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Persistence and Volatility of Real Exchange Rates: The Role of Supply Shocks Revisited

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Persistence and Volatility of Real Exchange Rates: The Role of Supply Shocks Revisited

March 1, 2016

Abstract

This paper re-examines the role of supply shocks for real exchange rate fluctuations. First, in a structural VAR analysis, we combine long run and sign restrictions to identify productivity and non-productivity supply shocks. Second, we show that a variance decomposition in the frequency domain generates quantitatively different results compared to the standard forecast error variance decomposition. In particular, productivity shocks emerge as the most important driver of US real effective exchange rate fluctuations at low frequencies, while real demand shocks are more salient at high frequencies. We use the spectrum at frequency zero to structurally decompose the persistence of the real exchange rate. Supply shocks explain more than half of the persistence of the exchange rate.

Keywords: real exchange rate, supply shocks, SVAR, spectral variance decomposition, spectrum at frequency zero

JEL Classification: C32, F31, F32, F41

1 Introduction

Real exchange rates of major industrialized economies have been volatile and persistent ever since the Bretton Woods system of fixed exchange rates was abandoned in the 1970s. Economic theory suggests that supply shocks explain a large fraction of the fluctuations of real exchange rates both in the short run and the long run. Balassa (1964) and Samuelson (1964) are among the early contributions to highlight the importance of relative productivity for long run equilibrium real exchange rates. More recently Steinsson (2008) shows that real shocks in general, such as productivity and labor supply shocks, are important for generating hump-shaped impulse responses of real exchange rates in sticky price models.

Despite the ample theoretical arguments in favor of a meaningful role of supply shocks, evidence from structural vector autoregressions (SVARs) on the structural sources of real exchange rate dynamics remains mixed. In a seminal paper, Clarida and Galí (1994) use triangular long run restrictions à la Blanchard and Quah (1989) to identify supply, demand and nominal shocks. They find that the role of supply shocks for real exchange rate fluctuations is negligible both in the short run and the long run. This view has been shared by SVAR studies based on other identification schemes.¹ Farrant and Peersman (2006) and Juvenal (2011) use sign restrictions and find that supply shocks only account for around 10 percent of real exchange rate dynamics. One exception is Alexius (2005). She shows that, when allowing for a stochastic long run relationship between the level of the real exchange rate and its fundamentals, supply shocks account for most of the forecast error variance of real exchange rates measured at long forecast horizons.

This paper re-examines the role of supply shocks for real exchange rate fluctuations both in the short run and the long run. We find that supply shocks are the most important driver of US real exchange rate persistence. Demand shocks matter only at higher frequencies. Our analysis differs from existing studies in two aspects. First, to achieve a sharper identification of supply shocks, we combine long run and sign restrictions to identify productivity and non-productivity supply shocks. Non-productivity supply shocks such as shocks to labor supply are highlighted by Steinsson (2008) as a potential explanation for real exchange rate (RER) persistence in open economy DSGE models. Likewise, Berka, Devereux, and Engel (2015) stress the relevance of labor supply

¹See, e.g., Rogers (1999) and Artis and Ehrmann (2006) for an identification with short run zero restrictions. These earlier VAR analyses focus on the role of monetary policy as also discussed in Eichenbaum and Evans (1995) and Chadha and Prasad (1997).

disturbances. They find that unit labor costs matter for real exchange rate dynamics in an empirical cross-country study. However, this source of RER fluctuations has not yet been analyzed formally in the open economy SVAR literature. Second, we decompose the structural drivers of RER dynamics from a frequency-domain perspective. We present new results based on a spectral variance decomposition (SVD) as proposed by Stiasny (1996) and Altig, Christiano, Eichenbaum, and Linde (2011). The SVD inspects the structural sources of the dynamic behavior of a process at different frequencies. A number of recent studies uses this approach for an analysis of business cycle frequencies only (see, e.g., Ravn and Simonelli, 2007, Justiniano, Primiceri, and Tambalotti, 2010, and Enders, Müller, and Scholl, 2011, among others). We argue that the frequency-based variance decomposition is of particular interest for inspecting the low frequency properties of the RER. We show that different conclusions emerge from the SVD at low frequencies compared to a standard forecast error variance decomposition of the RER.

In addition, we use a structural decomposition of the spectral density at frequency zero to analyze the structural sources of the RER *persistence*. Thus far, it has been common in the SVAR literature to use the forecast error variance decomposition at the infinite forecast horizon (FEVD(∞)) to evaluate the structural sources of the persistence of a process (see, e.g., Alexius, 2005). However, given that the FEVD(∞) is equal to a decomposition of the unconditional variance of the process, it does not cleanly measure persistence but, technically, represents the sum of the variances at all frequencies. In other words, the FEVD(∞) mixes variances from low frequencies to high frequencies, compromising inference about the long run dynamics of a time series. By contrast, our frequency zero measure is more precise given that it solely focuses on the variance at the lowest frequency. In the context of the US real exchange rate, we show that the two measures can lead to very different conclusions on the main driving forces of RER persistence. These differences are most obvious when inspecting the role of supply disturbances.

We estimate a VAR model for the US vis-à-vis an aggregate of industrialized countries using data from 1978Q1 to 2010Q4. Based on a standard variance decomposition of the forecast errors (FEVD), we find that productivity shocks account for around 10 percent of US real exchange rate volatility at different forecast horizons. Real demand shocks explain over 50 percent in the short run and over 30 percent in the long run. Monetary policy shocks are relatively unimportant across all forecast horizons. These results are largely in line with the findings from the previous SVAR studies (e.g. Clarida and Galí,

1994, Farrant and Peersman, 2006 and Juvenal, 2011, among others). The identified labor supply shock alone is about as important as the productivity shock and explains more of RER fluctuations than monetary policy. Accounting for this second supply shock clarifies and strengthens the role of supply factors for real exchange rates.

This becomes even more clear when inspecting the spectral variance decomposition. We observe quantitatively different results compared to the FEVD conditional on the inspected frequencies. In particular, the strong role of real demand is only salient at high frequency and business cycle movements. At frequencies below conventional business cycles, however, the role of productivity for real exchange rates increases to more than 30 percent. Changes in demand are less important. At high and medium frequencies, the spectral variance decomposition generates overall similar results in comparison with the FEVD.

The strong role of productivity for long run dynamics is even more prominent when focusing on the persistence of the RER. The spectral variance decomposition at frequency zero shows that productivity shocks explain more than half of RER persistence. In contrast, demand and monetary policy shocks account for less than 10 percent. An analysis of the variance of the forecast errors at a long forecast horizon clearly underestimates the importance of productivity shocks for the persistence of the RER. Our empirical findings at frequency zero are thus consistent with the notion of Balassa (1964) and Samuelson (1964) that productivity determines long run real exchange rates. This result is robust to defining persistence more generally by a range of low frequencies instead of frequency zero only, although the importance of the productivity shock declines when higher frequencies are considered. We also show the robustness of our findings across several different VAR setups.

Our main conclusions are in line with the findings by Alexius (2005). However, our methodology is more general in the sense that we do not rely on cointegration assumptions that impose restrictions on the spectrum of the RER at frequency zero. Our approach is also related to Rabanal and Rubio-Ramirez (2015) who investigate the spectrum of the RER directly. They show that international real business cycle models with permanent productivity shocks generate too much low frequency fluctuations of the RER compared to the data. They regard this “excess persistence of the RER” as yet another open economy puzzle and propose refinements to improve the model’s ability to match the shape of the RER spectrum. In light of our empirical results, however, the overall shape of the RER

spectrum is also triggered by other shocks. In particular, our empirical findings show that real demand shocks drive the volatility of the RER at high frequencies. Therefore, it is not necessarily a puzzle that a model with only productivity shocks generates too much low frequency volatility.

The remainder of the paper is organized as follows. Section 2 describes our empirical identification strategy and the theoretical model that is used to derive the sign restrictions. In Section 3, we describe our data and report our results and several robustness checks. Section 4 concludes.

2 Identifying supply shocks in the data

2.1 Strategy

To assess the importance of different structural shocks for real exchange rate dynamics, we use a conventional VAR setup based on a reduced form estimation of

$$Y_t = B(L)Y_{t-1} + u_t, \quad t = 1, \dots, T, \quad (1)$$

where Y_t is an $N \times 1$ vector of endogenous variables and the lag polynomial $B(L) = B_1 + B_2L + \dots + B_kL^{k-1}$ represents $N \times N$ coefficient matrices up to lag length k . In our baseline setting, the vector of endogenous variables consists of real GDP, inflation, the real exchange rate, hours worked, and interest rates for the US vis-à-vis an aggregate of industrialized countries. The reduced form innovations denoted by the $N \times 1$ vector u_t are independent and identically distributed with mean zero and variance-covariance matrix Σ_u . We obtain the underlying structural shocks e_t by transforming the reduced form innovations u_t with transformation matrix A such that $A^{-1}u_t = e_t$. The variance of each structural innovation is normalized to one ($\Sigma_e = E[e_t e_t'] = I_n$). The transformation matrix preserves the covariance structure of the VAR, such that $\Sigma_u = AA'$.

Our identification strategy is as follows: first, in line with Blanchard and Quah (1989), we assume that only changes in the level of relative productivity affect the level of the GDP differential between two countries in the long run. A similar identification strategy of relative productivity shocks has also been used in the study of Clarida and Galí (1994). However, it is important to stress that in contrast to Clarida and Galí (1994), we do not apply any long run restriction on the real exchange rate itself. In a VAR with

$N > 2$ variables, this leaves the system underidentified. Then, we use sign restrictions as advanced by Faust (1998), Uhlig (2005), and Canova and De Nicoló (2002) to disentangle shocks to labor supply, demand, exchange rates and monetary policy in the data.² Technically, we obtain candidate transformation matrices A from random draws based on QR decompositions as in Rubio-Ramirez, Waggoner, and Zha (2010). These random draws are constructed in such a way that they also satisfy the long run restrictions (Binning, 2013). For each candidate draw, we compute the impulse response functions and retain only the draws that satisfy the sign restrictions. The sign restrictions are derived from an open-economy DSGE model that has clear predictions on the responses of the different variables in the system to the set of structural shocks. The combination of long run and sign restrictions allows us to evaluate a set of structural shocks that is typically considered to be relevant for real exchange rate dynamics. We motivate these shocks and the sign restrictions in the theoretical model discussed in the next section.

2.2 Deriving robust sign restrictions from theory

We use a standard two-country DSGE model similar to the models used by Steinsson (2008) and Chari, Kehoe, and McGrattan (2002) to motivate the sign restrictions that we ultimately use to identify our SVAR.³ The world economy consists of two symmetric countries with equal sizes. In each country, the representative household supplies labor to firms, invests in state-contingent bonds, and consumes a non-traded final good. The final good is produced by competitive firms that combine varieties of intermediate goods produced in both countries and account for households' home bias towards domestic goods. Intermediate good producers are monopolistic competitors and set prices in the unit of the buyer's currency in a staggered fashion à la Calvo (1983). Using labor as an input in production, they produce the differentiated intermediate goods. Interest rates are set by the monetary authority according to a Taylor (1993) rule. Each government finances spending through lump-sum taxation.

²Other recent papers that combine sign and zero restrictions in very different contexts include Baumeister and Benati (2012), Beaudry, Nam, and Wang (2011), and Mountford and Uhlig (2009). See Peersman and Straub (2009) and Balmaseda, Dolado, and Lopez-Salido (2000) for different SVAR setups that also identify labor supply shocks.

³Steinsson (2008) presents different versions of the model. These models differ in treating labor as an homogeneous or heterogeneous input factor and capital as a fixed or an adjustable input in production. We adopt the former version with homogeneous labor for simplicity with the note that the different versions of the model do not have different implications for the sign restrictions used in our empirical analysis.

To limit the number of variables in the empirical model, we derive log-linearized equilibrium conditions in terms of differential variables (home versus foreign). As in Steinsson (2008), the core of the model consists of five equations.⁴ The aggregate consumption differential \hat{c}_t determines demand according to the consumption Euler equation

$$\sigma(E_t\hat{c}_{t+1} - \hat{c}_t) = \hat{i}_t - E_t\hat{\pi}_{t+1}, \quad (2)$$

where \hat{i}_t is the nominal interest rate differential and $\hat{\pi}_t$ denotes the rate differential of inflation between home and foreign country.⁵ $\sigma^{-1} > 0$ is the intertemporal elasticity of substitution. Uncovered interest rate parity (UIP) from international risk sharing implies that

$$q_t = \sigma\hat{c}_t + f_t, \quad (3)$$

where q_t is the real exchange rate and f_t captures a time-varying risk premium shock to the exchange rate.⁶

The New Keynesian Phillips curve (NKPC) governs the supply side and the dynamics of the inflation differential $\hat{\pi}_t$ according to

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + 2\kappa\alpha(1 - \alpha)q_t + \kappa(1 - 2\alpha)\hat{m}c_t, \quad (4)$$

where β is the subjective discount factor, and $\alpha \in [0, 1]$ measures the degree of home bias for home versus foreign goods. The parameter $\kappa = \frac{(1-\theta)(1-\theta\beta)}{\theta}$ measures the slope of the NKPC, where θ is the non-adjustment rate in the Calvo staggered price-setting.

The real marginal cost differential ($\hat{m}c_t$) is determined by

$$\hat{m}c_t = \frac{(1 - 2\alpha)(\phi + \sigma)}{1 + \phi\eta}\hat{c}_t + \frac{(1 - 2\alpha)\phi}{1 + \phi\eta}\hat{g}_t - \frac{(1 + \phi)}{1 + \phi\eta}\hat{a}_t + \frac{1}{1 + \phi\eta}\hat{\xi}_t,$$

where $\eta > 0$ is the elasticity of substitution between home and foreign goods and $\phi \geq 0$ is the inverse of the Frisch elasticity of labor supply. Similar to Steinsson (2008), real

⁴A detailed exposition of the model and the complete set of log-linearized equations is available on request.

⁵In the following, lowercase letters refer to variables expressed as log deviations from steady state, hatted variables refer to differential variables, i.e., home versus foreign.

⁶This shock can be interpreted as a systematic failure of exchange rate expectations (Kollmann, 2002) or as a result of noise trading in the foreign exchange market (Mark and Wu, 1998 and Jeanne and Rose, 2002).

marginal costs are influenced by three structural shocks: relative government spending shocks (\hat{g}_t), relative productivity shocks (\hat{a}_t), and relative labor supply shocks ($\hat{\xi}_t$). The government spending shock are real demand side disturbances, the latter two shocks capture supply side disturbances to the NKPC.

Each central bank implements an interest rate feedback rule following Taylor (1993) with interest rate smoothing. Consequently, the interest rate differential follows

$$\hat{i}_t = \rho_i \hat{i}_{t-1} + (1 - \rho_i) [\eta_\pi \hat{\pi}_t + \eta_y \hat{y}_t] + \hat{\varepsilon}_t,$$

where $\rho_i \in [0, 1]$ is the interest rate smoothing parameter, η_π and η_y are the response parameters to inflation and output and $\hat{\varepsilon}_t$ is a relative monetary policy shock that captures transitory deviations from the Taylor rule. The structural exogenous shock processes for \hat{a}_t , \hat{x}_t , \hat{g}_t and $\hat{\varepsilon}_t$ follow conventional AR(1) processes.

To obtain robust sign restrictions, we consider a range of calibrated values for the parameters of the model. We proceed in three steps. First, we specify a plausible range of values for each parameter. This range covers values typically used in the literature on open economy DSGE models. Second, we assume uniform and independent distributions over all ranges of specified values and draw 100,000 sets of realizations on the parameter space. Last, we compute impulse response functions for each set of parameter values. The range of impulse responses allows us to assess the uncertainty on the impulse signs depending on the parameterization of the model.

Table 1 summarizes the parameter ranges discussed in the following. We choose the subjective discount factor β over the range $[0.982, 0.99]$, which implies a steady state risk-free real return on financial assets of 4.2 to 7.5 percent per annum. The inverse Frisch elasticity of labor supply ϕ is set between 0.5 and 3. The upper bound follows Steinsson (2008). For the relative risk aversion parameter σ , we consider $[1, 6]$ as a plausible range of values. The upper bound is determined by the parameterization of Chari et al. (2002), who choose this value to match the relative volatility of the real exchange rate compared to consumption in US data. The steady state consumption to GDP ratio is set between $[0.56, 0.66]$, which is consistent with the long run great ratios considered in the literature. In steady state, the consumption home bias α is equal to the ratio of imports to GDP. The average ratio for the US between 1978 and 2010 is 0.12 in the World Bank data on imports of goods and services. We consider a wide range of $[0.025, 0.25]$ around the average value.

For the price elasticity parameter, we choose values between 1 and 2. Evidence from microeconomic price studies provides a probability of not adjusting prices θ between 0.55 and 0.75 (Bils and Klenow, 2004 and Nakamura and Steinsson, 2008 among others). For the monetary policy parameters, we use values commonly associated with standard Taylor rules. We set the inflation response parameter η_π in the range [1.1, 2.15]. The output-gap-response parameter η_y is set between 0.5 and 0.93. We consider values of the interest rate smoothing parameter ρ_i between 0.4 (Rudebusch, 2006) and 0.8, which corresponds to estimates commonly found for the Volcker-Greenspan period.

We set values for the persistence parameters of the shock processes according to Bayesian estimates of DSGE models (e.g., Smets and Wouters, 2007 and Lubik and Schorfheide, 2006). For the relative productivity process, we set a range between 0.94 and 0.99. The range of the persistence parameter of labor supply shocks is set according to estimates of Chang and Schorfheide (2003). Following Lubik and Schorfheide (2006), values of the persistence parameter for the relative government expenditure shock vary between 0.83 and 0.97. We set the persistence parameter for the risk premium shock according to the posterior distribution of interest rate premium disturbances estimated by Smets and Wouters (2007). The 90 percent posterior interval of this parameter lies between 0.07 and 0.36. For the monetary policy shock, the estimated interval is between 0.04 and 0.24. Given that our focus in this exercise is on the sign of the impulse response and not on the size, standard deviations of innovations are normalized to one.

2.3 Discussion of model implications

Given the parameter ranges in Table 1, we compute the theoretical impulse response functions (IRFs) of the five structural shocks across 100,000 parameter realizations. Figure 1 shows the median realization and the 5th and the 95th percentiles across all IRFs for the variables that are used in the empirical exercise. Except for some extreme parameter combinations, the impulse responses generate unambiguous signs in most cases.

If home productivity rises relative to foreign productivity, domestic output and the output differential rise. Relative prices and the inflation differential fall. Falling prices in the home country depreciate the real exchange rate. This depreciation is a standard finding in this class of models, but empirical evidence on this effect is mixed (Enders and Müller, 2009). As a result, we restrict only the responses in GDP and inflation and leave the response of the real exchange rate open. Table 2 summarizes our baseline sign restrictions.

Parameter	Value	Description
β	[0.982 - 0.99]	Discount factor
η	[1 - 2]	Elasticity of substitution between home and foreign goods
σ	[1 - 6]	Inverse of intertemporal elasticity of substitution
ϕ	[0.5 - 3]	Inverse of the Frisch elasticity of labor supply
α	[0.025 - 0.25]	Degree of consumption home bias
C/Y	[0.56 - 0.66]	Consumption to GDP ratio in steady state
θ	[0.55 - 0.75]	Calvo sticky price parameter
η_π	[1.5 - 2.15]	Inflation coefficient in the Taylor rule
η_y	[0 - 0.5]	Output gap coefficient in the Taylor rule
ρ_i	[0.4 - 0.8]	Interest rate smoothing in the Taylor rule
ρ_z	[0.94 - 0.99]	AR(1) coefficient of productivity shocks
ρ_d	[0.83 - 0.97]	AR(1) coefficient of government spending shocks
ρ_f	[0.07 - 0.36]	AR(1) coefficient of risk premium shocks
ρ_ε	[0.04 - 0.24]	AR(1) coefficient of monetary shocks
ρ_ξ	[0.797 - 0.93]	AR(1) coefficient of labor supply shocks

Table 1: Range of calibrated parameters.

An increase in domestic government spending relative to foreign government spending increases real domestic demand and both the output and the inflation differential rise. In addition, our theoretical model predicts that the real exchange rate appreciates due to the rising relative price level. If expansionary monetary policy decreases the interest rate in the home country relative to the foreign country, demand for foreign bonds and currency increases. This depreciates the nominal exchange rate and the real exchange rate if prices are sticky. Simultaneously, domestic output and inflation rise compared to the foreign economy. These qualitative predictions of our model are consistent with the arguments and the sign restrictions in Clarida and Galí (1994) and Farrant and Peersman (2006).

Additionally, the DSGE model sheds light on the impulse responses of a larger set of aggregate variables, namely, nominal interest rates and hours worked. This feature allows us to identify a broader set of structural shocks in the data compared to earlier SVAR studies. The impulse responses of the nominal interest rate disentangle monetary policy shocks from government spending shocks, as these two disturbances generate impulse responses with the same signs for all variables except the nominal interest rate. The relative nominal interest rate falls after an expansionary monetary policy shock, while it rises after a positive government spending shock due to the endogenous response of

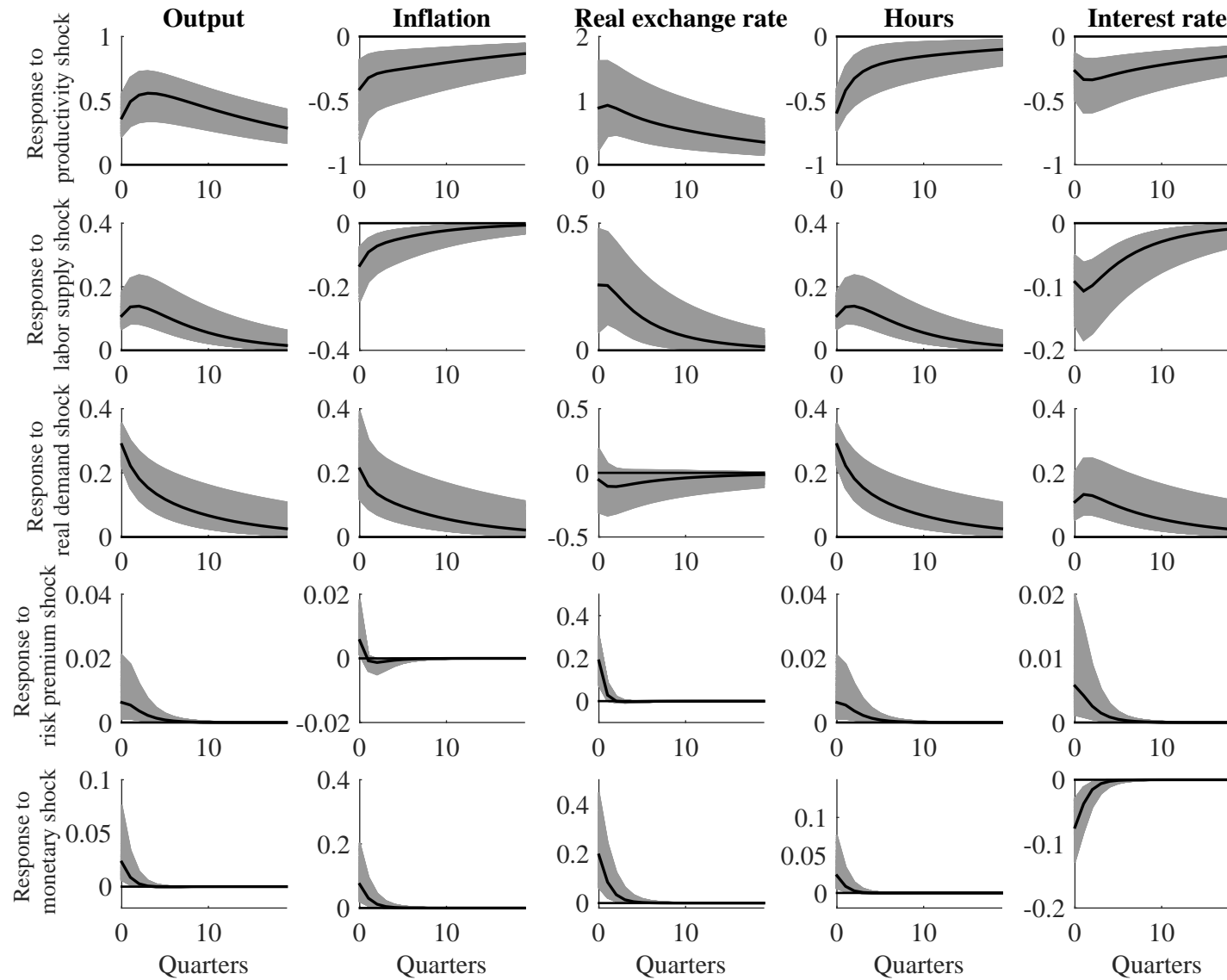


Figure 1: Theoretical impulse response functions across parameterizations. This figure shows the impulse responses of key variables to the five structural shocks in the DSGE model. The solid lines show the median across draws, while gray areas represent all impulse responses between the 5th and the 95th quantiles.

Shock/Variables	GDP	Inflation	REER	Hours	Interest rates	GDP (∞)
Productivity	+ (1-8)	- (1)	?	?	?	?
Labor supply	+ (1-6)	- (1)	?	+ (1-4)	- (1-4)	0
Government spending	+ (1-4)	+ (1)	- (3-4)	+ (1-4)	+ (1-4)	0
Risk premium	+ (1-4)	+ (1)	+ (1-4)	+ (1-4)	+ (1-4)	0
Monetary policy	+ (1-2)	+ (1)	+ (1-3)	+ (1-2)	- (1-4)	0

Table 2: Sign and long run restrictions of baseline SVAR. Shocks and variables are relative and expressed as differentials, except for the risk premium shocks and the real exchange rate. Question marks denote unrestricted responses. Numbers indicate the quarters after the shock for which the restriction applies.

the Taylor rule. The DSGE model distinguishes government spending shocks from risk premium shocks through the responses of the real exchange rate. A risk premium shock that causes the nominal and real exchange rate to depreciate boosts home demand relative to foreign demand as home goods become relatively cheaper. In contrast, the real exchange rate appreciates in response to an expansionary government spending shock in the home country.⁷ The sign restrictions that identify the government spending shock coincide with the sign restrictions used by Farrant and Peersman (2006) and Juvenal (2011) in order to identify a real demand shock. Thus, even though the DSGE model provides clear intuition for a government spending shock, we will interpret this shock in our empirical analysis more broadly as a generic real demand shock.

The theoretical model predicts that the hours differential falls in response to a relative productivity shock, but rises after all other structural shocks. This is a robust feature of many macroeconomic models with sticky prices but a highly debated issue in the empirical literature (e.g., Christiano, Eichenbaum, and Vigfusson, 2004). For this reason, we impose no restriction on the response of hours worked to productivity shocks. Instead, the labor supply shock differs from demand and nominal shocks given the opposed sign of the response in relative prices. The long run restriction differentiates productivity and labor supply shocks.

The sign restrictions as derived from the theoretical IRFs are summarized in Table 2. The first five columns present the sign restrictions used to identify labor supply, government spending, risk premium and monetary policy shocks, while the last column shows

⁷Enders et al. (2011) provide empirical evidence that the real exchange rate depreciates in responses to domestic fiscal shocks. In a robustness check with an alternative identification strategy, we show that our main results are not affected by relaxing this sign restriction.

the long run restrictions imposed on GDP to disentangle productivity shocks from other shocks.

3 Structural sources in the time and the frequency domain

3.1 Data, the SVAR setup, and estimation

We use data on real GDP, inflation, hours and interest rates for the US vis-à-vis an aggregate of industrialized countries (rest of the world, ROW). Our ROW aggregate covers Canada, the UK, Japan, and the Euro Area. Our data sources and construction follow Enders et al. (2011). For hours worked, we make use of the data set of Ohanian and Raffo (2012), which provides internationally comparable time series on hours worked.⁸ Detailed data sources for all series and for each country are summarized in Appendix A. As in our theoretical model, we define each data series as the differential between the home and the foreign country, i.e., the ROW aggregate is subtracted from the US data. For GDP and hours worked, we consider the log differential; inflation and interest rate differentials are expressed in absolute terms. The Main Economic Indicators of the OECD provide a series for the CPI-based real effective exchange rate for the US that we consider in logs. Our quarterly data covers the period from 1978Q1 to 2010Q4.

Following Farrant and Peersman (2006), we estimate the VAR using first differences in GDP, hours and the log real exchange rate. We impose the sign restrictions on the level of the responses. We fit a VAR with $k = 4$ lags for the quarterly data. We estimate the VAR with Bayesian methods to account for parameter uncertainty in the decision to accept or reject the identification scheme. As emphasized by Uhlig (2005), parameter uncertainty is neglected if acceptance or rejection is solely determined by point estimates. Instead, we consider 200,000 draws from the posterior distribution of the reduced form VAR parameters. For each draw, we check then the signs of the SVAR impulse responses derived from 50,000 candidate transformation matrices. In our baseline specification, we obtain approximately 1,300 accepted draws.⁹ We follow Uhlig (2005) and set a weak Normal-Wishart prior that generates posterior means of the reduced form VAR equal to the OLS estimates of $B(L)$ and Σ_u .

⁸The data set of Ohanian and Raffo (2012) uses data from a number of different sources, including national statistical offices and establishment and household surveys.

⁹This number is large enough so that additional draws do not change the results.

Compared to strict short or long run restrictions, the sign restriction approach makes the interpretation of the SVAR results less straightforward. The reason is the multitude of accepted models that satisfy the sign restrictions. Generally, the accepted models could have conflicting implications for the question at hand. The literature frequently reports the pointwise median and percentiles across accepted draws as a measure of the central tendency of the SVAR. However, as discussed in Fry and Pagan (2011), this measure lacks structural interpretability, because the pointwise median measure is generally not generated from a single identification matrix A . Instead, it mixes identification matrices that represent different structural models. This problem is most obvious in the context of a variance decomposition. The pointwise variance decomposition does not necessarily sum up to one, because the shocks that are constructed from the pointwise median measure are not necessarily uncorrelated. To address these concerns, we report a second measure of the median model as proposed by Fry and Pagan (2011) in addition to the pointwise median. This measure chooses the impulse response function from a single model that is closest to the pointwise median impulse responses. We call it the “median target” solution or the Fry and Pagan (2011) median.¹⁰

3.2 Empirical impulse responses

Next, we discuss the results of our baseline SVAR estimation. We start with the empirical impulse responses, which are depicted in Figure 2. Solid black lines show the pointwise median, the gray shaded areas correspond to the central 66 percent of accepted draws.¹¹

Not surprisingly, the empirical impulse responses reflect the sign and the long run restrictions imposed. A positive relative productivity shock has a permanent positive effect on the GDP differential. By contrast, relative inflation falls temporarily. The impulse response of the real exchange rate gives mild support for a depreciation at short horizons, but no clear evidence for long run effects. In earlier SVAR studies, no agreement has been reached on the sign of the REER response to a positive productivity shock. A real deprecia-

¹⁰The recent literature on sign restrictions proposes different ways to deal with this problem. Kilian and Murphy (2012) suggest to use additional external information to narrow down the set of identified models and Baumeister and Hamilton (2015) propose to use informative priors on the structural parameters. We work with the main approach used so far in the existing literature. This renders our results comparable to earlier papers.

¹¹Note that these regions reflect two different concepts: parameter uncertainty from the estimation and model uncertainty from the sign restriction identification. The broad range of impulses does not necessarily mean that the impulses are insignificant in a statistical sense.

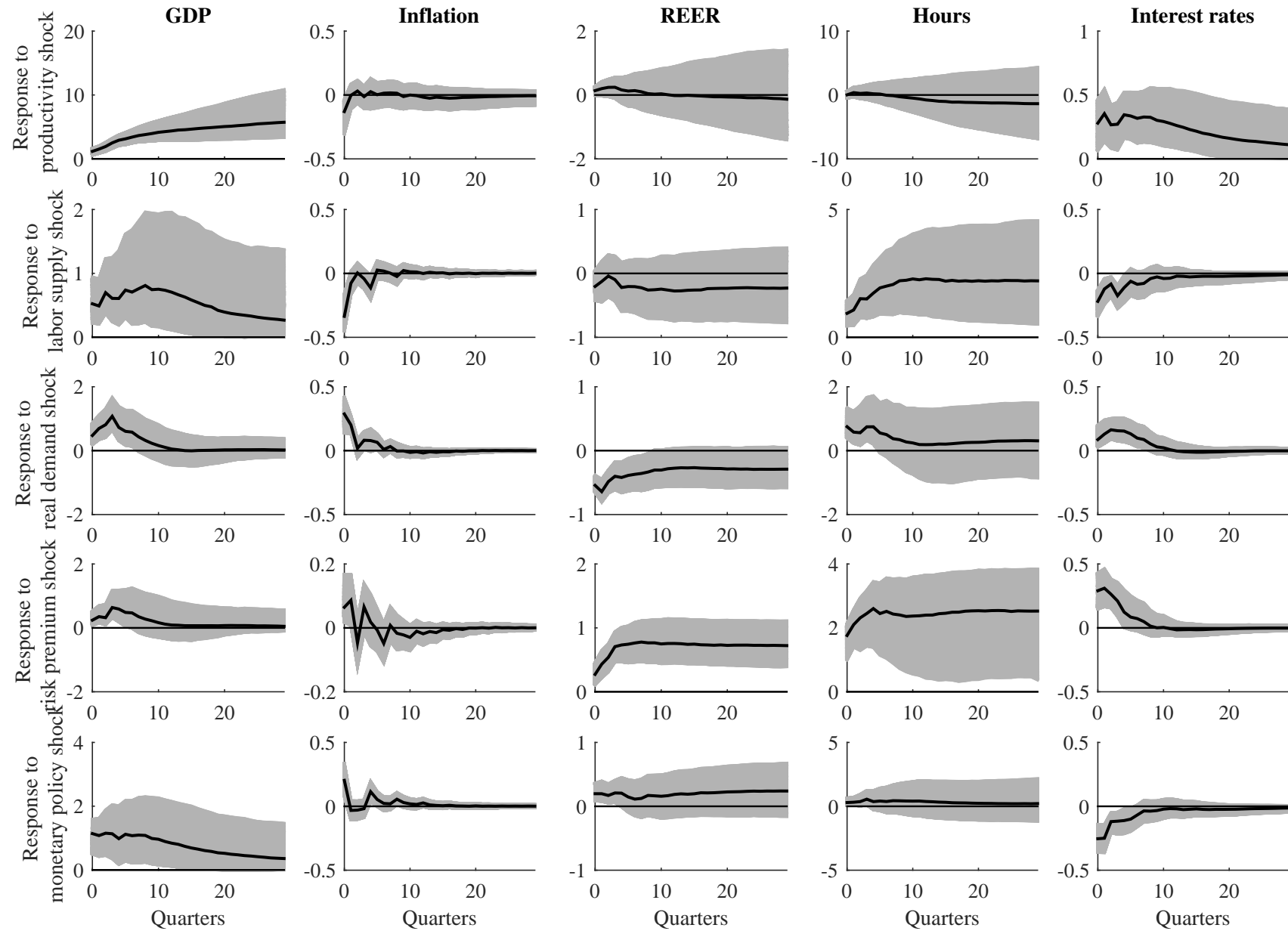


Figure 2: Impulse responses to structural shocks in baseline SVAR. The figure shows the impulse response functions to one-standard deviation relative shocks; the horizontal axis shows quarters. Solid black lines show the pointwise median impulse responses, and gray lines represent all responses between the 16th and 84th pointwise percentiles of all accepted draws. Results are based on 1,018 accepted draws. Note that shocks and variables are defined in terms of differentials between countries, except for the exchange rate and the risk premium shock.

tion has also been found by Farrant and Peersman (2006) and Corsetti, Dedola, and Leduc (2014), while Enders et al. (2011) find a real appreciation in the short run and a depreciation in the medium run. A positive labor supply shock shows similar effects on the output and inflation differential as the productivity shock in the short run. However, the hours worked differential goes up significantly. Again, the impulse response of the real effective exchange rate shows a weak appreciation on the impact, but no clear evidence afterwards. After a real demand shock, both the output and the inflation differential go up. Relative hours worked rise too. The real effective exchange rate, in this case, appreciates significantly in the short run. The impulse responses to a positive risk premium shock behave similar to a real demand shock, because this shock generates an unexpected depreciation in the exchange rate, which in turn gives exports a boom. As a result, it generates increases in output, hours, and relative inflation and a depreciation of the real exchange rate. Following an expansionary relative monetary policy shock, the output and the inflation differential both go up. The real effective exchange rate exhibits a depreciation in the short run due to the interest rate parity. This is in line with findings of the previous empirical literature (e.g. Eichenbaum and Evans, 1995 or Scholl and Uhlig, 2008).

3.3 Variance decomposition

In this section, we discuss the results of decomposing the fluctuations of the real exchange rate into structural sources both in the time-domain and the frequency-domain. In particular, we highlight the additional insights that can be gained from the frequency based decomposition. Table 3 summarizes these results for our baseline SVAR. First, we report the standard forecast error variance decomposition (FEVD) at the 1st, 8th and 40th quarter forecast horizon. These are the typical horizons used in SVAR studies to investigate short run, medium run and long run dynamics. We contrast these FEVDs with the spectral variance decomposition (SVD) over three ranges of frequencies. Following Altig et al. (2011), we define business cycle frequencies as the dynamic components of a time series with a periodicity between 8 and 32 quarters. Further, we define all movements in the real exchange rate with a periodicity below 8 quarters as “high-frequency” and fluctuations with a periodicity more than 32 quarters as “low-frequency”. We report results for the pointwise median and the median target draw. Although, the results differ, the general conclusions are the same across both measures.

As in Altig et al. (2011), we use the spectrum of the estimated VAR representation to compute the SVD. The spectrum, $f(\omega)$, of the VAR in (1) is given by

$$\begin{aligned} f(\omega) &= (2\pi)^{-1} \sum_{h=-\infty}^{\infty} E(Y_t Y'_{t-h}) e^{-i\omega h} \\ &= (2\pi)^{-1} (I - B(e^{-i\omega})e^{-i\omega})^{-1} A \Sigma_e A' \left((I - B(e^{-i\omega})e^{-i\omega})^{-1} \right)'. \end{aligned} \quad (5)$$

To compute the spectral density at frequency ω for the j th structural shock, we set all elements in Σ_e except for the variance of shock j to zero. We use $f^j(\omega)$ to denote the resultant spectral density for this j th shock.

The variance share explained by shock j at frequencies ω_1 to ω_2 is then given by¹²

$$SVD^j(\omega_1, \omega_2) = \frac{\int_{\omega_1}^{\omega_2} f^j(\omega) d\omega}{\int_{\omega_1}^{\omega_2} f(\omega) d\omega}. \quad (6)$$

A number of recent empirical studies highlight the importance of focusing on the variance decomposition at business cycle frequencies (e.g., Enders et al., 2011).¹³ We go one step further and use this approach to study the structural sources of the full spectrum of the RER. Thus far, the literature struggles to explain the pattern of the spectrum of the RER that unites persistence and volatility (Rabanal and Rubio-Ramirez, 2015). We argue that supply shocks play a crucial role for understanding the real exchange rate persistence and volatility.

The main lesson from the FEVD, as reported in Table 3, is that the real demand shock (government spending shock in our theoretical model) is the most important contributor to RER fluctuations. This shock drives more than 50 percent of short run fluctuations and more than 30 percent in the long run. Risk premium shocks explain up to 20 percent of RER fluctuations. By contrast, productivity shocks and monetary policy shocks do not play a large role. At the 1-quarter forecast horizon, productivity shocks contribute 4 percent to the RER forecast error variance. This role increases modestly to 14 percent at the 40-quarter horizon (as measured by the median draw). This finding indicates a changing

¹²For a more technical discussion see Stiasny (1996).

¹³As a result, this approach is often referred to as “business cycle variance decomposition” in the literature. It is more generally related to the large literature on time series filtering and detrending (Beveridge and Nelson, 1981, King, Plosser, Stock, and Watson, 1991 and Baxter and King, 1999). Justiniano et al. (2010) show that focusing on business cycle frequencies changes the relative importance of investment shocks on output and hours compared to a standard FEVD.

	Productivity shock			Labor supply shock			Government spending shock			Risk premium shock			Monetary policy shock		
	Median	MT	68% Int.	Median	MT	68% Int.	Median	MT	68% Int.	Median	MT	68% Int.	Median	MT	68% Int.
<i>Forecast error variance decomposition</i>															
Horizon (quarters)															
1	0.04	0.04	[0.00; 0.12]	0.08	0.01	[0.01; 0.30]	0.51	0.72	[0.25; 0.73]	0.13	0.17	[0.02; 0.35]	0.07	0.06	[0.01; 0.23]
8	0.10	0.06	[0.05; 0.18]	0.15	0.22	[0.07; 0.29]	0.38	0.44	[0.22; 0.53]	0.19	0.21	[0.10; 0.33]	0.09	0.07	[0.04; 0.19]
40	0.14	0.06	[0.07; 0.29]	0.15	0.22	[0.07; 0.26]	0.34	0.44	[0.19; 0.49]	0.18	0.21	[0.10; 0.30]	0.09	0.07	[0.05; 0.17]
<i>Spectral variance decomposition (SVD)</i>															
Frequencies (cycle in quarters)															
High	0.13	0.05	[0.06; 0.27]	0.15	0.25	[0.07; 0.28]	0.37	0.44	[0.20; 0.52]	0.15	0.18	[0.08; 0.27]	0.09	0.08	[0.05; 0.18]
Business cycle	0.13	0.08	[0.05; 0.28]	0.09	0.11	[0.03; 0.21]	0.29	0.44	[0.17; 0.45]	0.30	0.30	[0.15; 0.46]	0.08	0.08	[0.03; 0.21]
Low	0.36	0.21	[0.11; 0.76]	0.08	0.01	[0.02; 0.25]	0.06	0.17	[0.02; 0.19]	0.24	0.58	[0.06; 0.52]	0.04	0.03	[0.01; 0.14]
<i>Persistence decomposition</i>															
FEVD (∞)	0.15	0.06	[0.07; 0.33]	0.14	0.22	[0.07; 0.26]	0.33	0.44	[0.18; 0.48]	0.17	0.21	[0.09; 0.29]	0.09	0.07	[0.05; 0.17]
SVD (Frequency zero)	0.55	0.49	[0.07; 0.95]	0.04	0.01	[0.00; 0.24]	0.02	0.11	[0.00; 0.12]	0.13	0.38	[0.01; 0.50]	0.03	0.02	[0.00; 0.17]

Table 3: Variance decomposition of baseline SVAR. The 68% interval denotes the pointwise 16th and 84th percentile error bands. The forecast horizon and the cycle length is denoted in quarters. Median refers to the pointwise median across accepted draws, median target (MT) refers to a decomposition of the draw that is closest to the impulse responses of the pointwise median (Fry and Pagan, 2011).

role of productivity shock over the short and the long run. Our spectral variance decomposition, discussed later, provides further insights into the role of supply shocks. Overall, our results based on a decomposition of the forecast errors are in line with the findings of previous SVAR studies (Clarida and Galí, 1994, Farrant and Peersman, 2006 and Juvenal, 2011, among others). For example, Juvenal (2011) finds a strong role (20–40%) of real demand shocks in explaining real exchange rate fluctuations. Farrant and Peersman (2006) find that both real demand shocks and nominal shocks account for the majority of the forecast error variance in US bilateral real exchange rates. Both studies, in line with ours, show that monetary policy shocks do not contribute greatly to macroeconomic volatility.

We stress that labor supply shocks play an important role for RER fluctuations (10 to 20%) and are, in fact, more important than productivity shocks and monetary policy shocks. This result confirms the findings of Berka et al. (2015) who argue that labor supply and unit labor cost play a crucial role in explaining the link of productivity and real exchange rates, although with a very different approach. The new finding is that non-productivity supply shocks account for a significant fraction of real exchange rate fluctuations in the time domain.

Next, we discuss the results of our spectral variance decomposition (SVD). The findings based on the SVD show new and quantitatively different results compared to the FEVD. In particular, at low frequencies, different results arise compared to the FEVD at a long forecast horizon. The contribution of the productivity shock rises significantly when inspecting low frequencies (approximately 30%) compared to high frequencies (approximately 10%), while real demand shocks become relatively less important. At high frequencies, real demand shocks are the most important source of RER fluctuations (40%); at business cycle frequencies, however, its dominance recedes and is on par with the risk premium shock. At low frequencies, productivity shocks become the dominant source of RER fluctuations, while the role of real demand shocks reduces to approximately 10 percent. The median target draw supports a strong role for productivity shocks at low frequencies (20%) but finds a dominant role for risk premium shocks. We interpret this finding as evidence in favor of a strong role for differences in productivity in shaping the long term RER.

In sum, the SVD finds generally comparable results with the FEVD at the short- and medium-term forecast horizon. At low frequencies, however, the SVD shows that productivity shocks play a much stronger role compared to the FEVD at long horizons.

Below, we argue why, in our view, the SVD provides a more clear-cut picture of the long run properties of a time series. Interestingly, our finding of a strong role of productivity shocks at low frequencies is in line with Alexius (2005). She uses a vector error correction model to study the driving forces of RER fluctuations. This model imposes a cointegration relation between the level of the real exchange rate and the level of fundamentals. In our study, we do not take comparably strong assumptions but argue in favor of a more detailed decomposition technique that can isolate the contributions of different shocks at different frequencies. The quantitative difference of the variance contributions at low frequencies provides interesting insights into the structural sources of RER persistence. We discuss this issue in more detail in the next section.

3.4 Persistence decomposition

As famously pointed out by Rogoff (1996), real exchange rates in a floating exchange rate regime are both highly volatile and highly persistent. Since then, macroeconomists have been searching for a structural source of real exchange rate dynamics that can account for both volatility and slow mean reversion. The early literature focuses on monetary and financial shocks because these can easily account for real exchange rate volatility. However, this literature finds it difficult to justify the long lasting effect of nominal shocks beyond reasonable horizons at which nominal prices and wages are sticky.¹⁴ More recently, Steinsson (2008) argues that sticky price models can match the persistence and volatility of real exchange rates if real shocks are the dominant source of dynamics in the model. Given the nature of the debate on the “PPP puzzle”, it is also important to gauge the significance of structural shocks in driving the real exchange rate persistence.

In the SVAR literature, it is common to use the FEVD at a long forecast horizon to measure long run dynamics. Alexius (2005), for instance, uses the FEVD at the infinite horizon (FEVD(∞)), i.e., the unconditional variance, to measure the sources of long run variations in the real exchange rate. In this paper, we propose the spectral variance decomposition at frequency zero to measure the sources of real exchange rate persistence. We argue that the spectrum at zero provides a sharper picture of the persistence properties of a process compared to the unconditional variance. Technically, the FEVD(∞) decomposes the unconditional variance of the series. The unconditional variance is equal to the sum of

¹⁴See, e.g., Benigno (2004) who highlights the role of a monetary policy rule in propagating monetary policy shocks to real exchange rate persistence.

the spectra over all frequencies. As a result, the FEVD(∞) simultaneously reflects both high and low frequency variations of a process. In other words, the FEVD(∞) does not only measure persistence. For this reason, we propose to use the decomposition of the spectrum at frequency zero as a measure that focuses exclusively on persistence.

The relationship between the persistence of a process and the spectrum at frequency zero can be shown formally. From (5), it follows that the spectrum of Y_t at frequency zero is given by

$$f(0) = \frac{1}{2\pi} \sum_{h=-\infty}^{\infty} E(Y_t Y'_{t-h}) = \frac{1}{2\pi} (I - B(1))^{-1} \Sigma_u ((I - B(1))^{-1})', \quad (7)$$

where $B(1) = B_1 + B_2 + \dots + B_k$ is the lag polynomial of the VAR parameters with $L = 1$. If the VAR process is persistent, $B(1)$ is large. For a given Σ_u , $f(0)$ is strictly increasing in $B(1)$.

To illustrate this point, we use an univariate AR(1) process, $z_t = \rho_z z_{t-1} + \epsilon_t$ with $\epsilon_t \sim (0, \sigma_z^2)$, as an example. The spectrum at frequency zero is

$$f_z(0) = (2\pi)^{-1} \frac{\sigma_z^2}{(1 - \rho_z)^2} \quad (8)$$

and the unconditional variance of z_t is then given by

$$var(z_t) = \frac{\sigma_z^2}{1 - \rho_z^2}. \quad (9)$$

In Figure 3, we plot the spectrum $f_z(0)$ and the unconditional variance $var(z_t)$ as functions of the AR(1) coefficient, ρ_z . Clearly, the variance and the spectrum at zero increase with the persistence of the process and eventually go towards infinity. However, the spectrum at zero $f_z(0)$ rises much faster than the unconditional variance $var(z_t)$ as the AR(1) process becomes more persistent. As discussed above, this illustrates that the unconditional variance mixes high and low frequencies whereas the spectrum at zero exclusively focuses at the lowest frequency. The two measures coincide only for $\rho_z = 0$ and are then equal to the variance σ_z of the disturbances. In other words, $f_z(0)$ is more responsive to the persistence of a process than the overall time-domain measure. The same insight holds in the multivariate case. The SVAR, however, allows to additionally perform a structural decomposition of the disturbances.

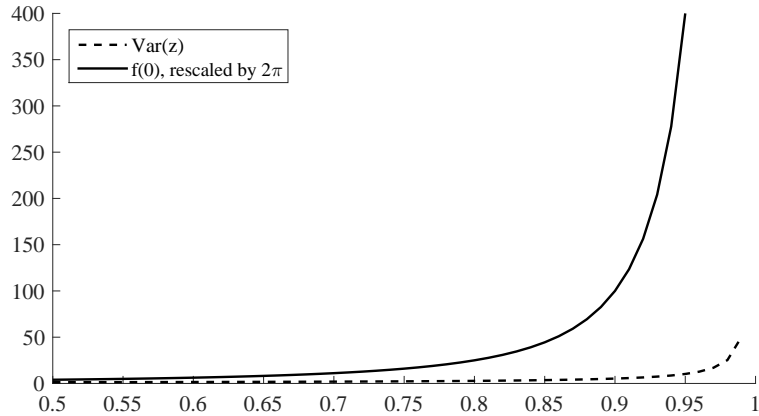


Figure 3: Comparison of the unconditional variance and the spectrum at frequency zero of an AR(1) process with different persistence (ρ_z). The spectrum is rescaled by 2π for visual reasons.

Based on $f(0)$ as given in (7) and the identified SVAR model, we can decompose the persistence of the RER into structural shocks. Using (6), we calculate the ratio between the spectral density triggered by each structural shock and the total spectrum of the RER at frequency zero only. We contrast the decomposition of $f(0)$ with the FEVD(∞) in the last two rows of Table 3. The two measures lead to very different conclusions on the key driver of RER persistence. The FEVD(∞) suggests that the real demand shock is the most important source of long run RER fluctuations and explains one third up to 40 percent. By contrast, the spectrum at frequency zero reveals that the real demand shock plays no role for the persistence of the RER. Instead, the productivity shock is dominant and explains at least half of RER persistence. In our view, this result provides strong arguments for reconsidering productivity shocks as an important source of real exchange rate persistence.

This conclusion is in line with the finding by Alexius (2005) without imposing restrictions on the spectrum at frequency zero.¹⁵ Our results go through if we define persistence more generally in the low frequency range compared to at frequency zero only. Under an alternative measure of persistence with the spectrum in the low frequency range, productivity shocks remain the most important force in explaining the long run dynamics of the real exchange rate, although its share becomes less dominant (compare the discussion in the previous section).¹⁶

¹⁵Alexius (2005) assumes a cointegration relation among the RER, output, and government spending. At the same time, long run restrictions impose that monetary shocks do not affect output and government spending in the long run. Productivity in turn does not affect government spending in the long run.

¹⁶In the economic growth literature, Levy and Dezhbakhsh (2003) and Mallick (2014) use the spectrum at

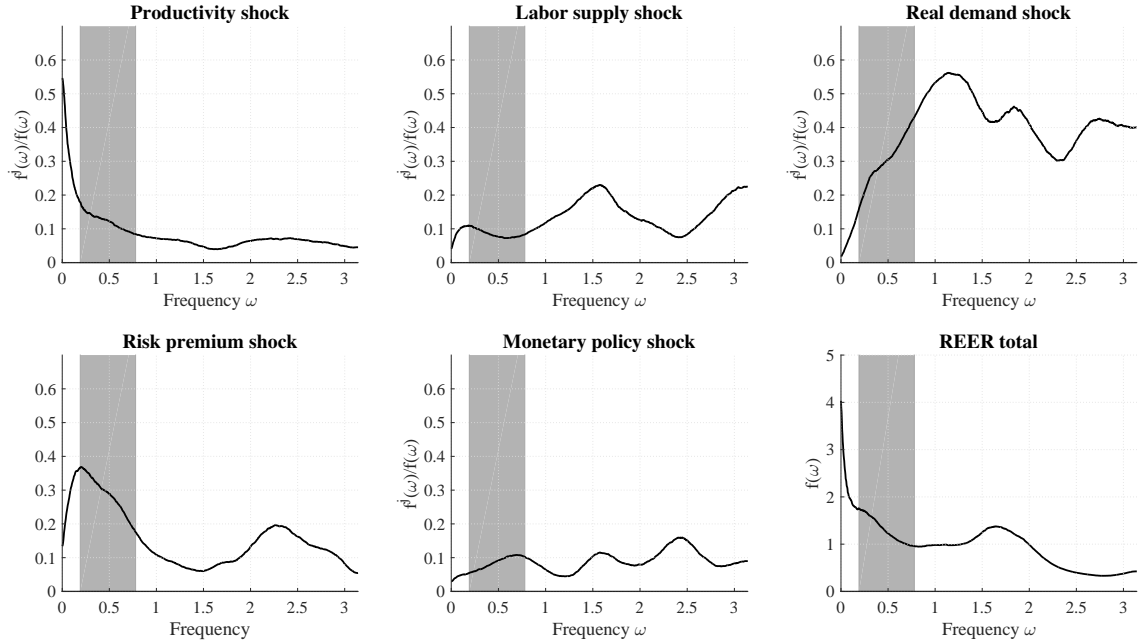


Figure 4: Variance decomposition of the RER across the entire spectrum in SVAR with long run and sign restrictions. The spectral density is computed from the SVAR representation using 1,000 frequency bins. We show the median across all posterior draws. Shaded areas mark business cycle frequencies with cycles between 8 and 32 quarters.

To illustrate why these two measures generate large quantitative different results, we plot the spectral density of the RER as explained by each shock over the whole frequency domain in Figure 4. Shaded areas mark business cycle frequencies. The area below the spectrum measures the volatility as explained by each shock in a specific frequency range. The final panel shows the unconditional spectral density of the RER. Here, the peak at zero highlights the strong and well-documented persistence properties of the RER (see, e.g., Rabanal and Rubio-Ramirez, 2015 for a similar picture). Figure 4 reveals that the quantitatively different SVD arises due to the shape of the spectrum. The $FEVD(\infty)$ is equal to the whole area under the spectrum, i.e., the sum over all frequencies. When the spectrum peaks at zero and declines with higher frequencies, the “average” spectrum is lower than the spectrum at zero. This is the case for the productivity shock. On the other hand, when the spectrum at zero is low but it is increasing with frequency, as in the case for the real demand shock, then $FEVD(\infty)$ can be significantly higher than a decomposition

frequency zero and the spectrum over low frequencies as a measure of the persistence of output growth. We propose to analyze the persistence of the RER and provide a structural decomposition at these frequencies based on a SVAR.

at frequency zero only. Note also that the relation of the unconditional variance and the spectrum at zero is non-linear (see Figure 3). As a result, the FEVD(∞) is only a vague measure of the persistence properties of a process and can lead to misleading results, in particular, when the shock generates large variations at low frequencies.

3.5 Robustness checks

In this section, we check the sensitivity of our central findings to our identifying assumptions, the data, and the empirical setup.

3.5.1 Relaxing sign restrictions

In our baseline SVAR we follow our DSGE model's prediction, Farrant and Peersman (2006), and Juvenal (2011), and identify a real demand shock with a negative sign restriction on the RER response. As shown in the third and fourth row of Table 2, this sign restriction distinguishes the risk premium shock from the government spending shock. Even though this negative sign is supported by many international business cycle models including ours, it is not a robust sign empirically. Kim and Roubini (2008), Monacelli and Perotti (2010) and Enders et al. (2011) find a real depreciation of the RER after a government spending shock using SVARs. Therefore it is important to check if our main finding is sensitive to this controversial sign restriction. To this end, we propose an alternative SVAR setting that identifies only four structural shocks instead of five, i.e., productivity, labor supply, government spending and nominal shocks. Table 4 summarizes the sign restrictions in this case. Apart from the labor supply shock, this setting closely follows Farrant and Peersman (2006) who also propose a SVAR setup with a generic nominal shock instead of specific risk premium and monetary policy shocks. The results of this first robustness check can be found in the first rows of Table 5 (for simplicity, the nominal shock is summarized in the column for the monetary policy shock).

As in our baseline setting, we clearly find that the importance of the productivity shock for RER dynamics rises for lower the frequencies of the spectral variance decomposition. From high to low frequency, the role of the productivity shock increases from 16 to 36 percent, while the role of the real demand shock drops from 14 to 6 percent. Also, nominal shocks are of less importance at lower frequencies. The identified labor supply shock plays a significant role, particularly at high and business cycle frequencies. Adding the two

Shock/Variables	GDP	Inflation	REER	Hours	Interest rates	GDP (∞)
Productivity	+ (1-8)	- (1)	?	?	?	?
Labor supply	+ (1-6)	- (1)	?	+ (1-4)	- (1-4)	0
Government spending	+ (1-4)	+ (1)	- (3-4)	+ (1-4)	+ (1-4)	0
Nominal	+ (1-2)	+ (1)	+ (1-3)	+ (1-2)	- (1-4)	0

Table 4: Sign and long run restrictions of SVAR with only four structural shocks. Shocks and variables are relative and expressed as differentials, except for the risk premium shocks and the real exchange rate. Question marks denote unrestricted responses. Numbers indicate the quarters after the shock for which the restriction applies.

supply shocks together, they account for approximately 30 percent of RER fluctuations at business cycle frequencies and almost half of RER volatility at low frequencies. Results for the median target solution are very similar.

As for the persistence decomposition, the frequency zero measure reveals that productivity shocks account for at least half of the very low frequency RER fluctuations. Demand shocks and nominal shocks, by contrast, are of little relevance at the lowest frequencies. In addition, the unconditional FEVD(∞) overstates the role of real demand shocks, but understates the role of productivity shocks. In sum, we detect only minor differences using this robustness check compared to our baseline setting. This robustness test confirms that productivity shocks are the most important driver of RER persistence and labor supply shocks play a non-negligible role for RER fluctuations.

3.5.2 A focus on productivity shocks

Our analysis differs from comparable studies in the literature in that we identify labor supply shocks in addition to the standard productivity shock. In this section, we evaluate whether our finding on the persistence decomposition of the RER is sensitive to this assumption. In other words, we remove the series on hours worked from our VAR and are left with a simplified VAR containing only real GDP, inflation, the RER, and the interest rate. We keep all identifying restrictions as in our baseline setting and our theoretical model, except for those on the labor supply shock and hours worked. This modification makes our setting close to the four variable SVAR of Farrant and Peersman (2006). Our results are displayed in the last rows of Table 5.

Again, the variance decomposition of the RER is sensitive to the frequencies one looks

	Productivity shock		Labor supply shock		Government spending shock		Risk premium shock		Monetary policy shock	
	Median	MT	Median	MT	Median	MT	Median	MT	Median	MT
Relaxing sign restrictions on the RER										
<i>Spectral variance decomposition</i>										
High (0-8)	0.16	0.09	0.20	0.31	0.14	0.12			0.22	0.31
Business cycle (8-32)	0.12	0.08	0.18	0.23	0.15	0.26			0.31	0.28
Low (32- ∞)	0.36	0.67	0.10	0.12	0.06	0.04			0.14	0.16
<i>Persistence decomposition</i>										
FEVD (∞)	0.18	0.12	0.18	0.29	0.14	0.14			0.22	0.29
Frequency zero	0.52	0.87	0.06	0.06	0.02	0.01			0.05	0.04
SVAR without hours										
<i>Spectral variance decomposition</i>										
High (0 - 8)	0.24	0.32			0.29	0.29	0.30	0.32	0.07	0.06
Business cycle (8-32)	0.18	0.25			0.34	0.25	0.31	0.43	0.07	0.06
Low (32- ∞)	0.27	0.23			0.17	0.26	0.36	0.46	0.05	0.05
<i>Persistence decomposition</i>										
FEVD(∞)	0.17	0.17			0.27	0.45	0.35	0.23	0.11	0.16
Frequency zero	0.28	0.24			0.13	0.26	0.34	0.46	0.03	0.04

Table 5: Summary of the variance decomposition of the RER across robustness tests. See Table 3 for details.

	Productivity shock		Labor supply shock		Government spending shock		Risk premium shock		Monetary policy shock	
	Median	MT	Median	MT	Median	MT	Median	MT	Median	MT
Subsample analysis (1984Q1-2007Q4)										
<i>Spectral variance decomposition</i>										
High (0 - 8)	0.17	0.10	0.11	0.04	0.25	0.50	0.20	0.16	0.13	0.21
Business cycle (8-32)	0.17	0.09	0.07	0.04	0.21	0.18	0.28	0.37	0.14	0.32
Low (32- ∞)	0.38	0.60	0.07	0.03	0.07	0.07	0.15	0.13	0.09	0.18
<i>Persistence decomposition</i>										
FEVD(∞)	0.19	0.14	0.11	0.04	0.24	0.43	0.21	0.18	0.13	0.22
Frequency zero	0.46	0.91	0.06	0.04	0.04	0.01	0.09	0.04	0.07	0.00
Different ROW aggregate										
<i>Spectral variance decomposition</i>										
High	0.13	0.08	0.15	0.25	0.37	0.39	0.15	0.16	0.09	0.11
Business cycle	0.14	0.12	0.10	0.21	0.28	0.30	0.30	0.21	0.09	0.15
Low	0.37	0.40	0.08	0.05	0.07	0.09	0.23	0.45	0.04	0.01
<i>Persistence decomposition</i>										
FEVD (∞)	0.15	0.09	0.15	0.24	0.33	0.38	0.17	0.17	0.09	0.11
SVD (Frequency zero)	0.58	0.63	0.04	0.01	0.02	0.02	0.12	0.31	0.03	0.03

Table 6: Summary of the variance decomposition of the RER across robustness tests (ctd.). See Table 3 for details.

at. The productivity shock contributes up to 30 percent to the persistence of the RER. Real and nominal demand shocks are less important. However, in line with the findings of Farrant and Peersman (2006), we identify a very important role for nominal shocks to the exchange rate, i.e., risk premium shocks in our case (30 to 40%). These shocks tend to be the most important at low to very low frequencies. This implies that they also drive the persistence of the RER.

Given our baseline results, we interpret this finding in line with Berka et al. (2015). They argue that labor supply and unit labor cost are important determinants of real exchange rate fluctuations, because the Balassa-Samuelson link between productivity and real exchange rates appears only when controlling for unit labor costs (in addition to productivity). Our baseline SVAR captures this mechanism by separately identifying labor supply shocks. The four variable VAR here, however, only accounts for productivity, and as a consequence, in line with Berka et al. (2015), understates the role of supply shocks for RERs. Instead, the importance of risk premium shocks is overestimated. In sum, we find it reassuring that our time series approach substantiates the panel findings of Berka et al. (2015).

3.5.3 Subsample analysis

Our original data period from 1978 to 2010 covers two regimes of special US monetary policy. First, in the early 1980s interest rates were very high in order to stabilize inflation. Second, from 2008 onward interest rates have touched upon the zero lower bound and monetary policy was implemented with alternative policy measures. In order to show that our results do not depend on these data periods in our sample, we reestimate our baseline SVAR with data from 1984Q1 until 2007Q4. The results are displayed in the first rows of Table 6. Our findings are not much affected by this modification. The productivity shock continues to be the main driving force of the persistence of the RER. Demand shocks are of importance at high frequencies, but less so at low frequencies.

3.5.4 Different country aggregate

In our baseline SVAR, we analyzed the US vis-à-vis an aggregate of industrialized countries capturing the most important trading partners of the US. Our ROW aggregate comprises Canada, the UK, the EU, and Japan and the construction follows Enders et al. (2011).

For the EU, we use aggregated data as provided by the AWM database. Alternatively, we construct a different ROW aggregate focusing on the G7 countries (except for the US, i.e., Canada, the UK, Germany, France, Italy, and Japan; see Juvenal (2011) for a similar approach). This approach does not use an EU aggregate. The results are summarized in the last rows of Table 6 and are very close to our baseline SVAR. None of our major conclusions are affected by this modification. Productivity shocks explain at least half of US real exchange rate persistence.

4 Conclusions

This paper provides new SVAR evidence on the role of supply shocks for US real exchange rate fluctuations. We find that supply shocks account for a significant fraction of the volatility of the real exchange rate and a majority of the persistence. By contrast, real demand shocks and monetary policy shocks are mainly important for high frequencies and contribute very little to the persistence of the real exchange rate. Contributing to these results are the facts that we explicitly identify non-productivity supply shocks and that we explore variance decompositions in the frequency domain.

References

- ALEXIUS, A. (2005): “Productivity Shocks and Real Exchange Rates,” *Journal of Monetary Economics*, 52, 555 – 566.
- ALTIG, D., L. J. CHRISTIANO, M. EICHENBAUM, AND J. LINDE (2011): “Firm-specific Capital, Nominal Rigidities and the Business Cycle,” *Review of Economic Dynamics*, 14, 225–247.
- ARTIS, M. AND M. EHRMANN (2006): “The Exchange Rate - A Shock-Absorber or Source of Shocks? A Study of Four Open Economies,” *Journal of International Money and Finance*, 25, 874–893.
- BALASSA, B. (1964): “The Purchasing-Power Parity Doctrine: A Reappraisal,” *Journal of Political Economy*, 72, pp. 584–596.
- BALMASEDA, M., J. J. DOLADO, AND J. D. LOPEZ-SALIDO (2000): “The Dynamic Effects of Shocks to Labour Markets: Evidence from OECD Countries,” *Oxford Economic Papers*, 52, pp. 3–23.
- BAUMEISTER, C. AND L. BENATI (2012): “Unconventional Monetary Policy and the Great Recession: Estimating the Macroeconomic Effects of a Spread Compression at the Zero Lower Bound,” *Bank of Canada Working Paper*, 2012-21.
- BAUMEISTER, C. AND J. D. HAMILTON (2015): “Sign Restrictions, Structural Vector Autoregressions, and Useful Prior Information,” *Econometrica*, 83, 1963–1999.
- BAXTER, M. AND R. G. KING (1999): “Measuring Business Cycles: Approximate Band-Pass Filters for Economic Time Series,” *Review of Economics and Statistics*, 81, 575–593.
- BEAUDRY, P., D. NAM, AND J. WANG (2011): “Do Mood Swings Drive Business Cycles and is it Rational?” *NBER Working Papers*, 17651.
- BENIGNO, G. (2004): “Real Exchange Rate Persistence and Monetary Policy Rules,” *Journal of Monetary Economics*, 51, 473–502.
- BERKA, M., M. B. DEVEREUX, AND C. ENGEL (2015): “Real Exchange Rates and Sectoral Productivity in the Eurozone,” *Mimeo*.

- BEVERIDGE, S. AND C. R. NELSON (1981): “A New Approach to Decomposition of Economic Time Series into Permanent and Transitory Components with Particular Attention to Measurement of the Business Cycle,” *Journal of Monetary Economics*, 7, 151–174.
- BILS, M. AND P. J. KLENOW (2004): “Some Evidence on the Importance of Sticky Prices,” *Journal of Political Economy*, 112, 947–985.
- BINNING, A. (2013): “Underidentified SVAR Models: A Framework for Combining Short and Long-run Restrictions with Sign Restrictions,” *Norges Bank Working Paper*, 2013/14.
- BLANCHARD, O. J. AND D. QUAH (1989): “The Dynamic Effects of Aggregate Demand and Supply Disturbances,” *American Economic Review*, 79, 655–73.
- CALVO, G. A. (1983): “Staggered Prices in a Utility-Maximizing Framework,” *Journal of Monetary Economics*, 12, 383–398.
- CANOVA, F. AND G. DE NICOLÓ (2002): “Monetary Disturbances Matter for Business Fluctuations in the G-7,” *Journal of Monetary Economics*, 49, 1131–1159.
- CHADHA, B. AND E. PRASAD (1997): “Real Exchange Rate Fluctuations and the Business Cycle: Evidence from Japan,” *Staff Papers - International Monetary Fund*, 44, 328–355.
- CHANG, Y. AND F. SCHORFHEIDE (2003): “Labor-Supply Shifts and Economic Fluctuations,” *Journal of Monetary Economics*, 50, 1751–1768.
- CHARI, V. V., P. J. KEHOE, AND E. R. MCGRATTAN (2002): “Can Sticky Price Models Generate Volatile and Persistent Real Exchange Rates?” *The Review of Economic Studies*, 69, 533–563.
- CHRISTIANO, L. J., M. EICHENBAUM, AND R. VIGFUSSON (2004): “The Response of Hours to a Technology Shock: Evidence Based on Direct Measures of Technology,” *Journal of the European Economic Association*, 2, 381–395.
- CLARIDA, R. AND J. GALÍ (1994): “Sources of Real Exchange-Rate Fluctuations: How Important are Nominal Shocks?” *Carnegie-Rochester Conference Series on Public Policy*, 41, 1–56.

- CORSETTI, G., L. DEDOLA, AND S. LEDUC (2014): “The International Dimension of Productivity and Demand Shocks in the US Economy,” *Journal of the European Economic Association*, 12, 153–176.
- EICHENBAUM, M. AND C. L. EVANS (1995): “Some Empirical Evidence on the Effects of Shocks to Monetary Policy on Exchange Rates,” *The Quarterly Journal of Economics*, 110, pp. 975–1009.
- ENDERS, Z. AND G. J. MÜLLER (2009): “On the International Transmission of Technology Shocks,” *Journal of International Economics*, 78, 45–59.
- ENDERS, Z., G. J. MÜLLER, AND A. SCHOLL (2011): “How do Fiscal and Technology Shocks affect Real Exchange Rates? New Evidence for the United States,” *Journal of International Economics*, 83, 53–69.
- FAGAN, G., J. HENRY, AND R. MESTRE (2001): “An Area-Wide Model AWM for the Euro Area,” *ECB Working Paper*.
- FARRANT, K. AND G. PEERSMAN (2006): “Is the Exchange Rate a Shock Absorber or a Source of Shocks? New Empirical Evidence,” *Journal of Money Credit and Banking*, 38, 939.
- FAUST, J. (1998): “The Robustness of Identified VAR Conclusions about Money,” *Carnegie-Rochester Conference Series on Public Policy*, 49, 207–244.
- FRY, R. AND A. PAGAN (2011): “Sign Restrictions in Structural Vector Autoregressions: A Critical Review,” *Journal of Economic Literature*, 49, 938–60.
- JEANNE, O. AND A. K. ROSE (2002): “Noise Trading And Exchange Rate Regimes,” *The Quarterly Journal of Economics*, 117, 537–569.
- JUSTINIANO, A., G. E. PRIMICERI, AND A. TAMBALOTTI (2010): “Investment Shocks and Business Cycles,” *Journal of Monetary Economics*, 57, 132–145.
- JUVENAL, L. (2011): “Sources of Exchange Rate Fluctuations: Are they Real or Nominal?” *Journal of International Money and Finance*, 30, 849–876.
- KILIAN, L. AND D. MURPHY (2012): “Why Agnostic Sign Restrictions Are Not Enough: Understanding the Dynamics of Oil Market VAR Models,” *Journal of the European Economic Association*.

- KIM, S. AND N. ROUBINI (2008): “Twin Deficit or Twin divergence? Fiscal Policy, Current Account, and Real Exchange Rate in the US,” *Journal of International Economics*, 74, 362–383.
- KING, R. G., C. I. PLOSSER, J. H. STOCK, AND M. P. WATSON (1991): “Stochastic Trends and Economic Fluctuations,” *American Economic Review*, 81, 819–840.
- KOLLMANN, R. (2002): “Monetary Policy Rules in the Open Economy: Effects on Welfare and Business Cycles,” *Journal of Monetary Economics*, 49, 989–1015.
- LEVY, D. AND H. DEZHBAKHSH (2003): “International Evidence on Output Fluctuation and Shock Persistence,” *Journal of Monetary Economics*, 50, 1499–1530.
- LUBIK, T. A. AND F. SCHORFHEIDE (2006): “A Bayesian Look at the New Open Economy Macroeconomics,” in *NBER Macroeconomics Annual 2005*, National Bureau of Economic Research, Inc, vol. 20 of *NBER Chapters*, 313–382.
- MALLICK, D. (2014): “Financial Development, Shocks, And Growth Volatility,” *Macroeconomic Dynamics*, 18, 651–688.
- MARK, N. C. AND Y. WU (1998): “Rethinking Deviations from Uncovered Interest Parity: The Role of Covariance Risk and Noise,” *Economic Journal*, 108, 1686–1706.
- MONACELLI, T. AND R. PEROTTI (2010): “Fiscal Policy, the Real Exchange Rate and Traded Goods,” *The Economic Journal*, 120, 437–461.
- MOUNTFORD, A. AND H. UHLIG (2009): “What are the Effects of Fiscal Policy Shocks?” *Journal of Applied Econometrics*, 24, 960–992.
- NAKAMURA, E. AND J. STEINSSON (2008): “Five Facts about Prices: A Reevaluation of Menu Cost Models,” *The Quarterly Journal of Economics*, 123, 1415–1464.
- OHANIAN, L. E. AND A. RAFFO (2012): “Aggregate Hours Worked in OECD countries: New Measurement and Implications for Business Cycles,” *Journal of Monetary Economics*, 59, 40–56.
- PEERSMAN, G. AND R. STRAUB (2009): “Technology Shocks And Robust Sign Restrictions In A Euro Area SVAR,” *International Economic Review*, 50, 727–750.

- RABANAL, P. AND J. F. RUBIO-RAMIREZ (2015): “Can International Macroeconomic Models Explain Low-Frequency Movements of Real Exchange Rates?” *Journal of International Economics*, 96, 199–211.
- RAVN, M. O. AND S. SIMONELLI (2007): “Labor Market Dynamics and the Business Cycle: Structural Evidence for the United States,” *The Scandinavian Journal of Economics*, 109, 743–777.
- ROGERS, J. H. (1999): “Monetary Shocks and Real Exchange Rates,” *Journal of International Economics*, 49, 269–288.
- ROGOFF, K. (1996): “The Purchasing Power Parity Puzzle,” *Journal of Economic Literature*, 34, 647–668.
- RUBIO-RAMIREZ, J. F., D. F. WAGGONER, AND T. ZHA (2010): “Structural Vector Autoregressions: Theory of Identification and Algorithms for Inference,” *The Review of Economic Studies*, 77, 665–696.
- RUDEBUSCH, G. (2006): “Monetary Policy Inertia: Fact or Fiction?” *International Journal of Central Banking*, 2, 85–135.
- SAMUELSON, P. A. (1964): “Theoretical Notes on Trade Problems,” *The Review of Economics and Statistics*, 46, pp. 145–154.
- SCHOLL, A. AND H. UHLIG (2008): “New Evidence on the Puzzles: Results from Agnostic Identification on Monetary Policy and Exchange Rates,” *Journal of International Economics*, 76, 1 – 13.
- SMETS, F. AND R. WOUTERS (2007): “Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach,” *American Economic Review*, 97, 586–606.
- STEINSSON, J. (2008): “The Dynamic Behavior of the Real Exchange Rate in Sticky Price Models,” *American Economic Review*, 98, 519–533.
- STIASSNY, A. (1996): “A Spectral Decomposition for Structural VAR Models,” *Empirical Economics*, 21, 535–555.
- TAYLOR, J. B. (1993): “Discretion versus Policy Rules in Practice,” *Carnegie-Rochester Conference Series on Public Policy*, 39, 195–214.

UHLIG, H. (2005): "What are the Effects of Monetary Policy on Output? Results from an Agnostic Identification Procedure," *Journal of Monetary Economics*, 52, 381–419.

A Data sources

Country	Series	Source	Remarks
US	GDP	OECD	volume, market prices, 2009-USD
	GDP deflator	OECD	2009 = 100
	short-term interest	OECD	3-month interbank rate, percent per annum
	hours worked	OH (2012)	total hours in potential hours (given population, 365 days per year, and 14hs per day)
Canada	GDP	OECD	volume, market prices, 2007-CAD
	GDP deflator	OECD	2007 = 100
	short-term interest	OECD	3-month interbank rate, percent per annum
	hours worked	OH (2012)	total hours in potential hours (given population, 365 days per year, and 14hs per day)
Euro Area	GDP	AWM	volume, market prices, 1995-EUR
	GDP deflator	AWM	1995 = 100
	short-term interest	AWM	3-month interbank rate, percent per annum
	hours worked	OH (2012)	total hours in potential hours (given population, 365 days per year, and 14hs per day)
Japan	GDP	OECD	volume, market prices, 2005-JPY
	GDP deflator	OECD	2005 = 100
	short-term interest	OECD	3-month interbank rate, percent per annum
	hours worked	OH (2012)	total hours in potential hours (given population, 365 days per year, and 14hs per day)
UK	GDP	OECD	volume, market prices, 2011-GBP
	GDP deflator	OECD	2011 = 100
	short-term interest	OECD	3-month interbank rate, percent per annum
	hours worked	OH (2012)	total hours in potential hours (given population, 365 days per year, and 14hs per day)

Table 7: Data sources are the Area-Wide Model for the Euro Area (AWM, see Fagan et al., 2001), the OECD Economic Outlook database (OECD), and Ohanian and Raffo, 2012 (OH (2012)).

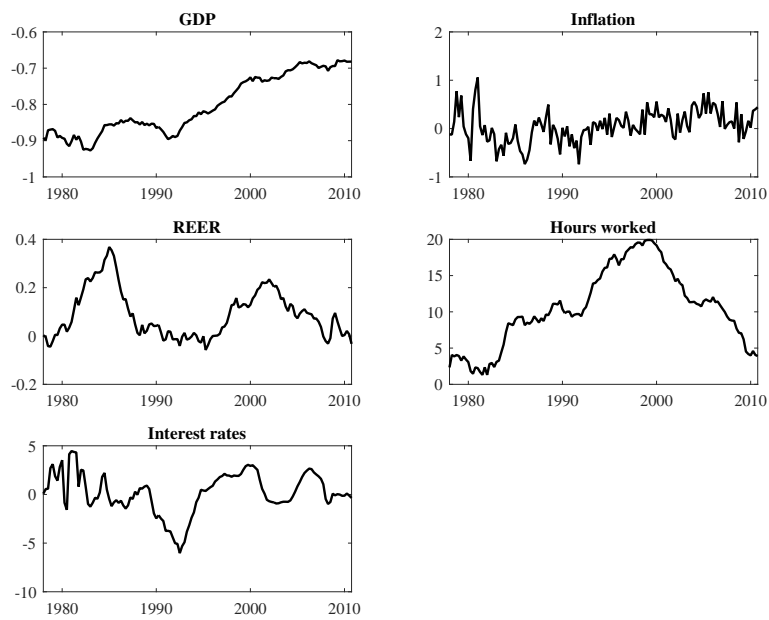


Figure 5: Data series used in baseline SVAR for the US vis-à-vis an aggregate of industrialized countries.