly volatile price of oil. In Table 3, the predicted contemporaneous correlation between the price of oil and output is -0.34. The model captures almost 70% of the volatility of the price of oil and reproduces the empirical fact that the price of oil is almost five times as volatile as output. Cyclical properties of oil prices are rarely reported in theoretical studies. Arora and Gomis-Porqueras (2011) simulate and compare several prominent model specifications. Their results demonstrate that it could be surprisingly difficult to explain simultaneously the oil price volatility and its comovement with aggregate output. Sectoral interactions are the main reason why our model performs relatively well on this dimension, as shown in section 6..

Table 3 also implies that the model captures about 70% of empirical volatility of US output. This result is comparable with the predictions of one sector real business cycle models with aggregate productivity shocks (e.g. Hansen, 1995 and King and Rebelo, 1999) and multisector models with sector-specific productivity shocks, studied by Horvath (2000) and Kim and Kim (2006).

4.2. Comovement of the price of oil with aggregate and sectoral variables

Figure 3 and 4 reproduce the empirical dynamic correlations of different variables with the price of oil from Figure 2. In addition to the point estimates (the black dashed lines), these

[23] We computed theoretical moments as averages over 1,000 replications. In each replication, we simulated the economy for 100 periods and truncated the first 67 periods to eliminate the dependence on the initial (steady state) conditions. The resulting length of 33 periods is the length of our empirical sample. In the model, as in the data, we expressed all prices relative to the aggregate consumption price index.

figures report the 95% bootstrap confidence bands. The dynamic correlations predicted by the benchmark (BMRK) model are denoted by the solid black lines.

Qualitatively, the model captures well the observed comovement with the price of oil, both at the aggregate and at the sectoral levels. Most of the predicted correlation coefficients between the price of oil and aggregate output, consumption, investment, labour input and labour input cost (the real wage) are within the empirical confidence bands. The model reproduces the fact that sectoral output and the price of oil tend to be negatively correlated. Both in the model and in the data, the price of oil is contemporaneously negatively correlated with the producer price of services, but positively correlated with output prices in the other sectors.

Quantitatively, the model has several weaknesses. Most notably, the model lacks a mechanism to explain why the price of oil leads aggregate and sectoral output and labour input. All predicted peak correlations occur contemporaneously. The model falls short of capturing the strength of the price correlations in the EIN and NEIN sectors. It also overpredicts the correlation of the price of oil with gross output in the energy sectors and underpredicts the correlation with value added in the energy-intensive sector. It is worth reminding, however, that none of the dynamic correlations were used in the parameter calibration and that existing studies do not provide comparable statistics.

4.3. Volatility and comovement with aggregate output

With respect to the cyclical properties of aggregate and sectoral variables, our model shares the strengths and the drawbacks of other real business cycle models driven by productivity shocks. Tables 3 and 4 report the actual and predicted statistics for volatility and comovement with aggregate output.

Aggregate variables and aggregate output. Horvath (2000) and Kim and Kim (2006) demonstrate that business cycle properties of multisector models with sector-specific productivity shocks are comparable with the predictions of one sector models with aggregate productivity shocks. Similar to those studies, our model reproduces the facts that consumption is less volatile, while investment is more volatile than output. Furthermore, it predicts strongly procyclical consumption and investment. The model matches the empirical correlation between output and labour input and generates a smooth aggregate wage. Similar to other models, our model has three counterfactual predictions: excessively smooth consumption, excessively smooth labour input, and strongly procyclical real wage. We speculate that higher than in the data investment volatility may be driven by the absence of capital and investment adjustment costs.

Sectoral variables and aggregate output. A positive comovement of output across sectors is a prominent feature of the business cycle (Burns and Mitchell, 1946; Lucas, 1977). Table 4 shows that production in all five sectors of the US economy is highly procyclical. Our model reproduces this fact. Furthermore, the predicted correlations of aggregate output with sectoral value added for the OIL, NEIN, and SERV sectors closely match the empirical correlations. The model reproduces the ranking and the range of output volatility. It captures from 66% to 87% of the observed volatility of sectoral value added. The model also predicts more than a six-fold difference between standard deviations of value added in the most and the least volatile OIL and SERV sectors.

Table 4 indicates that labour, capital and energy inputs are procyclical, except in the OIL sector. Explaining input comovement over the business cycle is challenging within standard models (e.g. Christiano and Fitzgerald, 1998). Input-output interactions provide a synchronization mechanism that could drive input comovement. Effectively, these interactions create production complementarities through which sector-specific shocks can trigger a chain reaction of other sectors (Horvath, 1998). Long and Plosser (1983), Hornstein and Praschnik (1997), Horvath (2000), Kim and Kim (2006) show that calibrated multisector models with sectoral productivity shocks can reproduce the extent of industry comovement of output and inputs. Hornstein and Praschnik (1997) and Kim and Kim (2006) highlight the role of limited labour mobility in explaining industry employment comovement. Our multisector model incorporates both features.

The results in Table 4 show that the model captures qualitatively, and often quantitatively, the empirical pattern of input comovement with aggregate output. It yields a relatively good match between the predicted and actual correlations for labour and energy inputs when the corresponding empirical correlations are statistically significant. In particular, the model generates strongly procyclical labour and energy inputs in the non-energy sectors, countercyclical capital in the OIL sector and procyclical capital in the OEN and SERV sectors. Similarly to Hornstein and Praschnik (1997) and Kim and Kim (2006), our model substantially underpredicts labour input volatilities and overpredicts correlations of labour input and aggregate output in the two energy sectors.

Relatively little is known about the predictions of business cycle models regarding the use of energy. An exception is the work of Kim and Loungani (1992) who report procylical and slightly more volatile than output use of energy in the aggregate data. They also show that the volatility of energy input in one sector business cycle model depends on the elasticity of substitution between capital and energy inputs. For the two values of the elasticities that they consider, Kim and Loungani report higher than in the data standard deviation of energy use. Aggregate use of energy is not defined explicitly in our model. At the sectoral level, the model correctly predicts that energy input is more volatile than capital and labour inputs. The only exception to that rule in the US data is the OIL sector, in which labour input is the most volatile.

4.4. Role of exogenous oil supply shocks

Oil supply shocks in our model correspond to TFP shocks in the OIL sector. To isolate the contribution of these shocks, we simulate the benchmark model with Z_{oil} series only.

The results are presented in the columns BOIL in Table 5.

Oil supply shocks are fundamental in explaining oil price volatility in the model. The simulated oil prices in the BOIL and BMRK models have a correlation coefficient of 0.99. Oil price is even slightly more volatile in the BOIL model.[24] Equations (10)-(11) show that a decline in Z_{oil} directly increases the price of oil. Yet, oil price changes also reflect the responses of households and firms to increasing energy costs. As a result, the endogenous mechanisms of the model amplify the exogenous TFP shocks. The predicted standard deviation of the price of oil of 8.89 exceeds the standard deviation of the productivity impulse in the OIL sector of 3.85 by more than two times.

Table 5 implies that oil supply shocks can account for 19% of empirical variability of aggregate output. This finding complies with existing studies. For example, energy price shocks explain from 16% to 35% of output volatility in Kim and Loungani (1992). Baumeister and Peersman (2013) estimate that oil supply shocks contribute from 15% to 20% to variance of US real GDP growth after 20 quarters in a time-varying VAR.[25]

Many economists doubt that oil supply shocks could be an important cause of output fluctuations. For example, Rebelo (2005, p. 224) writes: "Although energy prices are highly volatile, energy costs are too small as a fraction of value added for changes in energy prices to have a major impact on economic activity." Table 1 implies that the share of the OIL sector in aggregate value added is indeed very small - about 3%. Yet, the effects of oil supply shocks on output are amplified through the input-output interactions. In our model, 19% of output fluctuations originating from TFP shocks in a rather small sector of the economy seem to be a non-trivial amount. Furthermore, the BOIL version does not share a counterfactual prediction of Kim and Loungani (1992) that consumption is more volatile than output in one sector models driven by energy shocks alone. Table 5 reports

[24] In the BMRK model, other productivity shocks partially offset the effects of oil supply shocks.

[25] These authors find that oil supply shocks account from 20% to 35% of the volatility in the oil price, which is much smaller than our results suggest. It should be noted that our studies use different measures of oil prices.

that consumption is smother than output.

5. Results: sectoral heterogeneity of output and price responses

This section turns to the business cycle fact 4. We show that our theoretical model generates heterogeneity in the comovement patterns of the price of oil with sectoral output and prices, conditional on a type of productivity shocks. The sectoral TFP shocks are not direct analogues of empirical shocks to oil prices in the SVAR studies. Nevertheless, the predicted sectoral heterogeneity conforms with the observed pattern of industry responses to oil supply, oil-specific demand and global demand shocks in the SVARs.

We compute and analyze theoretical impulse responses to three types of TFP shocks. TFP shocks to oil production capture oil supply shocks. TFP shocks to production of energy-intensive goods proxy for oil-specific demand shocks. We take TFP shocks in the service sector as representing demand shocks unrelated to oil. To provide more intuition for our results, we use an example of oil supply shocks to describe how a sectoral shock is transmitted in our multisector model.

5.1. Summary of sectoral output and price responses

Figure 5 plots the impulse responses of gross output Y_j, value added VA_j and the producer price P_j,by sectors, to three experiments: negative productivity shocks in the OIL and EIN sectors (columns 1 and 2) and a positive productivity shock in the SERV sector (column 3). In each scenario, the size of a TFP shock is equal to one standard deviation, and the sign of the shock is chosen to generate an increase in the price of oil.

Figure 5 shows that output in all sectors respond to each shock in a similar way. Production falls after negative TFP shocks in the OIL and EIN sectors, but increases following a positive TFP shock in the SERV sector. However, there are differences in price responses. TFP shocks trigger demand and supply effects across the sectors. The joint behaviour of output and prices indicate which effect is dominant. A particular industry experiences an oil price increase mainly through a supply (demand) channel if its output and price move in the opposite (same) direction after the TFP shock.

To make the sectoral pattern more clear, Table 6 summarizes the signs of peak responses of output and prices. Lee and Ni (2002) and Fukunaga, Hirakata and Sudo (2011) adopt a similar approach to determine whether exogenous oil price increases are experienced as supply or demand shocks by the US manufacturing industries. Their industries include petroleum refining, six industries that enter our energy-intensive sector and seven industries enter our non-energy-intensive sector. Based on Table 7 in Lee and Ni (2002) and Table 6.4 in Fukunaga, Hirakata and Sudo (2011), we infer the dominant empirical effects for our sectors and report these dominant effects in Table 6.

Table 6 shows a perfect match between the predicted and actual dominant effects, conditional on TFP shocks in our model and exogenous oil price increases in the SVARs. A negative shock to oil production acts mainly like a supply shock in the oil intensive sectors (OIL, OEN and EIN), but mainly like a demand shock in the less oil intensive sectors NEIN and SERV. The other two productivity shocks induce different patterns of output-price responses. A TFP decline in the energy-intensitve sector has dominant supply-type effects in the OIL, EIN and NEIN sectors, but dominant demand-type effects in the OEN and SERV sectors. In contrast, a positive productivity shock in the SERV sector is experienced as a demand shock by all sectors, except for the SERV sector itself.

Table 7 reports the peak responses of the oil price and output measures for three types of productivity shocks. It also reports the ratios of these responses, or "oil price-output elasticities". Table 7 indicates that the elasticities are larger than the direct oil cost shares, reported in Table 2. Further, the results draw attention to the origin of an oil price increase. The value of the oil price-output elasticity in the case of oil supply shocks is right in the middle of the empirical range between -0.05 and -0.06 reported by Jones, Leiby and Paik

(2004). Productivity shocks to the EIN and SERV sectors induce weaker responses of the price of oil, but still significant responses of output. The implied elasticities for those experiments become much larger.

Many macroeconomic models predict oil price-output elasticities that are much lower than the empirical estimates. For example, Jones, Leiby and Paik (2004) cite the elasticities between -0.01 and -0.002, calculated from the macroeconomic models of the FRB, the IMF and the OECD. Kim and Loungani (1992), Rotemberg and Woodford (1996) and Finn (2000) demonstrate weak effects of exogenous oil price shocks on output in one sector business cycle models. All the above mentioned models abstract from the intersectoral linkages and typically limit quantitative effects of oil price shocks by the oil share in costs, which is small. The input-output linkages provide additional supply and demand channels, and amplify the effects of oil price changes.

5.2. Transmission of oil supply shocks

A TFP decline in the OIL sector represents a negative oil supply shock in our model, since it directly reduces oil production in (3). Figure 5 shows that this shock reduces output in all sectors, but generates different price responses. A detailed analysis of how oil supply shocks are transmitted in a multisector economy helps explain the results. Figure 6 gives a graphical illustration of our explanations.

A reduction in the oil supply makes the oil commodity more scarce, thereby raising the producer and user prices of oil. The higher user price of oil pushes the production costs up. All sectors experience an upward pressure on sectoral prices and a downward pressure on sectoral output. The magnitude of these negative supply effects depend largely on the oil share in production costs. The energy-intensitve sectors are affected the most by this *direct input cost channel*.

In contrast with one sector models, negative supply effects are not limited to the direct cost of oil. Higher oil and energy costs raise the prices of energy-intensive commodities. Since these commodities are used as intermediate inputs, their increased prices push up the production costs in all sectors further. As a result, the input-output linkages across the sectors amplify the supply effects of higher production costs. The strength of *the intermediate input supply channel* largely depends on the oil-intensity of the intermediate inputs, reported in Table 2.

There are several demand type effects in the model. Following a negative TFP shock, the OIL sector adjusts its demand for the intermediate inputs. There are a quantity effect and a price effect on upstream production. A fall in the oil production reduces the input demand by the OIL sector. However, an increase in the price of oil raises its sectoral demand for the intermediate inputs. When the production function is Cobb–Douglas, the quantity and the price effects cancel out (Shea, 2002). This does not happen in our model because of the Leontief production structure in (3). The OIL sector reduces its demand for the non-energy intermediate inputs M_{oil}^{ein}, M_{oil}^{nein} and M_{oil}^{serv}. This negative demand effect puts a downward pressure on output and prices in the non-energy sectors (EIN, NEIN and SERV). The OIL sector also reduces its demand for energy. However, an increase in the relative price of oil triggers a substitution of the OIL sector away from a more expensive source of energy, *oil*, to a less expensive one, *oen.* Consequently, the OEN sector experiences a positive demand effect from the OIL sector.

The *intermediate input demand channel* is not restricted to the OIL sector. As the other sectors contract in response to higher production costs, they adjust their input demand as well. Column 3 of Figure 6 indicates a decline in the use of all non-oil commodities. Ceteris paribus, the negative demand effects reduce sectoral prices and output.

Additional demand effects come from the household side. The relative demand for consumption goods, implied by (18), depends on their relative prices.[26] As oil and energy-

[26]Note that the utility function is separable in the individual commodities. Therefore, our model abstracts from possible demand complementarities.

intensive goods become more expensive, the representative household substitutes away from these goods towards others. In addition to these substitution effects, the representative household's demand is also affected by the general equilibrium effects. A reduction in wealth from lower capital and labour incomes drives down consumption expenditures. Through the intertemporal substitution mechanism, the lower return on capital induces the household to dissave, and hence to reduce its investment. As shown in Figure 6, the equilibrium use of all consumption and investment goods falls. The largest decline is observed for *oil*, the most expensive good.

A negative TFP shock in the OIL sector has important consequences on the use of primary inputs. These consequences can be seen through equations (12) and (13), which describe the sectoral demands for capital and labour. There are two opposing effects in the OIL sector. First, a decline in TFP decreases the marginal product of inputs and hence reduces the sectoral demand for capital and labour. Second, an increase in the price of oil reduces the relative input costs and exerts an upward pressure on the demand for labour and capital. In our model, the price effect dominates the TFP effect, and the OIL sector increases its demands for labour and capital. In other sectors, changes in the demand for capital and labour are mainly driven by the change in the relative input costs.

In equilibrium, the employment decisions of the firms are consistent with the household's labour supply decisions. There are two offsetting effects on the aggregate labour supply. It is positively affected by the reduction in wealth, but negatively affected by the intertemporal substitution mechanism. Preferences (6) are such that the intertemporal substitution dominates the wealth effect on labour supply, so the aggregate labour supply falls. Due to the preference for diversity of labour, the labour supply in each sector falls as well (see equation (19)). The real wages adjust to clear the sectoral labour markets. In particular, the wage increases in the OIL sector (to accommodate an increase in labour demand), but falls in the other sectors. Recall that capital is perfectly mobile and there is a single rental rate R. In equilibrium, capital flows to the OIL sector, in which the marginal product is the highest relative to the other sectors. The use of capital by the other sectors, and the aggregate stock of capital experience a temporary decline.

Overall, the equilibrium effects of the oil supply shock on prices and output in a specific sector depend on whether supply or demand effects dominate. The supply effects are particularly strong in the energy-intensive sectors (OIL, OEN, EIN). The equilibrium output prices in these sectors increase while output declines (see Figure 5). The demand effects are stronger in the NEIN and SERV sectors. The intermediate input demand channel is particularly important for these two latter sectors. While they have low energy-intensity, 66% and 26% of their output are used as intermediate inputs by other sectors. Following a negative TFP shock in the OIL sector, both prices and quantities fall in NEIN and SERV sectors, mainly through the intermediate input demand channel.

6. Discussion: role of intersectoral linkages in explaining the results

To highlight the role of the intersectoral linkages in explaining the comovement of the oil price with economic variables, we report the results for two alternative specifications. The SYMM model takes away production heterogeneity. This model is based on a fictional symmetric version of the input-output matrix, in which all total entries in Table 1 are equally distributed across the five sectors. It is important to note that we still have five sectors and five intermediate inputs. The main difference with the benchmark case is that all sectors use the same technology characterized by identical parameters and have the same shares in each component of final demand. The symmetric input-output matrix imposes a restriction that all sectors buy intermediate goods from each other in identical proportions. Each sector in the SYMM model is still subject to sector-specific productivity shocks. We keep the shocks unchanged from the benchmark specification. The DIAG model helps to isolate the impact of correlated productivity impulses. The parameter calibration of this model is the same as in the benchmark case, except the variance-covariance matrix of the productivity impulses Ω is diagonal.

6.1. Amplification of sectoral shocks

Table 5 illustrates the impact of the intersectoral linkages on the predicted volatilities. Both alternative specifications predict less volatile oil price. In fact, the predicted standard deviations of the price of oil in the SYMM and in the DIAG models are 34% and 72% of the corresponding standard deviation in the BMRK model. Our conclusions about the amplification effects of intersectoral linkages echo the findings in Linn (2009). As was stated in section 2., Linn attributed about one half of the total effect of oil price increases on industrial manufacturing output to the interindustry supply effects.

The alternative specifications have opposing effects on the volatility of macroeconomic aggregates. The symmetric production structure intensifies the firms' responsiveness to relative productivity changes across the sectors. As a result, volatility of all macroeconomic aggregates increases in the SYMM model. The predictions for investment is particularly problematic. Investment in the SYMM model become almost twice as volatile than in the US data. In contrast, the volatility of all aggregate variables declines. Thus, correlated productivity impulses reinforce the amplification mechanism of the intersectoral linkages on both quantities and prices.

6.2. Explaining comovement with the price of oil

The impact of the intersectoral linkages is the most pronounced on the comovement of the price of oil with sectoral output and prices. Figure 4 plots the dynamic correlations in the SYMM and DIAG models, represented by the dotted and dashed-dotted lines. The results make clear that the actual degree of the intersectoral linkages is required to explain the observed pattern of comovement. In particular, both alternative models predict a negative correlation of the price of oil with the output price in the NEIN sector. They also predict a positive, albeit small, correlation of the oil price with value added in that sector. The SYMM model also generates counterfactual results for the comovement of the price of oil with value added and the output price in the EIN sector, and with the output price in the OEN sector.

The predicted pattern of sectoral responses, conditional on the origin of productivity shocks, provides yet another support for modeling the realistic input-output structure in a multisector model. Table 6 demonstrates that the SYMM model that abstracts from the production heterogeneity cannot match the qualitative pattern of comovement of the price of oil with producer prices. Consequently, the SYMM model provides a wrong inference about the dominant type effects of oil supply shocks on the EIN sector, and of the oil-specific demand shocks on the OIL and NEIN sectors.

7. Concluding remarks

We examined a relation between oil prices and the US economy through the lens of a multisector business cycle model. In contrast to the previous theoretical research, we focused not only on traditional macroeconomic aggregates, but also on sectoral output and prices. We showed that the comovement patterns of sectoral output and prices with the price of oil, predicted by the theoretical model, varied with the oil-intensity of production and depended on the origin of a shock. These predicted patterns were consistent with the empirical evidence from unconditional correlations and structural econometric studies. Furthermore, the realistic intersectoral interactions amplified the effects of oil price changes. Overall, the results from our theoretical model with optimizing agents supported the conclusions of empirical industry-level studies on the importance of industry interactions for understanding the origins and effects of oil price shocks.

Our multisector model can be extended to incorporate other empirical industry-level evidence. First, industry responses to oil price shocks are distintly different from those to monetary policy shocks (Lee and Ni, 2002). Merging out approach with the monetary model of Bouakez, Cardia and Ruge-Murcia (2009) would give new insights on a long standing debate about the relative importance of monetary policy and oil price shocks. Second, industrial production at the disaggregated level reacts more strongly to price increases than to price declines.[27] This property is especially pronounced in energy-intensive industries, such as chemicals, and in industries that produce goods that are energy-intensive in use, such as transportation equipment (Herrera, Lagalo and Wada, 2011). Explaining asymmetries in a multisector model would enhance economic understanding of the transmission of oil price shocks. Finally, we restricted our analysis of the industry effects to the US economy. Limited existing evidence points to noticeable cross-country differences (Jiménez-Rodríguez, 2008 and 2011; Fukunaga, Hirakata and Sudo, 2011). Extending empirical and theoretical research on industry-level effects of oil prices shocks to other countries would be highly desirable.

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A Appendix A

This Appendix groups the 35 industries from the Jorgenson's dataset into five sectors. Numbers in parentheses are the industry numbers from the Jorgenson's dataset. The sectoral classification is explained in section I-A. Within each sector, the industries are ranked by the decreasing oil share in production costs.

Oil and gas sector OIL: (31) gas utilities, (16) petroleum refining, (4) crude oil and gas extraction. *Other energy sector* OEN: (30) electric utilities, (3) coal mining. *Energy intensive goods producing sector* EIN: (5) non-metallic mineral mining, (15) chemicals and allied products, (19) stone, clay and glass products, (2) metal mining, (13) paper and allied products, (20) primary metals, (11) lumber and wood products, (17) rubber and plastic products. *Non-energy intensive goods producing sector* NEIN: (1) agriculture, forestry, fisheries, (9) textile mill products, (12) furniture and fixtures, (18) leather and leather products, (21) fabricated metal products, (27) miscellaneous manufacturing, (7) food and kindred products, (10) apparel and other textile products, (22) non-electrical machinery, (23) electrical machinery, (14) printing and publishing, (24) motor vehicles, (25) other transportation equipment, (26) instruments, (8) tobacco manufactures. *Service sector* SERV: (28) transportation and warehousing, (35) government enterprises, (6) construction, (32) wholesale and retail trade, (34) personal and business services, (33) finance, insurance and real estate, (29) communications.

B Appendix B

We use cost minimization to solve the firm's problem, as cost minimization is equivalent to profit maximization in our model. The producer price in sector j is a weighted average of input prices and has the following expression:

$$P_{jt} = a_j^{kle} P_{jt}^{kle} + a_j^m P_{jt}^m. \tag{10}$$

$$P_{jt}^{kle} = \frac{1}{Z_{jt}} \left(R_t/\alpha_{Kj}\right)^{\alpha_{Kj}} \left(w_{jt}/\alpha_{Lj}\right)^{\alpha_{Lj}} \left[P_{jt}^e/(1-\alpha_{Kj}-\alpha_{Lj})\right]^{1-\alpha_{Kj}-\alpha_{Lj}} \tag{11}$$

The auxiliary dual price indices are defined as

$$\begin{aligned} P_{jt}^{kle} &= (1/Z_{jt}) \left(R_t/\alpha_{Kj}\right)^{\alpha_{Kj}} \left(w_{jt}/\alpha_{Lj}\right)^{\alpha_{Lj}} \left[P_{jt}^e/(1-\alpha_{Kj}-\alpha_{Lj})\right]^{1-\alpha_{Kj}-\alpha_{Lj}}, \\ P_{jt}^e &= (1/A_j^e)\left[\left(\varphi_j\right)^{\sigma_e} \left(p_{oil,t}\right)^{1-\sigma_e} + \left(1-\varphi_j\right)^{\sigma_e} \left(p_{oen,t}\right)^{1-\sigma_e} \right]^{1/(1-\sigma_e)}, \\ P_{jt}^m &= (1/A_j^m)\left[\sum_{s\in\{ein,nein,serv\}} (\theta_j^s)^{\sigma_m} \left(p_{s,t}\right)^{1-\sigma_m} \right]^{1/(1-\sigma_m)}. \end{aligned}$$

The input demands for capital, labour, energy aggregate and the five intermediate inputs are given by

$$\alpha_{K_j} KLE_{jt}/K_{jt} = R_{jt}/P_{jt}^{kle}, \tag{12}$$
$$\alpha_{L_j} KLE_{jt}/L_{jt} = w_{jt}/P_{jt}^{kle}, \tag{13}$$
$$\left(1-\alpha_{K_j}-\alpha_{L_j}\right) KLE_{jt}/E_{jt} = P_{jt}^{e}/P_{jt}^{kle}, \tag{14}$$
$$M_{jt}^{oil} = (A_j^e)^{\sigma_e-1}\left(\varphi_j\right)^{\sigma_e} E_{jt}[P_{jt}^e/p_{oil,t}]^{\sigma_e}, \tag{15}$$
$$M_{jt}^{oen} = (A_j^e)^{\sigma_e-1}\left(1-\varphi_j\right)^{\sigma_e} E_{jt}[P_{jt}^e/p_{oen,t}]^{\sigma_e}, \tag{16}$$
$$M_{jt}^{s} = (A_j^m)^{\sigma_m-1}(\theta_j^s)^{\sigma_m} M_{jt}[P_{jt}^m/p_{st}]^{\sigma_m},\ s \in \{ein, nein, serv\}, \tag{17}$$

where $KLE_{jt}= a_j^{kle}Y_{jt}$ and $M_t= a_j^{m}Y_{jt}$.

The household chooses the sequences $\{c_{jt}, h_{jt}, x_{jt}\}_{t=0}^{\infty}$ for every good $j = 1, ..., N$ to maximize the expected utility (6), subject to the budget constraints (8), the capital accumulation equation (7), the definition of consumption, hours and investment aggregate indices, a no-Ponzi game condition, and the initial stock of capital. The household demand for the good produced in sector j is

$$\begin{aligned} c_{jt} &= \xi_j \frac{P_t^c C_t}{p_{jt}} \text{ for } j \in N, \\ x_{jt} &= \gamma_j \frac{Q_t X_t}{p_{jt}} \text{ for } j \in N_x,\ x_{jt} = 0 \text{ for } j \notin N_x, \end{aligned} \tag{18}$$

where $P_t^c = (1/A_c)\,\Pi_{j\in N}\left(p_{jt}/\xi_j\right)^{\xi_j}$ and $Q_t = (1/A_x)\,\Pi_{j\in N_x}\left(p_{jt}/\gamma_j\right)^{\gamma_j}$ are the price indices for aggregate consumption and investment. Generally, $P_t^c \neq Q_t$ because the two aggregates do not necessarily have the same composition. The labour supply for sector j is given by

$$h_{jt} = \frac{1}{A_h^{1+\zeta}}\left(\frac{w_{jt}}{\eta_j W_t}\right)^{\zeta} H_t, \tag{19}$$

where $W_t = (1/A_h)[\Sigma_{j=1}^N \left(\eta_j\right)^{-\zeta}(w_{jt})^{1+\zeta}]^{1/(1+\zeta)}$ defines the aggregate wage. Consumption, investment and wage indices satisfy $\Sigma_{j=1}^N p_{jt}c_{jt} = P_t^c C_t$, $\Sigma_{j=1}^N p_{jt}x_{jt} = Q_t X_t$ and $\Sigma_{j=1}^N w_{jt}h_{jt} = W_t H_t$. Aggregate consumption C_t and hours supplied H_t satisfy two optimality conditions for $t \geq 0:$

$$\begin{aligned} \frac{\chi C_t}{1-H_t} &= (1-\tau_h)\frac{W_t}{P_t^c}, \\ \frac{1}{C_t} &= \beta E_t\left[\frac{1}{C_{t+1}}\frac{\left[(1-\tau_k)R_{t+1}+(1-\delta)Q_{t+1}\right]/P_{t+1}^c}{Q_t/P_t^c}\right]. \end{aligned}$$

Table 1: Input-output table, based on historical US averages and a GDP value of $1,000

	OIL	OEN	EIN	NEIN	SERV	c_j	x_j	G_j
oil	44.68	4.92	5.79	3.47	18.07	10.98	0.04	0.00
oen	1.28	6.10	8.48	5.71	20.19	9.91	0.00	0.00
ein	5.82	1.50	60.98	47.66	54.54	17.00	1.58	0.29
nein	1.35	1.87	15.86	197.49	112.86	100.28	60.67	8.13
serv	4.07	3.46	22.00	41.77	201.54	520.49	104.26	166.36
Wages	8.16	9.64	46.85	138.98	414.60			
Profits	19.05	17.19	27.20	58.58	194.73			
Ind. taxes	3.54	6.99	2.21	4.86	47.42			
Y_j	87.95	51.67	189.37	498.52	1063.96			
VA_j	30.75	33.82	76.26	202.42	656.75			

Notes: The table reports a decomposition of a fictional GDP value of $1,000 into factor costs and expenditure categories. The rows 1-5 describe the use of sectoral gross output as an intermediate input by other sectors and as a final good for consumption, investment and government expenditures. The rows 9-10 report measures of sectoral output. The columns break down total costs of each sector into input costs and producer taxes. The decomposition is computed by the authors based on the historical cost shares from Jorgenson's data set (1960-2005) and the Input-Output accounts from the BEA (1998-2005). Entries may not add up due to rounding. The notation correspons to that in the text, so that c_j is consumption, x_j is investment, G_j is government expenditures. Y_j and VA_j are gross and value-added output. The names in the upper (lower) case letters represent the sectors (the commodities).

Table 2: Selected production-related parameters

	OIL	OEN	EIN	NEIN	SERV	
A. Oil intensities						
	OIL	OEN	EIN	NEIN	SERV	
Direct oil intensity	0.508	0.095	0.031	0.007	0.017	
Oil intensity of intermediate inputs	0.262	0.062	0.032	0.012	0.016	
B. Parameters of productivity shocks						
	Variance-covariance matrix, Ω x 100					ρ_j
	OIL	OEN	EIN	NEIN	SERV	
OIL	14.809	0.987	0.351	2.363	-0.045	0.665
OEN	0.987	2.431	1.159	0.425	-0.111	0.421
EIN	0.351	1.159	10.287	1.513	0.325	0.487
NEIN	2.363	0.425	1.513	3.722	0.354	0.503
SERV	-0.045	-0.111	0.325	0.354	0.858	0.638

Notes: The direct oil intensity is the cost share of oil, as intermediate input, in total production costs of each sector. The oil intensity of intermediate inputs is a weighted sum of cost shares of all intermediate inputs of a sector, where the weights are equal to their direct oil intensities. The numbers are implied by Table 1. The parameters of productivity shocks are estimated by the authors based on equations (5) and (9) and sectoral US data, 1960-2005. The persistence of productivity shocks in sector j is denoted by ρ_j.

Table 3: Volatility and comovement of oil price and macroeconomic aggregates with aggregate output: benchmark model

	Standard deviation		Std rel. to output		Corr. with output	
	Data	BMRK	Data	BMRK	Data	BMRK
Oil price P_{oil}	12.94	8.82 (1.83)	4.78	4.85 (1.21)	**-0.45**	-0.34 (0.21)
Output Y	2.71	1.86 (0.31)				
Consumption C	1.87	0.98 (0.30)	0.69	0.52 (0.11)	**0.83**	0.69 (0.10)
Investment X	8.75	8.81 (1.26)	3.23	4.77 (0.38)	**0.79**	0.95 (0.02)
Labour Input H	2.78	1.12 (0.16)	1.03	0.61 (0.07)	**0.84**	0.87 (0.07)
Real wage W	1.31	1.09 (0.29)	0.48	0.58 (0.09)	0.29	0.85 (0.05)

Notes: The US series are logged and detrended using the HP-filter with the weight 100. Empirical moments are computed by the authors for the 1973-2005 sample. Boldface numbers indicate that an empirical correlation is significant at least at the five percent level of significance. Theoretical moments are average statistics over 1,000 simulated economies of 33 periods. Numbers in parentheses are standard errors. Output Y is aggregate value added constructed from sectoral value added. The notation for other variables corresponds to that in the text.

Table 4: Sectoral volatilities and comovement with aggregate output

	Data				BMRK Model			
	VA_j	L_j	K_j	E_j	VA_j	L_j	K_j	E_j
A. Contemporaneous correlation with aggregate value added								
OIL	**0.47**	-0.15	**-0.42**	-0.15	0.46	0.16	-0.32	0.55
OEN	**0.65**	0.01	**0.42**	0.29	0.40	0.86	0.15	0.55
EIN	**0.76**	**0.79**	0.09	**0.60**	0.65	0.76	0.07	0.52
NEIN	**0.91**	**0.72**	0.28	**0.58**	0.89	0.90	0.52	0.66
SERV	**0.91**	**0.78**	**0.42**	**0.79**	0.91	0.84	0.04	0.53
B. Standard deviations								
OIL	14.27	8.89	4.85	8.80	10.21	1.65	3.61	6.07
OEN	2.68	3.40	1.72	4.25	2.32	1.12	1.70	5.60
EIN	5.40	5.18	2.24	5.57	3.83	1.20	2.10	5.41
NEIN	4.61	4.99	2.17	4.55	3.06	1.47	1.88	5.35
SERV	1.95	2.35	1.96	5.10	1.54	1.04	1.65	5.60

Notes: The US series are logged and detrended using the HP-filter with the weight 100. Empirical moments are computed by the authors for the 1973-2005 sample. Boldface numbers indicate that an empirical correlation is significant at least at the five percent level of significance. Theoretical moments are average statistics over 1,000 simulated economies of 33 periods. Numbers in parentheses are standard errors. VA_j denotes sectoral value added. The notation for other variables corresponds to that in the text.

Table 5: Volatility and comovement of oil price and macroeconomic aggregates with aggregate output: alternative model specifications

	Standard deviation				Corr. with output			
	Data	BOIL	SYMM	DIAG	Data	BOIL	SYMM	DIAG
Oil price P_{oil}	12.94	8.89	3.01	6.38	**-0.45**	-0.95	-0.46	-0.18
Output Y	2.71	0.53	3.24	1.41				
Consump. C	1.87	0.39	1.63	**0.67**	0.83	0.91	0.74	0.38
Investment X	8.75	2.05	15.31	7.60	**0.79**	0.95	0.96	0.95
Lab. Input H	2.78	0.28	1.85	1.01	**0.84**	0.89	0.87	0.89
Real wage W	1.31	0.43	1.84	0.70	0.29	0.95	0.88	0.70

Notes: The table reports the statistics for three modifications of the benchmark model. The BOIL model relies only on TFP shocks in the OIL sector. The SYMM model is based on the symmetric input-output matrix. The DIAG model uses the diagonal variance-covariance matrix of productivity impulses. The US series are logged and detrended using the HP-filter with the weight 100. Empirical moments are computed by the authors for the 1973-2005 sample. Boldface numbers indicate that an empirical correlation is significant at least at the five percent level of significance. Theoretical moments are average statistics over 1,000 simulated economies of 33 periods. Numbers in parentheses are standard errors. Output Y is aggregate value added constructed from sectoral value added. The notation for other variables corresponds to that in the text.

Table 6: Summary of peak responses of output and prices

A. Supply shocks to production of OIL

	Benchmark model BMRK					Symmetric model SYMM				
↓ TFP(oil)	OIL	OEN	EIN	NEIN	SERV	OIL	OEN	EIN	NEIN	SERV
Peak Y_j	-	-	-	-	-	-	-	-	-	-
Peak P_j	+	+	+	-	-	+	-	-	-	-
Dominant	↓ S	↓ S	↓ S	↓ D	↓ D	↓ S	↓ D	↓ D	↓ D	↓ D
Dominant effect in the U.S. data of a decline in oil supply										
	↓ S	n.a.	↓ S	↓ D	n.a.	↓ S	n.a.	↓ S	↓ D	n.a.

B. Oil-specific demand shocks

	Benchmark model BMRK					Symmetric model SYMM				
↓ TFP(ein)	OIL	OEN	EIN	NEIN	SERV	OIL	OEN	EIN	NEIN	SERV
Peak Y_j	-	-	-	-	-	-	-	-	-	-
Peak P_j	+	-	+	+	-	-	-	+	-	-
Dominant	↓ S	↓ D	↓ S	↓ S	↓ D	↓ D	↓ D	↓ S	↓ D	↓ D
Dominant effect in the U.S. data of an increase in oil-specific demand										
	↓ S	n.a.	↓ S	↓ S	n.a.	↓ S	n.a.	↓ S	↓ S	n.a.

C. Non-oil related demand shocks

	Benchmark model BMRK					Symmetric model SYMM				
↑TFP(serv)	OIL	OEN	EIN	NEIN	SERV	OIL	OEN	EIN	NEIN	SERV
Peak Y_j	+	+	+	+	+	+	+	+	+	+
Peak P_j	+	+	+	+	-	+	+	+	+	-
Dominant	↑ D	↑ D	↑ D	↑ D	↑ S	↑ D	↑ D	↑ D	↑ D	↑ S
Dominant effect in the U.S. data of an increase in global demand										
	↑ D	n.a.	↑ D	↑ D	n.a.	↑ D	n.a.	↑ D	↑ D	n.a.

Notes: The table reports the signs of the peak responses of sectoral output and prices, following a decline in the TFP in the OIL and EIN sectors and an increase in the TFP in the SERV sector, in two versions of the model. BMRK corresponds to the benchmark model. The SYMM model is based on the symmetric input-output matrix. The signs of TFP shocks are normalized to generate an increase in the price of oil. A sector experiences an increase in the price of oil mainly through supply (demand) channels, if its output and price move in the opposite (same) direction. The negative (positive) dominant supply and demand effects are denoted by ↓ S (↑ S) and ↓ D (↑ D). The dominant effects of oil-related shocks in the US data are inferred from Tables 7 in Lee and Ni (2002) and Table 6.4 in Fukunaga, Hirakata and Sudo (2011). The empirical evidence on output and price responses for industries in the OEN and SERV sectors is not available.

Table 7: Peak responses

	Oil price P_{oil}	Output Y	Sectoral gross output Y_j				
			OIL	OEN	EIN	NEIN	SERV
A. Decline in TFP (oil)							
Peak response	7.448	-0.367	-5.913	-1.500	-0.873	-0.430	-0.361
"Elasticity"		-0.049	-0.794	-0.201	-0.117	-0.058	-0.048
B. Decline in TFP (ein)							
Peak response	0.091	-0.244	-0.484	-0.166	-2.565	-0.345	-0.211
"Elasticity"		-2.688	-5.320	-1.826	-28.205	-3.793	-2.324
C. Increase in TFP(serv)							
Peak response	0.611	0.550	0.295	0.292	0.391	0.566	0.966
"Elasticity"		0.901	0.482	0.478	0.640	0.926	1.581

Notes: This table report peak responses, defined as the maximum percentage change in the producer price of oil P_{oil} and output measures following unexpected productivity shocks in the OIL, EIN or SERV sectors in the benchmark model BMRK. Output Y is aggregate value added constructed from sectoral value added. The rows "Elasticity" represent the percent change in output divided by the percent change in the oil price.

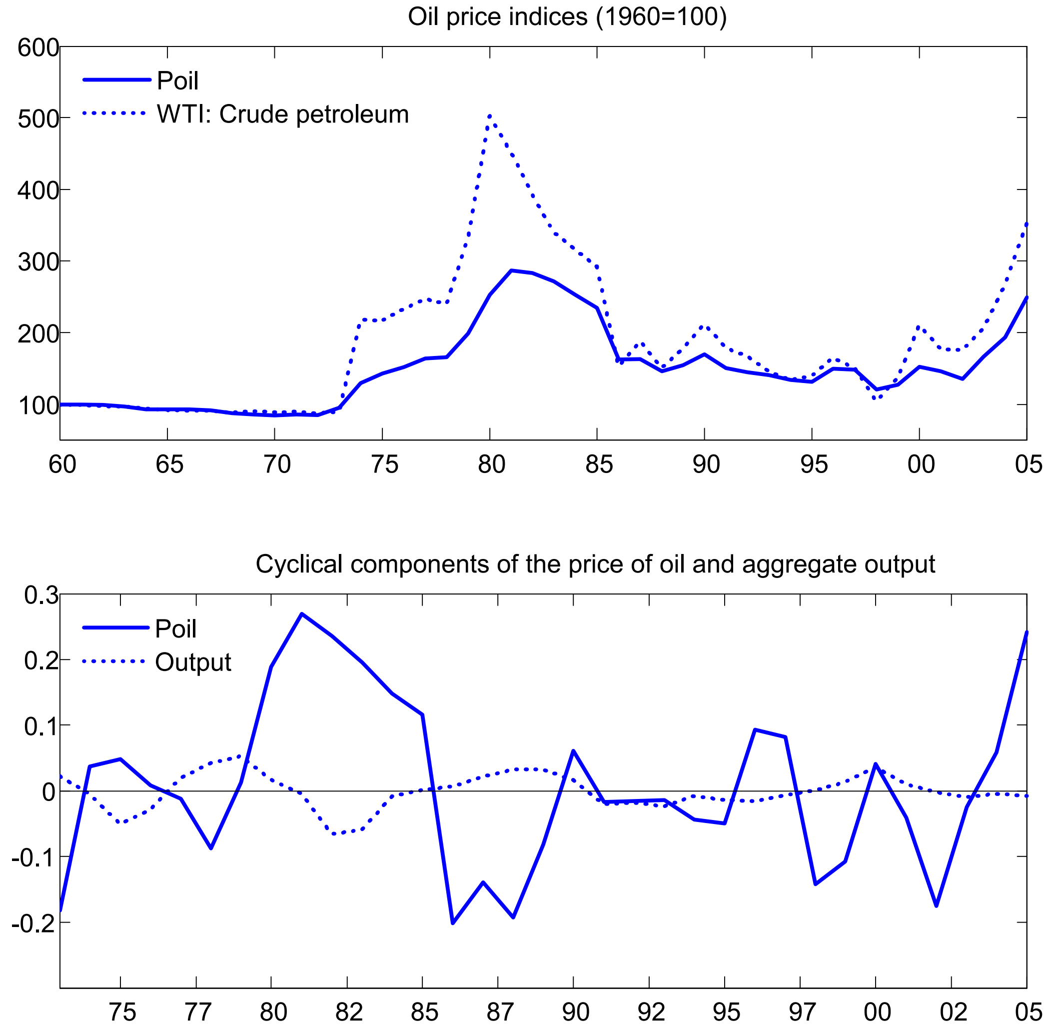

Figure 1: Energy prices and aggregate output

Notes: *Poil* is the producer price for the oil and gas sector, computed from the Jorgenson's dataset. WTI: Crude petroleum is the annual average price of West Texas Intermediate crude oil. Both price indices are deflated with the BEA's price index for personal consumption expenditures. Output is aggregate value added computed from the Jorgenson's dataset. The series in the bottom panel are logged and detrended using the HP filter with a smoothing parameter 100.

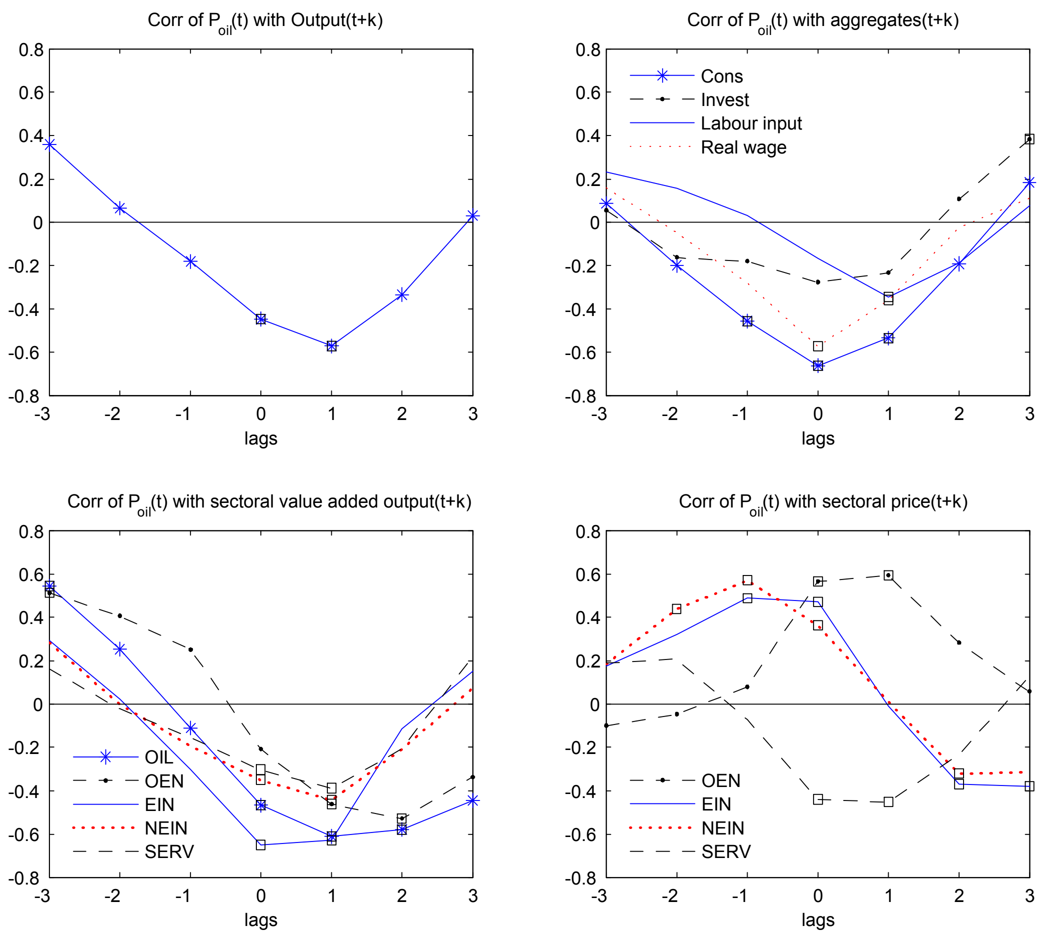

Figure 2: Dynamic correlations of the price of oil with aggregate and sectoral variables in the US data (1973-2005)

Notes: The figure reports correlation between the price of oil in period t with lags and leads of other variables (all expressed in detrended log form). The squares indicate that the correlation coefficient is statistically significant at 5 percent level of significance, based on bootstrap confidence intervals. Output is aggregate value added. Cons and Invest denote real personal consumption expenditures and gross private domestic investment. Labour input is the Törnqvist aggregate of industry level inputs from the Jorgenson's dataset. The real wage is the corresponding aggregate labour input cost, divided by the BEA's price index for PCE. Sectoral value added and output prices are computed from the Jorgenson's dataset. The sectoral composition is given in Table 1.

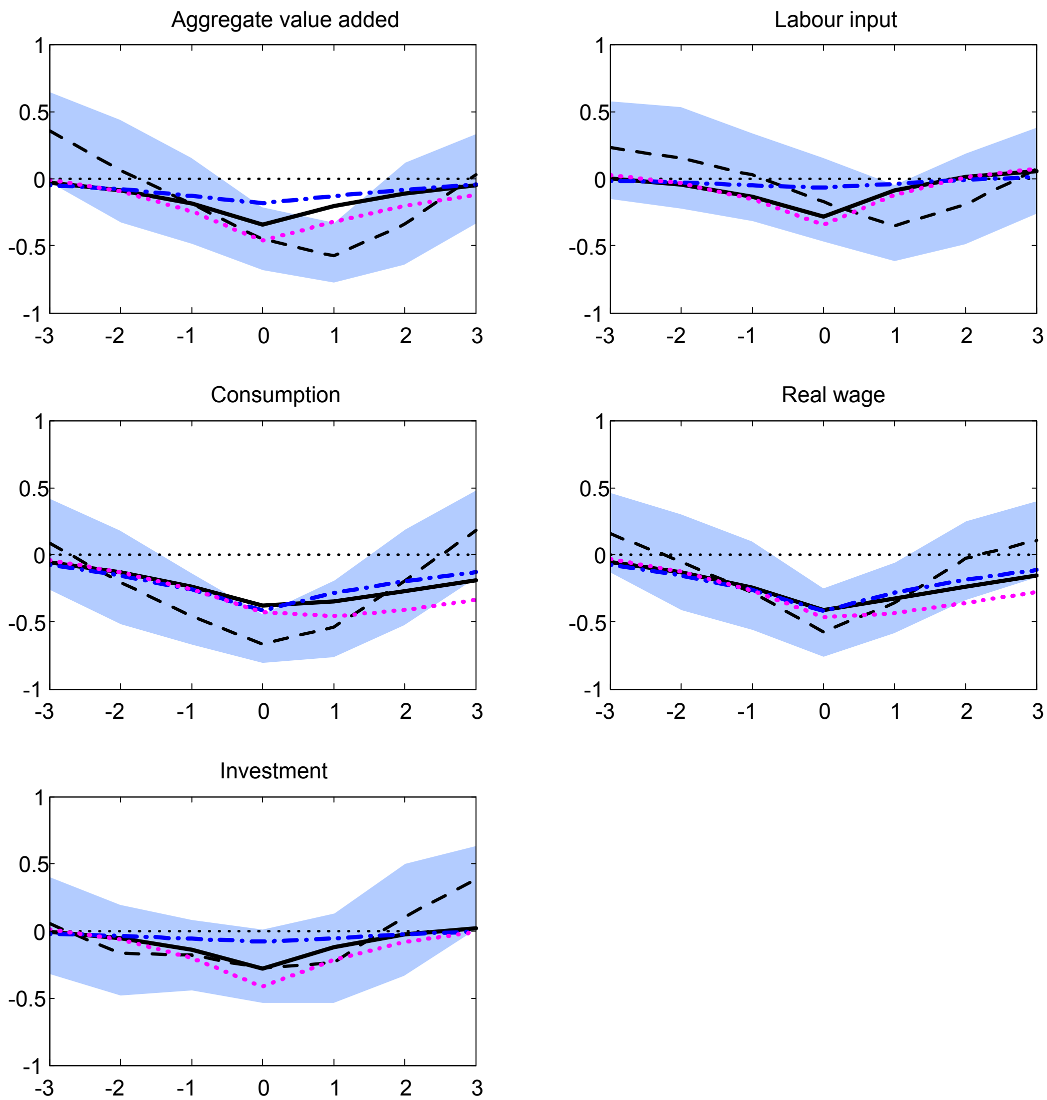

Figure 3: Dynamic correlations of the price of oil with aggregate variables in the model and in the US data

Notes: The figure reports correlations of the price of oil in period t with lags and leads of aggregate variables. The long-dashed lines are the point estimates for the sample 1973-2005. The shaded areas indicate that the 95% bootstrap confidence intervals The other lines indicate the predicted correlations for three versions of the model: BMRK (the solid lines), SYMM (the dotted lines) and DIAG (the dashed-dotted lines). Theoretical correlations are average statistics over 1,000 simulations of 33 periods, computed for each horizon.

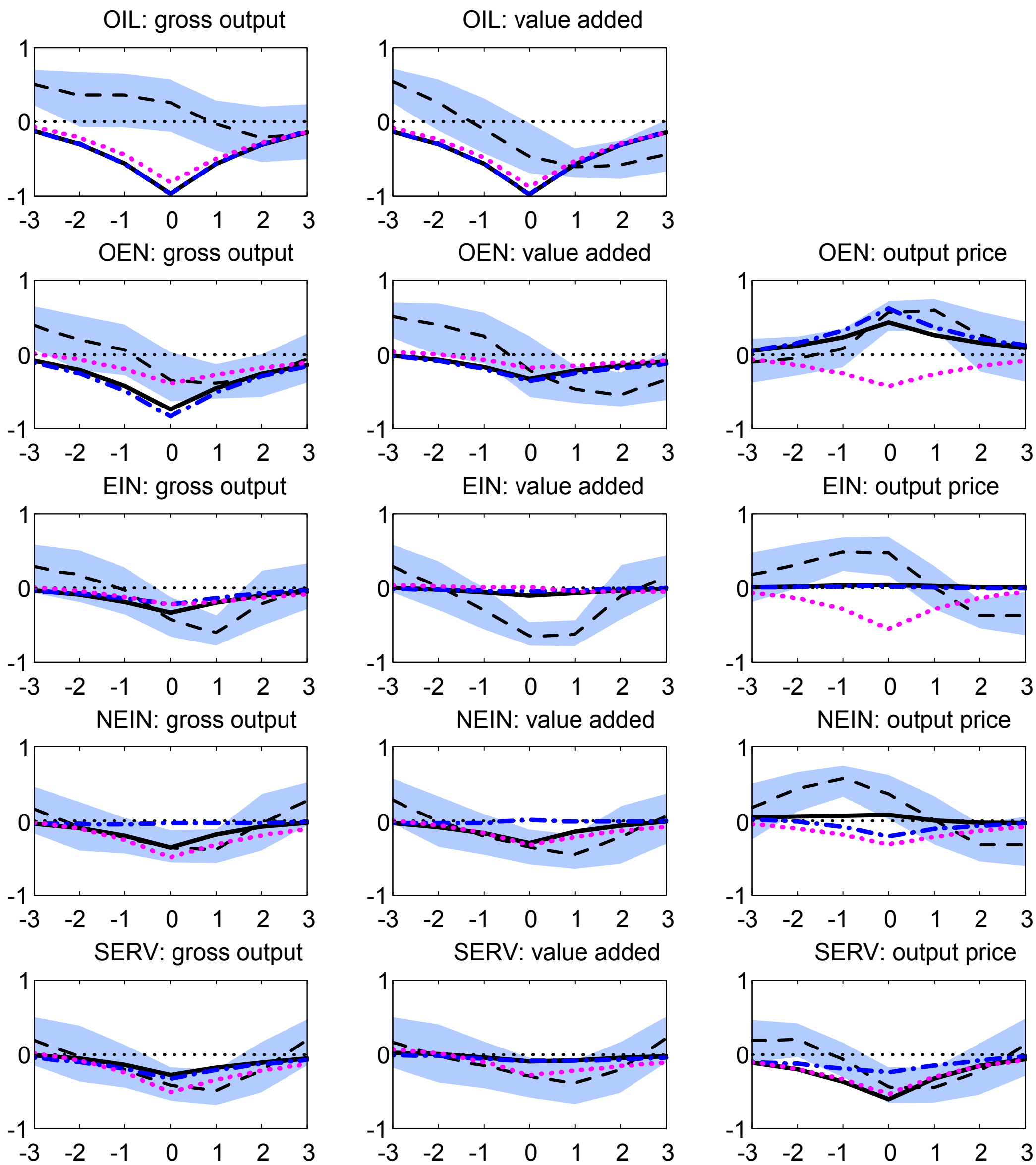

Figure 4: Dynamic correlations of the price of oil with sectoral output and prices in the model and in the US data

Notes: Notes: The figure reports correlation of the oil price in period t with lags and leads of sectoral variables. The long-dashed lines are the point estimates for the sample 1973-2005. The shaded areas indicate that the 95% bootstrap confidence intervals The other lines indicate the predicted correlations for three versions of the model: BMRK (the solid lines), SYMM (the dotted lines) and DIAG (the dashed-dotted lines). Theoretical correlations are average statistics over 1,000 simulations of 33 periods, computed for each horizon.

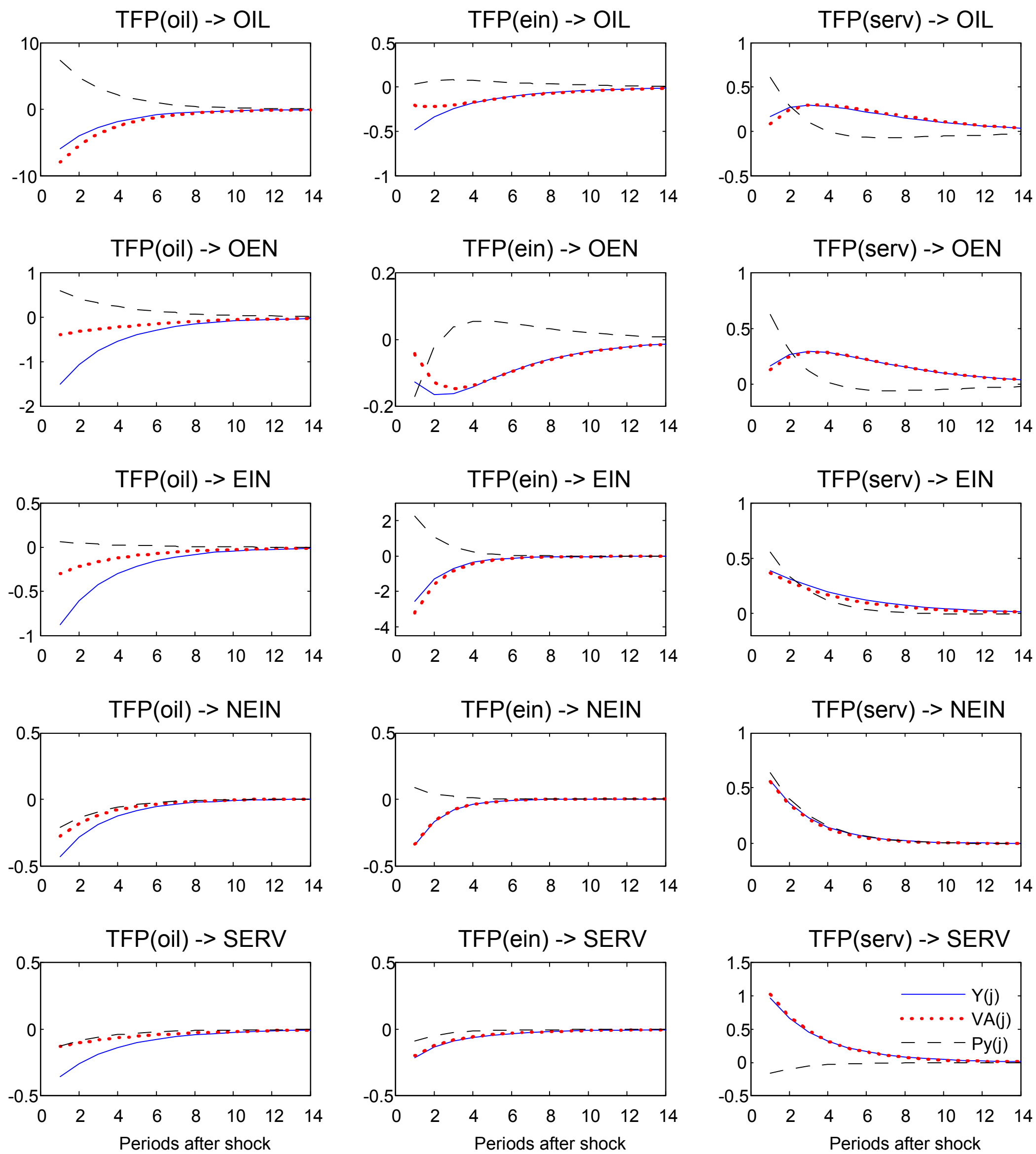

Figure 5: Sectoral output and price responses in the model

Notes: The figure plots impulses responses to an unexpected decline of the TFP in the OIL sector (column 1), to an unexpected decline of the TFP in the EIN sector (column 2), and an unexpected increase of the TFP in the SERV sector (column 3). The scale is the percentage deviations from the steady state.

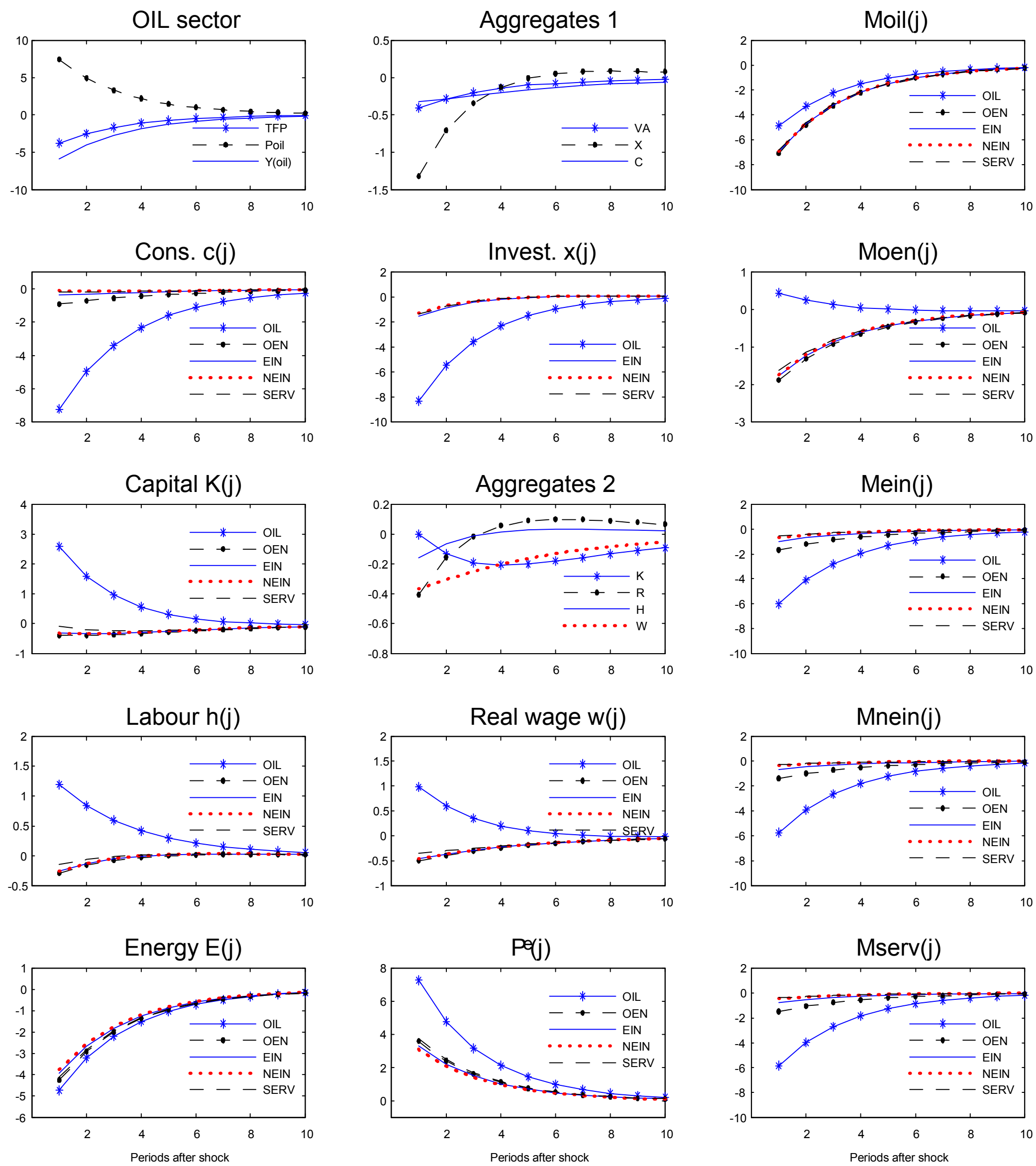

Figure 6: Impulse responses to a decline of the TFP in the OIL sector

Notes: The figure plots impulses responses to an unexpected decline of the TFP in the OIL sector (column 1), to an unexpected decline of the TFP in the EIN sector (column 2), and an unexpected increase of the TFP in the SERV sector (column 3). The scale is the percentage deviations from the steady state.