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NOMINAL RIGIDITIES AND THE REAL EFFECTS OF MONETARY POLICY IN A STRUCTURAL VAR MODEL[♣]

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Abstract

The paper proposes an empirical VAR for the UK open economy in order to measure the effects of monetary policy shocks from 1981 to 2003. The identification of the VAR structure is based on short-run restrictions that are consistent with the general implications of a New Keynesian model. The identification scheme used in the paper is successful in identifying monetary policy shocks and solving the puzzles and anomalies regarding the effects of monetary policy shocks. The estimated dynamic impulse responses and the forecast error variance decompositions show a consistency with the New Keynesian approach and other available theories.

JEL codes: C30; E30; E32; E52.

Keywords: Structural VAR; Nominal Rigidities; Monetary Policy Shocks; New Keynesian Theory

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1. Introduction

The vector auto-regression (VAR) methodology has become the most popular empirical method in studying the effects of monetary policy after the publication of the seminal paper by Sims (1980). During the past two decades there has been an extensive literature applying the VAR approach to estimating the effects of monetary policy. However, there is still a lack of consistency in the results. Different authors use different identifying assumptions, different sample periods and different data sets and consequently, produce plausible but not consistent results.[1]

In the framework of the VAR, the presence of puzzles in estimating the effects of monetary policy makes it difficult for researchers to interpret. In particular, the VAR practitioners often find a strong positive response of prices to a monetary policy restriction. This phenomenon is well known as the *price puzzle*. Sims (1992) argues that if the central bankers have information about inflation better than that can be estimated from VAR models they might know that inflationary pressure is about to arrive and so contract the money supply to dampen the effects of these pressures.

Furthermore, the phenomenon that the interest rate increases accompanying a rise in the money supply, known as the *liquidity puzzle*, also often appears in VAR models. In confronting the liquidity puzzle, Sims (1992) and Christiano and Eichenbaum (1995) argue that innovations in broad money aggregates are more likely to reflect other structural shocks, especially money demand shocks and they are not exogenous. They suggest the use of some

[1] See Walsh (2003, ch.1) for a recent survey.

variable that are under the direct control of the central bank, such as the short-term interest rate or the narrow monetary aggregate, as a measure of the monetary policy.

Recently, many papers such as Grilli and Roubini (1995), Kim and Roubini (2000), Astley and Garratt (2000), Fisher and Huh (2002) have tried to use the VAR approach to model open economies. In such models, along with the reaction of prices and interest rates to a monetary policy shock, the behavior of the exchange rate is also studied as another important criterion for assessing the plausibility of the VAR models. Unfortunately, many studies indicate that there is an *exchange rate puzzle* – that is, the exchange rate persistently depreciates following a monetary restriction rather than appreciates (see Grilli and Roubini, 1995 for example) as would be predicted by theoretical models with sluggish price adjustment of Dornbusch (1976). Sims (1992) and Grilli and Roubini (1992) argue that this anomaly of the exchange rate is probably due to the fact that the monetary contraction is implemented during the period when the depreciation is observed.

In addition to the impulse responses in the VAR framework, researchers also examine the forecast error variance decompositions to assess the relative importance of the monetary policy shocks in accounting for variance in both policy and non-policy variables of the system. Most of the authors find that monetary shocks are not major sources of output fluctuations in G-7 countries. More paradoxically, their models also suggest that money supply shocks play a more important role in longer horizons (e.g., Turner, 1993).

In this paper we apply the structural VAR approach, which was first developed by Bernanke (1986), Blanchard and Watson (1986) and Sims (1986), with the New Keynesian modeling strategy to study the effect of monetary policy for the United Kingdom. It is shown that the paper, with the given specification and data in question, does not suffer from the notorious puzzles found elsewhere in the literature and can provide evidence supporting the New Keynesian theory.

Up to now there are only a few empirical VAR models based on the New Keynesian perspective that can provide evidence consistent with the predictions of models that assume nominal rigidities and the real effects of money, especially for the United Kingdom. The structural VAR models such as Turner (1993) and Jenkins and Tsoukis (2000) are developed for the United Kingdom closed economy and show no significant role of money in accounting for output fluctuations or evidence of price or wage inertia. The results are not supportive for theoretical models with menu costs (Mankiw, 1985) or staggered price and wage contracts (Calvo, 1983 and Taylor, 1979). Moreover, the two models ignore the role of the interest rate as the main instrument of the Bank of England in establishing a monetary reaction function. As a consequence, they can not distinguish money demand shocks from monetary policy shocks. Monetary policy shocks are not exogenous and the price puzzle which is one of the most crucial criteria to judging the validity of the VARs appears.

The structural VAR we construct in this paper is based on short run restrictions that are consistent with the general implications of a New Keynesian model for the United Kingdom open economy. Contemporaneous restrictions are imposed to separate monetary policy shocks from money demand shocks. Our identification scheme is successful in identifying monetary policy shocks and solving the puzzles and anomalies regarding the effects of monetary policy shocks. The estimated dynamic impulse responses of the variables to a contractionary monetary policy shock show a consistency with the New Keynesian approach and other available theories. There is no liquidity, price, exchange rate, or forward premium puzzle. The responses of prices and wages indicate nominal rigidity as suggested by Calvo/Taylor type models with staggered contracts or by menu cost theory. The forecast error variance decompositions show that monetary policy shocks account for an extremely low proportion of fluctuations of nominal prices and wages. However, they contribute significantly, up to 40%, to real output movements. This striking evidence is strongly supported by recent dynamic general equilibrium models with sticky prices or sticky wages and makes our model different from most previous structural VARs.

The remainder of this paper is organized as follows. Section 2 describes econometric methodology. Section 3 describes data and pre-tests. Section 4 presents the structure of the model. Section 5 examines the effects of monetary policy shocks in the United Kingdom economy. Section 6 concludes.

2. Econometric Methodology

First of all, we briefly describe the econometric methodology used in this study. Following the structural VAR approach developed by Bernanke (1986), Blanchard and Watson (1986) and Sims (1986) we assume that the economy is described by a system of linear simultaneous equations which model the dynamic interaction between the time series variables as follows.

$$Ay_t = C + \varsigma(L)y_t + B\varepsilon_t \qquad (1)$$

where y_t is a vector of k time series variables; A and is the square matrix containing the structural contemporaneous parameters of the variables; C is the vector of deterministic variables; $\varsigma(L)$ is a matrix of polynomials, i.e. $\varsigma(L) = \varsigma_1 L + \varsigma_2 L^2 + ... + \varsigma_\rho L^\rho$; ε_t is the structural disturbance vector and by construction $E(\varepsilon_t) = 0$, $E(\varepsilon_t \varepsilon_s^{'}) = \Sigma_\varepsilon = I_k$ for $s = t$ and $E(\varepsilon_t \varepsilon_s^{'}) = 0$ otherwise; and B is the square matrix reflecting the contemporaneous relationship between structural disturbances and the time series variables. The non-zero off-diagonal elements of B allow some shocks to affect directly more than one endogenous variable in the system.

The matrices A and B are constructed based on economic theories. Pre-multiplying (1) by A^{-1} we have:

$$y_t = \delta + \phi(L)y_t + u_t \qquad (2)$$

where $\phi = A^{-1}\varsigma$ and u_t is the vector of reduced form VAR residuals which satisfies $E(u_t) = 0$, $E(u_t u_s^{'}) = \Sigma_u$ for $s = t$ and $E(u_t u_s^{'}) = 0$ otherwise. Σ_u is a $(k \times k)$ symmetric, positive definite matrix and determined by the data. The relation between the structural disturbances and the reduced form residuals are given by

$$u_t = A^{-1}B\varepsilon_t \qquad (3)$$

Consequently,

$$\Sigma_u = A^{-1}BB'A^{-1}{}' \qquad (4)$$

where the sample matrix of the reduced form residuals, Σ_u can be derived from the data as:

$$\Sigma_u = \frac{1}{T}\sum_{t=1}^{T}\hat{u}_t \hat{u}_t' \qquad (5)$$

The main purpose of structural VAR estimation is to obtain non-recursive orthogonalization of the error terms for impulse response analysis. This alternative to the recursive Cholesky orthogonalization requires us to impose enough restrictions to identify the orthogonal (structural) components of the error terms. Since the variance-covariance matrix Σ_u is a $(k \times k)$ symmetric, positive definite matrix and determined by the data we have $k(k+1)/2$ estimates. The structural coefficients in $(k \times k)$ square matrices A and B are unknown. The diagonal elements of A are normalized to 1s. Therefore, as long as we impose theoretical restrictions such that the total number of structural parameters to be identified in A and B is less than or equal to $k(k+1)/2$. This means that we impose at least $2k^2 - k(k+1)/2 = k(3k-1)/2$ restrictions, then all the structural parameters in A and B can be recovered from (4).

After the model is estimated the impulse response functions will be generated to trace the effects of a structural monetary policy shock on all the variables in the VAR system. A long with the impulse response functions we will also compute the forecast error variance decompositions to examine the relative importance of each random innovation in affecting the variables in the VAR. The computation of the impulse response functions and the forecast error variance decompositions can be found in Lütkepohl and Krätzig (2004, chapter 4).

3. Data and Pre-tests

In this study, since monthly data for output and employment are not available we use quarterly series for the sample period from 1981:2 to 2003:2. This sample is chosen based on the availability of the data and to avoid the structural shift in monetary policy operation of the Bank of England during 1979-1981 resulting from the establishment of the European Monetary System in 1979 and the oil crisis in the 1979-1980. All the series are taken from National Statistics (except for the interest rate which is taken from the Bank of England), seasonally adjusted (except for the retail price index, the interest rate and the exchange rate), and in logarithmic form (except for the interest rate). A complete set of dummy seasonal dummies is included in the price equation in order to take into account the seasonality of the variable[2].

Following most papers in the VAR literature (Sims, 1980, 1992, Leeper et al., 1996, Kim, 1999, and Kim and Roubini, 2000, etc.), we do not investigate the possible cointegrations or impose any long-run restrictions among variables. Given the relatively small size of our data set, tests for integration and cointegration are likely to have low power. If we impose false restrictions the economic inference would be incorrect at later stage. Furthermore, endogenous growth models with nominal rigidities suggest that the long run neutrality of money restriction may be invalid since any temporary disturbance can have a permanent effect on output as long as it reallocates the amount of resources used for productivity improvements. Therefore, we estimate the model in log-level form without imposing any long run restrictions.

[2] The dummies in the price equation are jointly statistically significant at conventional levels. However, the estimation results are not sensitive to the exclusion of these variables.

The time series vector is $(n, y, p, w, m, r, e)'$, where n is total employee jobs, y is real gross domestic product, p is the retail price index, w is the wage index, m is the monetary aggregate, r is the interest rate measured as the official bank rate, and e is the exchange rate index. Employment, output, prices, the monetary aggregate and the interest rate are commonly used in analyzing business cycles. Since the model aims to examine different sources of nominal rigidities, the nominal wage variable is also included. The exchange rate variable is the average rate (of a basket of currencies) against Sterling as used in Garratt et al (2003) and Osborn and Sensier (2004). This variable is included in the model to allow for the Bank of England to use information about the values of other currencies in setting the monetary rule in order to stabilize the value of Sterling. Moreover, fluctuations in the exchange rate index partly reflect changes in world prices. Therefore, the inclusion of the exchange rate index also allows the Bank of England to respond to foreign price shocks and reduces the problem of endogeneity of monetary shocks.

We use the retail price index instead of the more common CPI because, as noted in Osborn and Sensier (2004), the UK inflation target relates to the retail price index[3]. Since M1 or M2 are not available for the UK we choose M0 rather than M4 as in other VAR models of the UK by Jenkins and Tsoukis (2000) and Garratt et al (2003). Finally, we use the official bank rate which is under direct control by the bank of England as the monetary policy variable. The Bank seeks to meets their targets through the decisions on the official bank rate taken by the Monetary Policy Committee. When the official bank rate is set, the commercial banks change their own base rates from which deposit and lending rates are calculated. The interest rate set

[3] CPI has only been used by the Bank of England since the beginning of 2004 which is out of the sample of this study.

by the Bank is quickly passed throughout the financial system, influencing interest rates for the whole economy[4].

We limit the maximum lag length of the model to six and implement the lag length test. Since different criteria for minimising the forecast MSE indicate different lag length orders we do rely on any single information criterion. Instead, we first perform different VAR orders and then check the whiteness of the residuals with different types of tests in order to choose an adequate VAR order. Both Portmanteau and LM-type tests for autocorrelation indicate that that VAR(3) should be estimated.[5] Finally, due to small sample problem the Chow test for structural stability may not be reliable. Therefore, as in other VAR models of the UK (e.g., Jenkins and Tsoukis, 2000, and Garratt et al, 2003) we do not carried out structural break tests. The sample period is chosen so as to avoid all possible structural breaks as mentioned above.

4. Structure of the Model

The model presented here is similar to that of Blanchard and Watson (1986) and Turner (1993). The ordering of the quarterly time series vector is $(n, y, p, w, m, r, e)'$. After the VAR was estimated, we identified the *A* and *B* matrices that orthogonalized the variance-covariance matrix of the residuals. Equation (3) can be described as follows.

[4] See the Bank of England website for the detail of how the monetary policy works.
[5] All the key estimation results still hold for VAR(4) model.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & 1 & a_{34} & 0 & 0 & 0 \\ 0 & a_{42} & 0 & 1 & 0 & 0 & 0 \\ 0 & a_{52} & a_{53} & 0 & 1 & a_{56} & 0 \\ 0 & a_{62} & a_{63} & 0 & 0 & 1 & a_{67} \\ 0 & 0 & a_{73} & 0 & a_{75} & a_{76} & 1 \end{bmatrix} \times \begin{bmatrix} u_n \\ u_s \\ u_p \\ u_w \\ u_{md} \\ u_{mp} \\ u_e \end{bmatrix} = \begin{bmatrix} b_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_{22} & 0 & 0 & 0 & b_{26} & 0 \\ 0 & 0 & b_{33} & 0 & 0 & 0 & 0 \\ b_{41} & 0 & 0 & b_{44} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & b_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_{77} \end{bmatrix} \times \begin{bmatrix} \varepsilon_n \\ \varepsilon_s \\ \varepsilon_p \\ \varepsilon_w \\ \varepsilon_{md} \\ \varepsilon_{mp} \\ \varepsilon_e \end{bmatrix}$$

where $\varepsilon_n, \varepsilon_s, \varepsilon_p, \varepsilon_w, \varepsilon_{md}, \varepsilon_{mp}$ and ε_e are the structural disturbances, that is, labor supply shocks, supply shocks, price shocks, wage shocks, money demand shocks, monetary policy shocks and exchange rate shocks, respectively. The terms $u_n, u_s, u_p, u_w, u_{md}, u_{mp}$ and u_e are the residuals in the reduced form VAR, which represent unexpected changes of each variable in the system. The presence of the non-triangular shape of the A matrix (which allows for the separation of the monetary policy and money demand equations and for the contemporaneous interaction between the interest rate and the exchange rate), coupled with the non-zero off-diagonal elements of the B matrix (which allows some structural shocks to affect directly more than one endogenous variable in the system) differentiates this model from the recursive VAR formulation.

Given this identification, and ignoring the lagged structural parameters, the contemporaneous relationships between variables in the structural model can be written as:

(i) $n = b_{11}\varepsilon_n$

(ii) $y = -a_{21}n + b_{22}\varepsilon_s + b_{26}\varepsilon_{mp}$

(iii) $p = -a_{32}y - a_{34}w + b_{33}\varepsilon_p$

(iv) $w = -a_{42}y + b_{41}\varepsilon_n + b_{44}\varepsilon_w$

$$(v) \qquad m = -a_{52}y - a_{53}p - a_{56}r + b_{55}\varepsilon_{md}$$

$$(vi) \qquad r = -a_{62}y - a_{63}p - a_{67}ex + b_{66}\varepsilon_{mp}$$

$$(vii) \qquad e = -a_{73}p - a_{75}m - a_{76}r + b_{77}\varepsilon_{e}$$

Generally, with this identification we follow the New Keynesian economics in the sense that due to menu costs or Calvo/Taylor staggered settings, nominal prices and wages respond to unexpected changes in financial markets only with a lag. The monetary aggregate, the interest rate and the exchange rate are all excluded from equations determining prices and wages. More concrete discussion for each equation is presented below.

Initially, equation *(i)* implies that employment is determined solely by the labor supply disturbances, ε_n and not affected simultaneously by other variables. That is, within a period, firms cannot adjust their employment in response to unexpected changes in product or financial markets due to adjustment costs (e.g., firms have to pay compensations when they lay off workers before the labor contracts expire). Real output is determined through equation *(ii)* according to an Okun's law relationship with employment. With employment included, the supply disturbances in this equation can be interpreted as productivity shocks. Furthermore, equation *(ii)* assumes that output is also determined by the monetary policy disturbances. An argument for this identification is that a monetary policy restriction can affect investment and this is more likely to create productivity innovations hence increasing output. This assumption will be verified by examining the sign and the significance of the coefficient b_{26} in matrix B discussed later.

Equation *(iii)* states that the price is determined according to a marginal productivity condition along with its own disturbances ε_p as in Turner (1993). Prices are responsive to changes in wages since firms set price as a mark-up of labor costs. Equation *(iv)* implies that the wage is determined by output, employment disturbances and its own disturbance. The productivity (TFP-like) disturbance, ε_s may affect the wage equation in some way however, instead of introducing it directly in the equation we use output since most of the effect of the productivity disturbance on the wage is transmitted through the effect it has on output. In addition, the wage series includes bonuses thus this assumption is quite appropriate. All the variables in the financial markets are excluded from equations determining prices and wages to reflect the nominal inertia.

We employ a standard money demand function. The demand for real money balances depends on real income and the nominal interest rate - the opportunity cost of holding money. Therefore, in equation *(v)* all the other variables are contemporaneously excluded. Equation *(vi)* plays the most important role in the model. It is known as the monetary feedback rule or monetary reaction function. This equation is a modified Taylor's rule and implies that, within a quarter, the monetary authority sets the interest rate after observing the current values of output, prices, and the exchange rate. However, employment is excluded due to information delays. By including the exchange rate in the monetary reaction function the concern of the Bank of England about the effects of a depreciation of Sterling on inflation can be taken into account and the systematic responses to foreign shocks are believed to be excluded from the monetary policy shocks. ε_{mp} is known as a monetary policy shock. It represents an unexpected change in the short-term interest rate.

The last equation describes the exchange rate market. We assume that only prices, the interest rate and the money supply can affect the nominal exchange rate simultaneously. This assumption is based on purchasing power parity (PPP) condition and uncovered interest parity (UIP) condition. All other variables are excluded from the equation reflecting the delayed impact of variables such as output and employment on the exchange rate through import and export activities.

In summary, the contemporaneous structure is composed of several blocks. Equations *(i)* and *(iv)* describe labor market equilibrium. Meanwhile equation *(ii)* and *(iii)* reflect the equilibrium in product market. Money demand and money supply functions illustrated by equations *(v)* and *(vi)* describe monetary market equilibrium. Finally, the exchange rate market is summarized by equation *(vii)*. Next we will examine the plausibility of the identification by looking at the sign and standard error of the estimated coefficients in matrices A and B as well as implementing LR test for over-identification.

Estimation of A and B matrices

We choose a normalization so that the diagonal elements of the factorization matrix $A^{-1}B$ are all positive. This normalization ensures that all structural impulses have positive signs (as does the Cholesky factorization). Provided that A and B are non-singular they can be estimated by maximum likelihood. Table 1 reports the estimates of all the elements in the matrices A and B.

Most of the coefficients in the matrices A and B have the correct signs and relatively low standard errors. Importantly, all coefficients in the equation describing monetary policy have the correct sign. Coefficient a_{62} and a_{63} are negative. This implies that the monetary authority raises the interest rate when it observes unexpected increases in output and prices. That is, the Bank of England takes a contractionary policy against a boom in the economy. Additionally, the positive sign of a_{67} means that the monetary authority also increases the interest rate to stabilize the value of domestic currency when there is unexpected exchange rate depreciation.

Coefficient a_{21} is negative reflecting the positive relationship between employment and output as stated by Okun's law. A negative a_{34} implies cost push inflation in equation *(iii)*, while a negative a_{42} implies that wages (included bonuses) are positively proportional to output. The sign of a_{73} is questionable because, if home prices increase relative to foreign prices then according to the PPP condition the exchange rate will fall and a_{73} in equation *(vii)* should be positive. Otherwise, a_{73} will be negative. Moreover, under capital mobility, the UIP condition requires that a fall in the domestic money supply or an innovation in the domestic interest rate should be followed immediately by an appreciation of the home currency, otherwise there is a exchange rate puzzle. Therefore, a_{75} and a_{76} should be positive and negative respectively.

Finally, Coefficients b_{26} and b_{41} which determine the contemporaneous impact of money shocks on real gross domestic product and of employment shocks on wages respectively have expected signs and relatively low standard errors. Importantly, all the diagonal elements of the matrix B which are the standard deviations of the structural shocks are statistically significant at 5%. This may indicate that the structural shocks are well identified in the model. Some coefficients in the matrix A have moderate standard errors. However, these seem to be due to the multicollinearity rather than due to low significance.

Since we impose six restrictions more than the minimum required, the Structural VAR is over-identified at six degrees of freedom. Table 2 reports LR test for over-identification. The LR test statistic is computed and given in the table.[6] Under the null hypothesis that the restrictions are valid, the LR statistic is asymptotically distributed $\chi^2(q)$ where q is the number of over-identifying restrictions. The result suggests that the structure can not be rejected at any conventional significance level.

5. The Effects of Monetary Policy Shocks

5.1 The Expected Effects of a Contractionary Monetary Policy

Before reporting the empirical results we briefly discuss the expected movements of the variables in response to a monetary contraction. Furthermore, we also summarize the expected contribution of a monetary policy shock to fluctuations of output in the economy. If the variables react as theoretically predicted the model can be considered plausible.

As mentioned above, VAR practitioners consider the absence of some puzzles, such as the price and liquidity puzzles, as criteria for the validity of a model. If such puzzles appear there is no way to say that the identified monetary policy shocks in our model precisely represent true monetary shocks. A monetary contraction must be accompanied by a fall in the money supply and a rise in the interest rate. The duration of the impact of the action on the interest rate depends on the degree of nominal stickiness. The higher the nominal inertia, the more persistent the effect becomes. If the menu cost theory proposed by the New Keynesian School

[6] Test detail is provided in Lütkepohl and Krätzig (2004).

is valid, prices and/or wages do not decrease immediately. Consequently, employment and output must decline at least in the short-run following the contraction.

Additionally, in a model with the exchange rate included, the absence of the anomaly of the exchange rate behavior is also another important criterion for judging the validity of the model. Given expected inflation, an increase in the interest rate is predicted to lead to an appreciation of the domestic currency. Under rational expectations, the appreciation of the exchange rate occurs as long as prices are sticky and there is an increase in the real interest rate after the monetary contraction. For this point, the Dornbusch (1976) "overshooting" model with sluggish price adjustment suggests that a negative monetary innovation will have a positive impact on nominal interest rates and lead to an initial appreciation in the home currency. However, according to the UIP condition, this appreciation will create the forward premium puzzle; by borrowing aboard and then investing in domestic assets people can earn extra profits. Therefore, if the UIP condition holds the value of the home currency must fall after the initial appreciation following the monetary contraction. With a high degree of sensitiveness of the financial markets this depreciation is expected to happen after one or two quarters.

In computing forecast error variance decompositions, we can evaluate the importance of monetary policy in the model. As claimed by Leeper et al. (1996) and Christiano et al. (1996), for a good monetary policy, most variations in monetary policy instruments must be attributable to systematic responses of policy to the development of the economy, not to random disturbances to policy behavior. In addition, according to the New Keynesian approach, monetary policy shocks, while not contributing much to price and wage movements, should play an important role in output fluctuations at least in the short run. The effects on real output should die out gradually in the medium run. Furthermore, for the theoretical validity of the model the role of the productivity shocks can not be denied.

5.2 Impulse Response Functions

In this subsection we mainly examine the effects of a contractionary monetary shock on the system through the estimated impulse response functions. In our model the monetary authority sets the interest rate as a monetary policy instrument. This is consistent with the performance of the Bank of England in practice. The monetary policy feedback rule can be expressed as follows.

$$r_t = \phi_0 + \phi_1 y_t + \phi_2 p_t + \phi_3 e_t + \text{lag terms of all variables} \quad (7)$$

First we discuss the consequences of a monetary policy shock in detail and consider how they comply with the New Keynesian theory. Then we will decompose the variance of each variable in the system to examine the relative importance of each variable to the fluctuations of other variables.

The estimated impulse responses of the system to a one-standard-error monetary policy shock are plotted in Figure 2. The upper and lower dashed lines in each graph are two-standard-error bands computed by Hall's percentile interval bootstrap method. These bands allow us to determine whether the responses of the variables are significant or not at 95% confidence level. As implied by the structure of the model, an innovation in the interest rate does not have contemporaneous impact on nominal prices and wages but it does on money demand, exchange rates and output. Figure 2 shows that, in response to a contractionary monetary policy shock, the interest rate rises and the monetary aggregate falls significantly. This pattern is consistent with liquidity effects. The impact response of the interest rate is always positive following a contractionary monetary policy. However, it will gradually turn to the initial level due to the deflation after the contraction.

More interesting, the monetary contraction starts to reduce prices and wages significantly only after about two quarters. The response graph of nominal prices and nominal wages show that they are sticky. Initially, they do not simultaneously decrease even though the rise in the interest rate and the fall in the money supply are very significant. The response of nominal prices shows a little bit more hysteresis. The pattern is consistent with New Keynesian theory of menu cost and staggered contracts and suggests that prices and wages are quite persistent in the United Kingdom economy. Both prices and wages tend to return to their long-run equilibrium levels in two or three years after the monetary contraction. Generally, the effects of the monetary contraction on prices and wages are very satisfactory in the context of the New Keynesian theory. There is no evidence of price or wage puzzles. After the shock, the price and wage levels do not respond much. They only start falling substantially in about two or three quarter.

Consider next the effects of the monetary contraction on employment and output. Both employment and output have the expected reactions. Employment decreases and reaches its trough after about two years following the shock. It also shows a lag in response as compared to output. This fact implies that, in facing a recession, firms adjust their production before they can fire workers since labor contracts are always signed for long-term. The response of output implies the non-neutrality of money, i.e. a change in money lead to a change in output. The output level declines significantly right after the monetary contraction. It gets the lowest level after about one year and tends to rise again when prices start to return gradually to the initial level. The figure shows that the declines in the employment and output levels are very persistent. They approach their long-run equilibrium levels about five years following the contraction.

Finally, consider the effects of monetary shocks on the Sterling exchange rate. The response of the exchange rate index also fits quite well with the theoretical behavior of the exchange rate after a monetary contraction under the flexible exchange rate regime. Sterling appreciates immediately following an innovation in the domestic interest rate. However, this appreciation is short-lived reflecting a high degree of responsiveness of the financial market. After the initial appreciation the exchange rate depreciates. This is not surprising because the UIP states that under perfect capital mobility and rational expectations the following condition must be satisfied:

$$r_t^d = r_t^f - (e_{t+1} - e_t) \tag{8}$$

where e_t is the price of Sterling against foreign currencies, and r_t^d and r_t^f are domestic and foreign interest rates respectively. Other things being equal, after an increase in the home interest rate the home currency must depreciate otherwise there is a forward premium puzzle; an investor can earn extra profits by borrowing abroad and then investing into the United Kingdom financial assets. The behavior of the exchange rate in our model fits quite well with existing theories about exchange rates. A persistent depreciation follows quite soon after the impact change in the interest rate. The delayed overshooting lasts for only up to two quarters. On this point, most of the previous VAR models such as Eichenbaum and Evans (1995), Grilli and Roubini (1995) observed the persistence of appreciation for more than two years after the initial monetary shocks. Kim and Roubini (2000) also find the delayed overshooting for about two years for the United Kingdom economy and about one year for other G-7 countries. These periods of delayed overshooting are too long and do not illustrate the sensitivity of the financial market.

5.3 Forecast Error Variance Decompositions

Along with the impulse response functions we compute the forecast error variance decompositions (FEVDs) to assess the relative importance of the structural shocks in accounting for variance in both policy and non-policy variables of the system. This is a useful way to determine whether monetary shocks have much contribution to fluctuations in output or not. Table 3 reports the FEVDs for employment, output, prices, wages, monetary aggregates, interest rates and exchange rates for various time horizons. At the top are the structural shocks. Each value in the tables shows the fraction of the forecast error variance for the corresponding variable that is attributed to the column variable shocks. The far-left column presents the time horizons in quarters.

Table 3(a) shows that most of the employment fluctuations are attributable to its own shocks. Output and monetary policy shocks have a little role, about 10% each after one year, in forecast error variance of employment. However, their contributions rise remarkably in the medium and long run. Table 3(b) reports the FEVD for output. As predicted by New

Keynesian theory, monetary policy shocks account for up to 40% of real output variance at a quarter horizon. The importance of the monetary policy shocks gradually reduces to about 30% after one year. In the VAR literature, most of the authors find that monetary shocks are not major sources of output fluctuations in G-7 countries. More paradoxically, their models also suggest that monetary policy shocks play a more important role in longer horizons. In particular, Turner (1993) and Jenkins and Tsoukis (2000) in their structural VAR models for the United Kingdom conclude that the forecast error variance for real output is mostly determined by its own shocks, and that monetary shocks contribute less than 15% output variance at a horizon of three years.

In addition, price and wage shocks which can be interpreted as cost-push shocks contribute almost nothing to output fluctuations at one quarter horizon. However, price shocks make up about 10% of output fluctuations at one year horizon and this proportion increases further, to about 25%, in the long run. Employment shocks also play a low role, about 5%, in output variance at almost horizons. Meanwhile, the role of technological shocks, the crucial determinant of output fluctuations in the Real Business Cycles literature, can not be denied. They account for more than 40% of output variance at all most horizons. Finally, money demand and exchange rate shocks contribute extremely little to output fluctuations. This evidence implies that the United Kingdom economy is quite independent of foreign shocks. Most of the forecast error variance of real gross domestic product is determined by productivity and monetary shocks. This evidence, coupled with nominal rigidities given by the impulse response functions, strongly supports the New Keynesian type models.

Tables 3(c) and 3(d) present the FEVDs for prices and wages respectively. As can be seen, at any horizon, more than 50% of price and wage fluctuations are due to their own shocks. In particular, price shocks account for approximately 80% of price fluctuations at one and two quarter horizon and more than 50% thereafter. Employment shocks and wage shocks play a moderate role in price fluctuations, with about 10% of the fluctuations comes from employment shocks and about 5% comes from wage shocks at four quarter horizon. Monetary policy shocks almost have no contribution to price variance within four quarters. Their role rises up to only 10% afterwards. Money demand shocks and exchange rate shocks also play a very modest role in price variance. Meanwhile, Table 3(d) also indicates that most of wage fluctuations are attributable to its own shocks, with more than 50% after two years. Employment shocks play a moderate role of up to 10% at almost horizons. In addition, output shocks account for about 15% and 30% of wage fluctuations after one and two years respectively. Monetary policy shocks as well as other shocks contribute very little to wage fluctuations.

The FEVDs for monetary aggregates and interest rates are reported in Table 3(e) and Table 3(f) respectively. Table 3(e) shows that a very large proportion, more than 65%, of monetary aggregate movements are from its own shocks at two quarter horizon. Interest rate and price shocks, which are the important determinants of demand for money, play a remarkable role. They collectively contribute up to about 40% to money demand variance after one year. However, income contributes very little. This is not surprising because we use M0 as the monetary aggregate and most of its movements are determined by the central bank behavior. Interestingly, Table 3(f) shows that, almost all fluctuations in interest rates are attributable to the shocks of other variables rather than its own shock. This suggests that the interest rate, the monetary policy instrument in the model, is not decided by the random behavior of the central bank but rather that it adapts to the unexpected changes of other economic variables. Equation (7) can be considered as a good monetary policy reaction function of the central bank, as claimed by Leeper et al. (1996) and Christiano et al. (1996).

Among the variables, the exchange rate plays the most important role in explaining the movements in monetary policy. It accounts for 40% of the fluctuations in the interest rate at one quarter horizon. This fact can explain why even the United Kingdom economy is a small one but foreign shocks are not major sources of output fluctuations as shown in Table 3(b). Prices play the second most important part in explaining interest rate fluctuations with more than 30% at two quarter horizon. These results are very reasonable since, in practice, the inflation rate and the exchange rate are the two most important objectives of the Bank of England. They set the target for inflation at around 2% annually and also deal in the exchange rate market every day to control the value of Sterling in terms of other currencies. In order to control inflation and the value of the Sterling the monetary policy maker must set the interest rate systematically reacting to the developments of prices and exchange rates. Employment, output and wage shocks contribute moderately to interest rate movements, around 5%, at one year horizon. However, the contribution of output shocks increases significantly in the long run, up to 25% of interest rate fluctuations.

Finally, the FEVD for nominal exchange rates is presented in Table 3(g). Monetary policy shocks are the most important source of nominal exchange rate fluctuations. They account for around 40% and 30% of exchange rate movements at one and two quarter horizons respectively. This evidence is strongly supported by Kim and Roubini (2000) and Fisher and Huh (2002). In a structural VAR model for G-7 countries, Kim and Roubini (2000) find that monetary policy shocks explain a very large proportion of nominal exchange rate movements in the short run. They account for about 34% and 29% of nominal exchange rate fluctuations in the United Kingdom at six and twelve month horizon respectively, a very similar result with our model. Fisher and Huh (2002), in another structural VAR model for G-7 economies, also find a very similar result for the United Kingdom.

Employment and output shocks also account for a high proportion, about 30% and 20%, of nominal exchange rate movements after one year. This is because changes in income can lead to changes in trade balances and hence the demand for foreign currencies. This effect is significant only in the medium run. Additionally, price and wage shocks contribute almost nothing to nominal exchange rate variance. This evidence may suggest that the PPP condition does not hold.

5. Conclusions

In this paper we employed a structural VAR approach to study the effects of monetary policy in the United Kingdom during the last twenty years. We identified the structural VAR model based on the New Keynesian theory. The identification scheme is successful in identifying monetary policy shocks and solving the puzzles and anomalies regarding the effects of monetary policy shocks. The estimated dynamic impulse responses of the variables to a contractionary monetary policy shock show a consistency with the New Keynesian approach and other available theories. There is no liquidity or price/wage puzzle. The responses of prices and wages indicate nominal rigidities as implied by Calvo/Taylor type models with staggered contracts or by menu cost theory. At the aggregate level, prices and wages almost do not respond within one or two quarters after a monetary innovation. This consequently allows monetary policy shocks to have significant effects on real variables of the economy such as output and employment. The impulse response functions also suggest that nominal prices are a little stickier than nominal wages in the United Kingdom economy. Additionally, in the context of an open economy, our model also contributes to solving the exchange rate puzzle which quite often appeared in previous studies for the United Kingdom. As predicted by theory, the nominal exchange rate appreciates right after the monetary contraction. However, this appreciation lasts only for a few months. This provides evidence that the delayed overshooting is not a problem and the UIP holds in our model.

Coupled with the impulse response functions, we generate the FEVDs which measure the relative importance of each variable to the fluctuations of the others in the system. The results show that monetary policy shocks account for an extremely low proportion of fluctuations in prices and wages. However, they contribute significantly to real output movements, more than 30%, in the short run. The role of monetary shocks gradually decreases in the medium run as prices and wages adjust. This striking evidence is strongly supported by recent dynamic general equilibrium models with sticky prices or wages and makes our model different from most previous structural VARs.

The FEVDs also indicate that production costs play an important role in price determination of enterprises, with cost-push shocks accounting for more than 50% of fluctuations in prices. Moreover, the significant contributions of exchange rate and price shocks to monetary instrument fluctuations are consistent with the operation of the Bank of England in practice. Last but not least, our model does not deny the contribution of productivity shocks which make up about 30% of employment and 40% real output fluctuations in the long run respectively. Overall, the results presented above are in line with the New Keynesian models and show the validity of the identification scheme used in our structural VAR model.

APPENDIX: DATA DESCRIPTION

All data are obtained from National Statistics (except for the interest rate which is taken from the Bank of England website). They are measured in quarterly frequency from 1981:Q2 to 2003:Q2 and include:

- Y: Gross Domestic Product at constant 1995 prices, seasonally adjusted, code ABMI.
- N: United Kingdom Employee Jobs, total – thousands, seasonally adjusted, code BCAJ.
- M0: Wide Monetary Base (end period), level #m, seasonally adjusted, code AVAE.
- R: The Official Bank Rate - not seasonally adjusted, code BEDR.
- P: All items Retail Prices Index (January 1987=100) - RPI, not seasonally adjusted, code CHAW.
- W: Whole economy wages (include bonuses) index, seasonally adjusted, Index 2000 = 100, code LNMQ (AEI).
- Ex: Average Rates against Sterling, Sterling Effective Exchange rate index 1990=100, not seasonally adjusted, code AJHX.

The model was estimated using JMulti software provided by Lütkepohl and Krätzig (2004).

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Figure 1: The Time Series (Log-Levels)

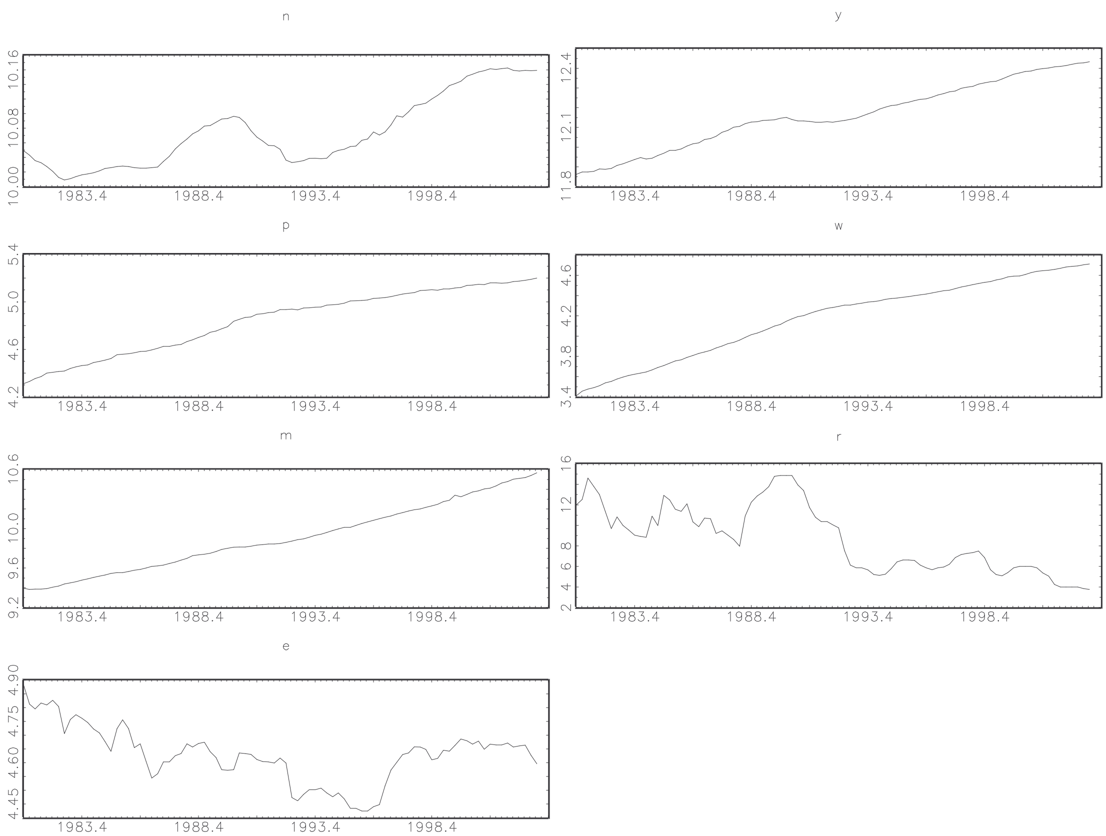
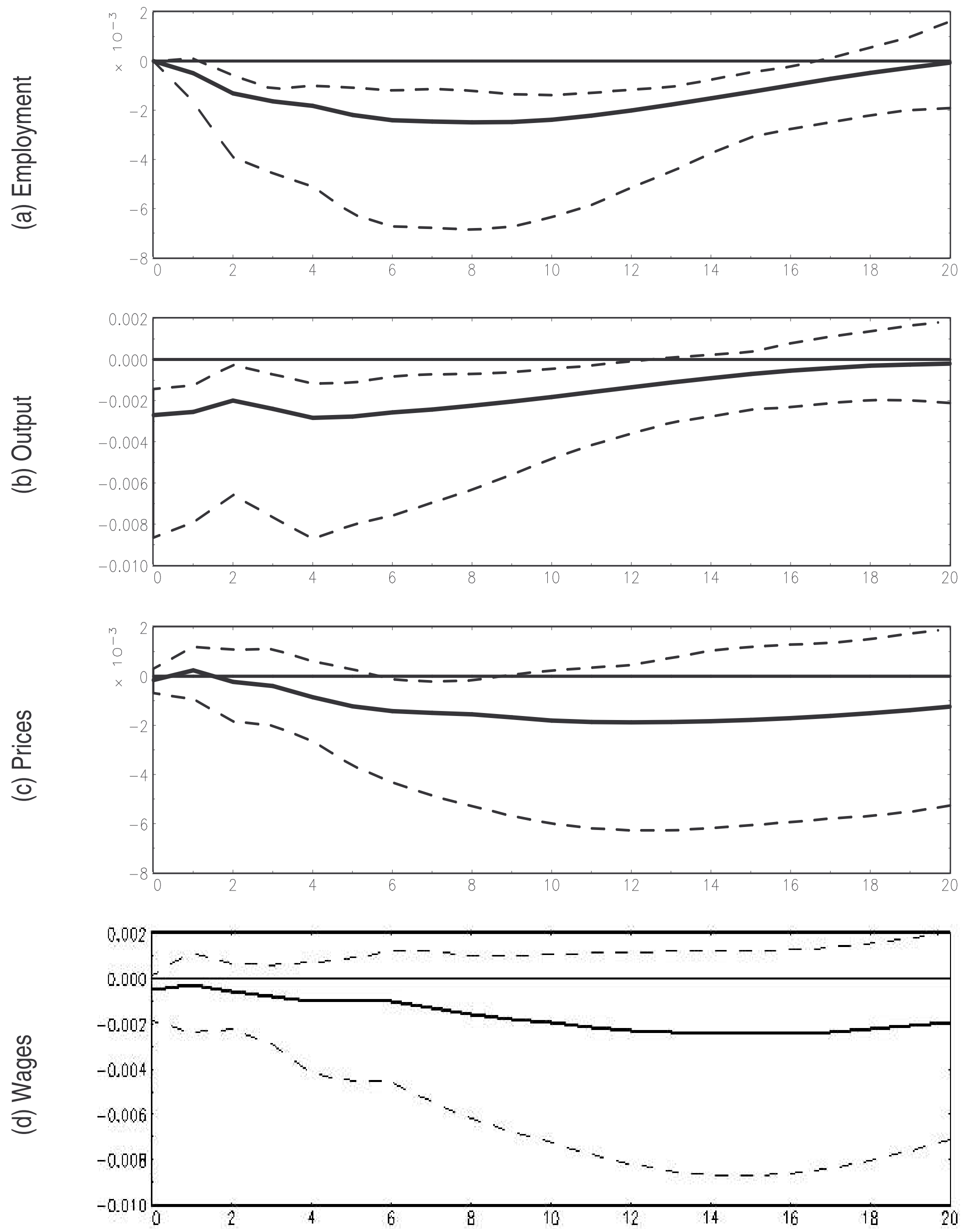
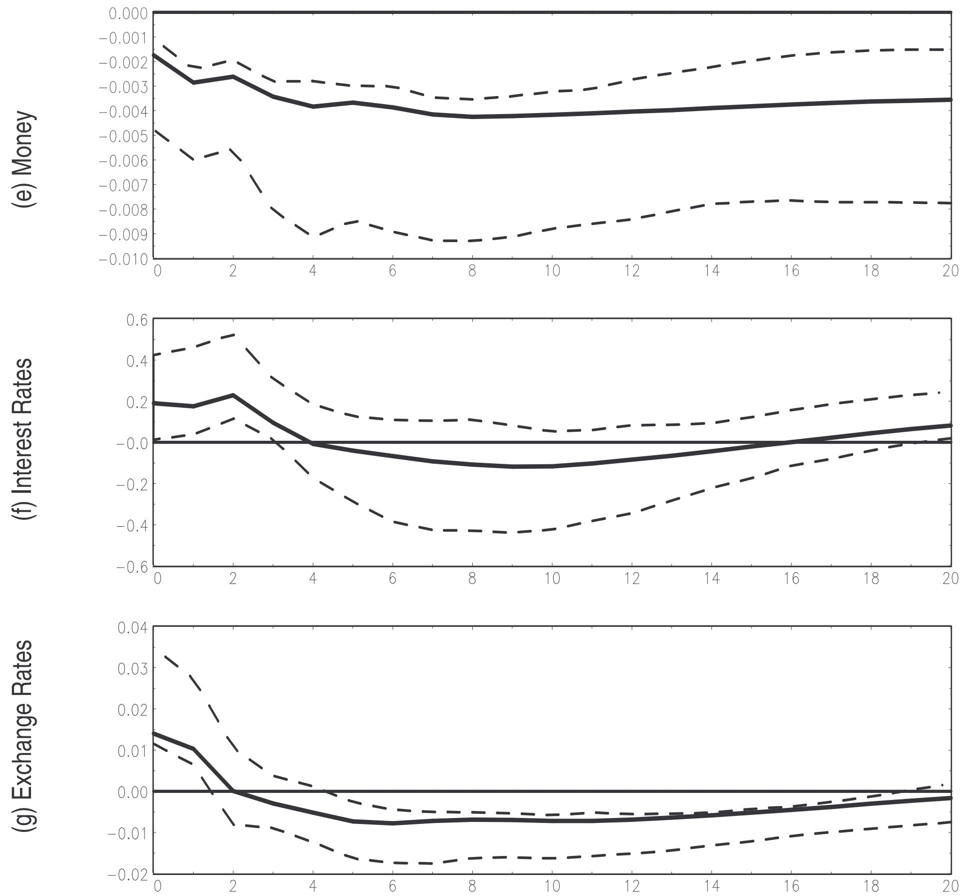


Figure 2: Impulse Responses to a One-Standard Error Monetary Policy Shock





(e) Money
(f) Interest Rates
(g) Exchange Rates

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Table 1: Coefficient in Matrices A and B of the Structural Model

	Expected Sign	Coefficient	Std. Error
Matrix A			
a_{21}	-	-0.258	0.155
a_{32}	-	-0.010	0.082
a_{34}	-	-0.251	0.101
a_{42}	-	-0.198	0.086
a_{52}	-	-0.399	0.149
a_{53}	-	-0.448	0.367
a_{56}	+	0.003	0.003
a_{62}	-	-131.470	149.575
a_{63}	-	-72.888	30.661
a_{67}	+	28.905	19.690
a_{73}	?	5.228	3.759
a_{75}	+	2.492	2.316
a_{76}	-	-0.047	0.039
Matrix B			
b_{26}	-	-0.003	0.001
b_{41}	+	0.000	0.000
b_{11}	+	0.003	0.000
b_{22}	+	0.003	0.001
b_{33}	+	0.003	0.000
b_{44}	+	0.003	0.000
b_{55}	+	0.006	0.000
b_{66}	+	0.962	0.559
b_{77}	+	0.035	0.018

Table 2: LR Test for Over-Identification

Log likelihood	LR Test Chi-square(6)	Probability
2508.854	9.129	0.166

Table 3: Forecast Error Variance Decompositions

(a) Employment

Hz	N	Y	P	W	M	R	E
1	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.94	0.04	0.00	0.00	0.01	0.01	0.00
3	0.83	0.08	0.00	0.00	0.01	0.07	0.00
4	0.74	0.10	0.01	0.00	0.03	0.12	0.00
5	0.63	0.14	0.03	0.00	0.05	0.15	0.01
6	0.52	0.18	0.04	0.01	0.06	0.18	0.01
7	0.44	0.21	0.05	0.01	0.07	0.20	0.02
8	0.37	0.23	0.07	0.01	0.08	0.22	0.02
9	0.32	0.25	0.08	0.01	0.08	0.23	0.03
10	0.28	0.26	0.09	0.02	0.09	0.24	0.03
11	0.25	0.26	0.10	0.02	0.08	0.25	0.03
12	0.23	0.26	0.11	0.02	0.08	0.25	0.04

(b) Output

Hz	N	Y	P	W	M	R	E
1	0.03	0.55	0.00	0.00	0.00	0.42	0.00
2	0.03	0.54	0.01	0.01	0.00	0.40	0.00
3	0.04	0.53	0.05	0.02	0.01	0.34	0.01
4	0.03	0.53	0.08	0.01	0.01	0.31	0.02
5	0.03	0.50	0.11	0.01	0.02	0.31	0.02
6	0.02	0.48	0.14	0.01	0.02	0.30	0.03
7	0.02	0.47	0.16	0.01	0.02	0.29	0.03
8	0.02	0.46	0.18	0.01	0.02	0.28	0.04
9	0.03	0.45	0.19	0.01	0.02	0.27	0.04
10	0.04	0.43	0.20	0.00	0.02	0.26	0.04
11	0.05	0.42	0.21	0.00	0.02	0.25	0.04
12	0.06	0.40	0.22	0.00	0.02	0.25	0.04

(c) Prices

Hz	N	Y	P	W	M	R	E
1	0.00	0.00	0.93	0.07	0.00	0.00	0.00
2	0.03	0.01	0.88	0.03	0.04	0.00	0.02
3	0.06	0.01	0.77	0.05	0.08	0.00	0.03
4	0.08	0.01	0.72	0.06	0.10	0.00	0.03
5	0.10	0.02	0.69	0.06	0.10	0.01	0.03
6	0.11	0.02	0.68	0.06	0.09	0.02	0.03
7	0.11	0.01	0.66	0.07	0.08	0.03	0.03
8	0.12	0.02	0.64	0.07	0.08	0.04	0.03
9	0.13	0.02	0.62	0.08	0.07	0.05	0.03
10	0.14	0.04	0.58	0.09	0.07	0.06	0.03
11	0.14	0.06	0.55	0.10	0.06	0.07	0.03
12	0.14	0.09	0.51	0.11	0.06	0.08	0.02

(d) Wages

Hz	N	Y	P	W	M	R	E
1	0.00	0.03	0.00	0.94	0.00	0.03	0.00
2	0.01	0.15	0.01	0.79	0.01	0.01	0.00
3	0.05	0.13	0.02	0.77	0.01	0.02	0.00
4	0.07	0.14	0.02	0.73	0.01	0.03	0.00
5	0.08	0.17	0.03	0.67	0.01	0.04	0.01
6	0.09	0.20	0.03	0.63	0.01	0.05	0.01
7	0.09	0.23	0.03	0.59	0.00	0.05	0.01
8	0.10	0.27	0.03	0.54	0.00	0.05	0.01
9	0.10	0.31	0.03	0.50	0.00	0.06	0.01
10	0.09	0.35	0.02	0.46	0.00	0.07	0.01
11	0.09	0.38	0.02	0.42	0.01	0.07	0.01
12	0.08	0.42	0.02	0.39	0.01	0.08	0.01

(e) Monetary Aggregate

Hz	N	Y	P	W	M	R	E
1	0.00	0.01	0.01	0.00	0.84	0.09	0.04
2	0.02	0.03	0.03	0.01	0.64	0.22	0.05
3	0.02	0.03	0.06	0.05	0.48	0.25	0.12
4	0.02	0.02	0.09	0.07	0.37	0.30	0.13
5	0.01	0.02	0.12	0.08	0.28	0.34	0.15
6	0.01	0.02	0.15	0.08	0.23	0.35	0.16
7	0.01	0.02	0.17	0.08	0.18	0.36	0.17
8	0.01	0.02	0.19	0.09	0.15	0.37	0.18
9	0.01	0.02	0.20	0.09	0.13	0.37	0.18
10	0.01	0.02	0.21	0.10	0.11	0.38	0.18
11	0.01	0.01	0.22	0.10	0.10	0.38	0.18
12	0.01	0.01	0.22	0.10	0.09	0.38	0.19

(f) Interest Rates

Hz	N	Y	P	W	M	R	E
1	0.01	0.12	0.26	0.02	0.07	0.10	0.42
2	0.02	0.06	0.31	0.04	0.09	0.10	0.38
3	0.04	0.05	0.31	0.07	0.11	0.12	0.31
4	0.05	0.04	0.33	0.07	0.11	0.11	0.28
5	0.07	0.04	0.34	0.07	0.10	0.10	0.27
6	0.08	0.05	0.34	0.07	0.10	0.10	0.26
7	0.08	0.09	0.32	0.07	0.10	0.10	0.25
8	0.09	0.12	0.30	0.07	0.10	0.09	0.23
9	0.08	0.16	0.28	0.06	0.10	0.09	0.22
10	0.08	0.19	0.26	0.06	0.11	0.10	0.20
11	0.07	0.22	0.25	0.06	0.11	0.10	0.19
12	0.07	0.24	0.25	0.05	0.12	0.10	0.17

(g) Exchange Rates

Hz	N	Y	P	W	M	R	E
1	0.01	0.11	0.02	0.00	0.07	0.41	0.39
2	0.12	0.25	0.01	0.00	0.06	0.30	0.26
3	0.24	0.27	0.01	0.00	0.06	0.21	0.21
4	0.34	0.23	0.01	0.00	0.06	0.17	0.19
5	0.38	0.20	0.02	0.01	0.06	0.16	0.17
6	0.39	0.18	0.01	0.02	0.07	0.17	0.15
7	0.38	0.17	0.01	0.04	0.08	0.18	0.14
8	0.38	0.16	0.01	0.05	0.08	0.19	0.14
9	0.37	0.15	0.01	0.06	0.08	0.20	0.13
10	0.37	0.15	0.01	0.06	0.08	0.20	0.13
11	0.36	0.14	0.01	0.07	0.08	0.21	0.12
12	0.36	0.14	0.01	0.08	0.07	0.22	0.12