Structural VARs and DSGE models:

applications to macroeconomics

A dissertation

by

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To the memory of my Grandad

One night a man had a dream. He dreamed he was walking along the beach with the LORD. Across the sky flashed scenes from his life. For each scene, he noticed two sets of footprints in the sand; one belonged to him, and the other to the LORD.

When the last scene of his life flashed before him, he looked back at the footprints in the sand. He noticed that many times along the path of his life there was only one set of footprints. He also noticed that it happened at the very lowest and saddest times in his life. This really bothered him and he questioned the LORD about it. "LORD, you said that once I decided to follow you, you'd walk with me all the way. But I have noticed that during the most troublesome times in my life, there is only one set of footprints. I don't understand why when I needed you most you would leave me."

The LORD replied, "My precious, precious child, I love you and I would never leave you. During your times of trial and suffering, when you see only one set of footprints, it was then that I carried you."

With love,

Stefano

Abstract

Chapter 1 investigates if and how the standard results of the VAR literature on the macroeconomic effects of monetary policy, which typically overlooks fiscal policy, are affected when monetary and fiscal policy are jointly considered. To this end, structural VAR models are set up using U.S. post-war data. It is found that the magnitude of the responses of output and price to a monetary policy shock are halved once fiscal policy is considered. Both monetary and fiscal policy shocks have small effects on output and the prices. Chapter 2 evaluates the effects of monetary policy shocks on stock market indices in the G-7 countries and Spain using structural VARs. A contractionary shock has a negative and transitory effect on stock market indices. In Chapter 3 a limited participation model with households trading in stocks is set up and validated by means of impulse responses using U.S. data. The model is able to account for the empirical response of stock prices to monetary policy shocks. Chapter 4 compares three alternative models of the business cycle that rely on sticky prices and real rigidities in the form of adjustment costs for investment. In the first model these costs arise endogenously as the result of asymmetric information and agency costs. In the second model the costs for adjusting the level of investment are exogenously imposed while in the last model these costs are imposed on the changes in investment. The models are estimated with maximum likelihood using U.S. post-war data. The model with exogenous adjustment costs on the level of investment seems to provide the best representation of the U.S. business cycle and the responses to technology and monetary policy shocks.

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Chapter 1

Structural VARs: monetary and fiscal policy

1.1 Introduction

Over the last 20 years, the large empirical literature that has adopted the structural VARs approach for policy analysis has focused almost exclusively on the macroeconomic effects of monetary policy. Different aspects of the transmission mechanism have been studied both in the U.S. (e.g. Gordon and Leeper (1994), Christiano *et al.* (1996a), Galí (1992) and Bernanke and Blinder (1992)) and in the G-7 (e.g. Canova and De Nicoló (2002) and Kim (1999)).

Structural VARs have become popular for several reasons. They have the advantage of imposing a minimal set of economic restrictions and they also make it possible to simulate the dynamic responses to identified shocks and to evaluate the contribution of the different shocks to economic fluctuations.

Only recently, within this framework, some attention has been devoted to the analysis of fiscal policy. Renewed interest on fiscal policy as an effective stabilisation tool has been generated by the European Monetary Union (EMU) process, as within the limits imposed by the Stability Pact participating countries are left with taxation and public expenditure as the only policy tools. Another important reason for reconsidering the study of fiscal policy is the debate on balanced budget rules and the federal surplus in the U.S. at the end of the nineties. Recently some papers that have used structural VARs to study the effects of fiscal policy have appeared in the literature. Blanchard and Perotti (1999) look separately at the effects of shocks to government spending and taxes on output in the U.S. Edelberg, Eichenbaum and Fisher (1998) focus on the effects of military spending in the U.S. Fatás and Mihov (1998) use the ratio of primary surplus to GDP as the measure of fiscal policy while Fatás and Mihov (1999) analyse the effects of different components of government spending on a set of macroeconomic variables. A sign-restriction approach to the identification of fiscal shocks is used by Mountford and Uhlig (2002). Finally, Perotti (2002) analyses the effects of fiscal policy in some OECD countries.[1]

However, little attention has thus far been given to the joint analysis of fiscal and monetary. In this chapter we jointly analyse fiscal and monetary policy to assess to what extent the standard conclusions of the VAR literature about the effects of monetary policy in the U.S. are modified by the introduction of fiscal variables. At the same time the effects of these policies on output and prices are measured. We consider two alternative specifications of fiscal policy that have been used in the literature: in the first one we

[1]Empirical analysis of the effects of fiscal policy has also been carried out with large-scale econometric models or with reduced form models that looked at specific exogenous fiscal policy events, such as the 1975 tax rebate in the U.S. (e.g Blinder (1981)).

use the ratio of the primary surplus to GDP, as in Fatás and Mihov (1998), while in the second we use revenue minus transfers and expenditures separately, following Blanchard and Perotti (1999).

To the best of our knowledge, Blanchard and Watson (1986) is the only work that has jointly analysed the effects of fiscal and monetary policy with a structural VAR. The authors provide evidence that all the identified shocks (aggregate demand, aggregate supply, fiscal and monetary) are important in explaining fluctuations in output and prices. The approach followed in the present analysis differs from Blanchard and Watson (1986) in three key aspects. First, whereas they use M1 as the indicator of monetary policy, we use the federal funds rate. In principle, use of M1 can raise problems since it is widely recognised that the federal funds rate is the appropriate measure of monetary policy stance since the mid-1960s, with the sole exception of the Volcker period (e.g. Bernanke and Mihov (1998)). Moreover, Sims (1992) points out that innovations in monetary aggregates are not good candidates as measures of monetary policy shocks. Second, following Gordon and Leeper (1994), we provide a full model of demand and supply sides of the market for total reserves, in order to disentangle monetary policy shocks from reserve demand shocks.[2] We decided to follow the approach of Gordon and Leeper (1994) in order to keep the dimension of the VAR low. However, as it will be shown later, our results are robust to the use of the model described in Christiano *et al.* (1996a). Third, contrary to Blanchard and Watson (1986) we will estimate the fiscal rule instead of imposing it.

Two results emerge from the analysis. First the introduction of fiscal variables in a model that considers only monetary policy has important consequences on the magnitudes of the response of output and prices to a monetary policy shock. A statistical test on

[2]Other papers (e.g. Bernanke and Mihov (1998) and Christiano *et al.* (1996a)) have used borrowed reserves, nonborrowed reserves and the federal funds rate to identify monetary policy shocks.

the significance of the differences between the mean responses shows that the impact on output is significantly smaller in the VARs that include fiscal policy variables. Second fiscal and monetary policy have both small effects on output and prices.

The organisation of the chapter is the following. Section 1.2 presents a brief history of monetary and fiscal policy in the U.S. Section 1.3 considers a small monetary VAR that is used as a benchmark. Section 1.4 introduces the ratio of primary surplus to real GDP as the indicator of fiscal policy. In Section 1.5 the primary surplus is disaggregated into revenue minus transfers and government expenditure. In Section 1.6 the significance of the differences in the responses of output and prices to a monetary shock is tested. Section 1.7 presents the conclusions.

1.2 A brief history of monetary and fiscal policy in the U.S.

The information provided here on monetary policy can be found in more detail in Walsh (1998) and Strongin (1995). The information on fiscal policy come from Poterba (1988), Edelberg *et al.* (1998) and Blanchard and Perotti (1999). The federal funds market began to function as the main source of liquidity for commercial banks in the mid-1960s. Between 1972 and 1979 the Federal Reserve adopted a federal funds rate operating procedure under which it allowed nonborrowed reserves to stabilise the interest rate within a narrow band around the target rate. Shocks to the demand for total reserves were offset by open market operations in order to keep the federal funds rate constant. In the period between 1979 and 1982 there was a shift to a nonborrowed reserves operating procedure. This corresponds to the Volcker period which ran from 1979:10 to 1982:10. The shift to nonborrowed targeting was motivated by the need to exert greater control on monetary aggregates growth rates and reduce inflation. The Volcker period represents the most important shift in the Federal Reserve's operating procedures since all the other regimes can be seen as variants of federal funds rate or borrowed reserves targeting. Using a two-states Markov switching regime model, Bernanke and Mihov (1998) identify a structural change in the Federal Reserve operating procedures during the Volcker period. Since 1982 the Federal Reserve has followed a borrowed reserves operating procedure whereby nonborrowed reserves are adjusted in order to insulate borrowed reserves from non-policy shocks. Nowadays monetary policy the Federal Open Market Committee (FOMC), which fixes a target for the federal funds rate.

With respect to fiscal policy, two points deserve some attention. First, major fiscal shocks occurred in the 1950s and 1960s (for example, the Korean military build-up, two large tax increases in 1950:2 and 1950:3, the 1964 Kennedy-Johnson tax cut and the Vietnam war) and in the 1980s (Reagan's tax cuts in 1981 and 1986 and the increase in military spending). Second, the fiscal policies of the 1980s, especially during the Reagan administration, resulted in increased budget deficits and public debt. This in turn led to the approval in 1985 of the Gramm-Rudman-Holling bill which had two objectives: first to accelerate budget discussions and to place deadlines earlier in the calendar year and, second, to introduce deficit targets together with a mechanism for ensuring that actual deficits did not exceed them. However, the Supreme Court ruled the law unconstitutional. Analysts predicted that this legislation would not help to control budget deficits since the President and Congress could always agree to modify the targets. The failure to achieve deficit targets led to the approval of the 1990 Budget Enforcement Act (BEA) which introduced annual caps on discretionary spending and required any proposal to increase spending on one program to be offset by cuts in other programs. The BEA was in force from 1990 to 1998 (including the extension of the Omnibus Budget Reconciliation Act of 1993). The main difference between the BEA and the Gramm-Rudman-Holling is that the former reformed the budget process while the latter was only a declaration of deficit targets. Under the BEA, policies could be expected not to increase deficits in any of the following five years.

The most important fiscal event as far as magnitudes are concerned was the 1975 tax rebate (which included an increase in transfer payments). This involved a 10 per cent tax rebate of 1974 income taxes up to a maximum of 200 dollars and was designed to stimulate aggregate demand after the first oil shock. The intervention transferred 8.1 billion dollars from the Treasury to households between late April and mid-June. Measured in 1987 prices it represented an increase in disposable income of more than 100 billion dollars.[3] This tax rebate is examined in Blanchard and Perotti (1999) and in Poterba (1988) in an event study analysis where a dummy variable is defined for this event and the effects of the dummy on output are evaluated. Their work assumes that the event is exogenous. However, the tax rebate in question was designed to stimulate aggregate demand in response to the recession caused by the first oil shock and therefore does not exactly qualify as an exogenous fiscal policy shock.

[3]These figures come from Poterba (1988), who shows that the fiscal experiments of 1970s and 80s had a detectable effect on consumption, while the news effect was very small. This may be due to the fact that, for example, consumers face considerable liquidity constraints. The finding that the news effect of a fiscal intervention is small can be helpful in justifying the use of VARs in analysing of fiscal policy.

1.3 The benchmark monetary VAR

In this section we present a simple benchmark monetary VAR (M-VAR henceforth) for the analysis of the effects of monetary policy shocks in the U.S. This model will be used in Sections 1.4 and 1.5 to evaluate if and how the conclusions on the effects of monetary policy are modified when fiscal policy is explicitly taken into account.

Following Gordon and Leeper (1994), a demand for and a supply of total reserves are specified. The demand comes from commercial banks who need to satisfy reserve requirements, while the supply is assumed to be controlled by the Federal Reserve. The federal funds rate is the corresponding measure of monetary policy. Explicit modelling of the reserves market allows us to disentangle monetary policy shocks from shocks to the demand for reserves. The use of total reserves implicitly assumes that borrowed and nonborrowed reserves are perceived by the market as perfect substitutes.

The variables in the model are divided into two blocks: the non-policy one, Y_t, that includes the log of a commodity price index (PC), the log of real GDP (Y) and the log of the implicit GDP deflator (P), and the policy vector P_t including, initially, the federal funds rate (R) and the log of total reserves (TR).

In order to identify the structural VAR we assume that the vector of non-policy variables Y_t cannot respond simultaneously to monetary policy shocks. This is a standard assumption in the literature both with monthly and quarterly data (see e.g. Christiano *et al.* (1996a)). The monetary policy rule (i.e. the interest rate equation) specifies the supply of total reserves as a function of all the variables in the model. This is an information based assumption, given that the Federal Reserve observes the commodity price index, real GDP, the GDP deflator and the federal funds rate and reacts to changes in these variables by modifying the supply of total reserves. The commodity price index is introduced in order to capture the information the Federal Reserve has on future developments of the price level. Its introduction contributes to eliminating the so-called "price puzzle", the finding that price level initially increases after a contractionary monetary policy shock (Sims (1992)). In the reserves demand equation, total reserves are assumed to depend on the level of economic activity (i.e. real GDP), the price level and the federal funds rate. We differ from Gordon and Leeper (1994) with respect to the choice of the frequency of the data (quarterly) since fiscal variables are not available at a higher frequency.

Letting $X_t = [Y_t, P_t]$, the reduced form of the VAR is given by:

$$X_t = \sum_{i=1}^{k} A_i X_{t-i} + U_t \tag{1.1}$$

and the structural form is obtained by premultiplying equation (1) by A_0, by

$$A_0 X_t = \sum_{i=1}^{k} A_0 A_i X_{t-i} + A_0 U_t \tag{1.2}$$

where A_0 and A_i are N *x* N matrices and N is the number of variables. Since the covariance matrix of the reduced form VAR has $N(N+1)/2$ different elements, a maximum number of 15 coefficients of A_0 can be estimated in the M-VAR. In this case the elements of the main diagonal are not normalised to 1, and the covariance matrix of the structural shocks is assumed to be the identity matrix. The identification matrix of the M-VAR is reported in Appendix A.2.

The reduced form VAR in (1.1) is estimated consistently in levels with OLS.[4] Data are quarterly and the sample period goes from 1965:1 to 1996:4. The reason for choosing

[4]The selection of the lag number was made using the Akaike and Schwarz criterion and looking at the autocorrelation function of the reduced form innovations. These two criteria led to the selection 6 lags for all the VARs.

this sample period is that the commodity price index, which is taken from Bernanke and Mihov (1998), is available up to 1996. However the extension to 1999 with an alternative commodity price index leads to the same conclusions.

Then the concentrated log-likelihood is maximised with respect to the free coefficients of the A_0 matrix. An important issue in estimating structural VARs, as in all systems of equations, is the question of normalising the coefficients on the dependent variables. Waggoner and Zha (1997) showed that this normalisation can significatively affect the shape of the likelihood function and consequently the estimated coefficients. Instead of using their proposed solution, we will proceed in two steps. First we estimate the model leaving the main diagonal elements free, then we reestimate the model normalising these coefficients to one. By comparing the resulting estimates we can evaluate whether the shape of the likelihood function is distorted. Table 1 reports the estimated monetary policy rule of the M-VAR.

Table 1.1

Monetary policy rule: M-VAR[a]

$$R = \underset{(0.027)}{0.045} \cdot PC + \underset{(0.02)}{0.49} \cdot Y + \underset{(0.045)}{0.799} \cdot P + \underset{(0.047)}{0.378} \cdot TR + v_M$$

[a] Standard errors are reported in parentheses.

All the coefficients are statistically significant and have the expected signs. The Federal Reserve increases the federal funds rate whenever the commodity index increases, since this will produce an increase in the price level in the near future, and whenever real GDP and the GDP deflator increase. The coefficients of the total reserves demand equation, which are not reported, also have the expected signs: the demand for total reserves varies inversely with the federal funds rate and positively with the level of economic activity and the price level. However, this last coefficient is not significant.

Figure 1.1 displays the first principal component of the impulse responses of the variables included in the M-VAR to a one per cent increase in the federal funds rate.[5] A monetary policy shock triggers: (i) an increase in the federal funds rate, (ii) a decrease in total reserves, (iii) a sharp and fast decline in commodity prices, and (iv) a decline in real GDP and a delayed reduction in the GDP deflator.

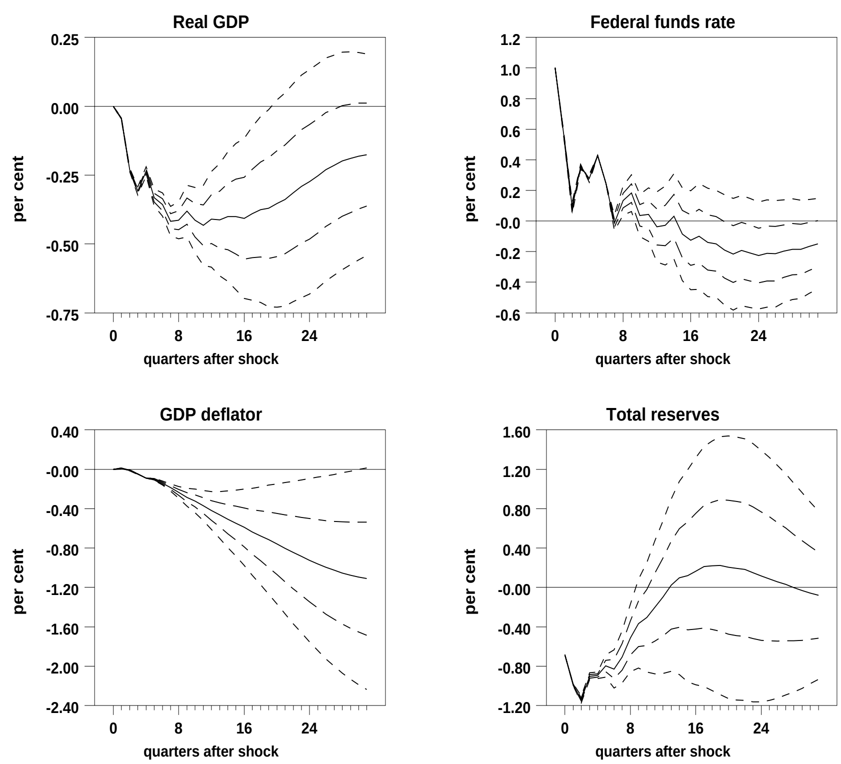

Fig. 1.1 Monetary policy shock (M-VAR)

[5]Error bands corresponding to .68 and .95 probability intervals are computed by means of Monte Carlo integration, following the methodology suggested by Sims and Zha (1999). In this paper the authors show how to compute error bands for overidentified structural VARs. All the figures in this chapter will report the first principal component of the impulse responses.

After a contractionary shock, real GDP decreases with the classical hump-shaped response, reaching the maximum contraction after 12 quarters and gradually fading away in the next 6 quarters. An unexpected increase of 1.0 per cent in the federal funds rate produces a maximum decrease of output of slightly more than 0.4 per cent. The response of the price level is permanent. It builds up slowly and is still significant after 8 years with a decrease of more than 1.0 per cent. The patterns of these responses are very similar to the ones in Bernanke and Mihov (1998) and Christiano *et al.* (1996a), who utilise a different identification scheme that separates total reserves into its nonborrowed and borrowed components.

1.4 Introducing fiscal policy: the primary surplus

Different methods have been proposed in the literature for constructing indicators of discretionary changes in the government budget, i.e changes due not to the endogenous response of budget components to the state of the economy but to exogenous fiscal policy actions. They all follow Blanchard's (1990) advice that the indicator should be simple even at the cost of ignoring relatively important considerations. The author estimates what government revenue and expenditure would be if the unemployment rate were at the level of the previous period and uses the difference between actual and estimated surplus as the indicator of fiscal policy. The simplest measure of fiscal impulse is the change in the primary surplus with respect to the previous year. Other methods are used by the IMF and the OECD.

In this section we will use the ratio of primary surplus (PS) to real GDP as the indicator of fiscal policy as in Fatás and Mihov (1998). The primary surplus equation of the VAR (PS-VAR henceforth) is used to eliminate any fluctuation in the primary surplus that is due to the state of the economy. The difference between the actual surplus and its endogenous component is used to derive the fiscal shocks.

The use of VARs for fiscal policy analysis is subject to a simple criticism, namely, the long lag between the announcement of a fiscal intervention (say, a tax cut) and the time the measure is actually enacted by the congress and affects taxpayers. However, the presence, for example, of liquidity constraints can significantly reduce the announcement effect on consumption. Moreover, the announcement of a tax cut might raise expectations of future tax increases, in which case under Ricardian equivalence, there would be no effect on consumption. Poterba (1988) studied the effect on consumption of the fiscal experiments of the 1970s and 80s. He found a significant effect on consumption following the implementation of policies but a very slight announcement effect.

In the estimation of the VAR we will use fiscal data for the federal government, which is responsible for setting the bulk of fiscal policy in the US. The use of the primary surplus for the general government leads to the same qualitative results. Contrary to Fatás and Mihov (1998) we will use total GDP instead of private sector GDP (i.e. GDP net of government spending), since this is a more conventional measure of economic activity and has been used in most empirical VAR analyses of monetary policy.

In order to identify fiscal shocks, we will assume that output and prices cannot respond to the fiscal indicator: this means that there are lags in the transmission mechanism of fiscal policy as it is the case for monetary policy.[6] Contrary to Blanchard and Watson (1986) we will estimate the fiscal rule instead of imposing it. It is assumed that the ratio of primary surplus to GDP depends contemporaneously on output and prices; while expenditure may be acyclical, revenue and transfers depend on the level of economic

[6]Allowing output and prices to respond simultaneously to a fiscal shock does not alter the impulse responses in any way.

activity and also on the overall price level since they are expressed in nominal terms. With respect to the relationship between monetary and fiscal policy we will assume that the two are set independently. This restriction denies any contemporaneous response of one policy variable to the other. The estimated monetary and fiscal rules are reported in the table below.

Table 1.2

Monetary and fiscal policy rules: PS-VAR[a]

Monetary policy
$R = \underset{(0.026)}{0.063} \cdot PC + \underset{(0.019)}{0.555} \cdot Y + \underset{(0.041)}{0.739} \cdot P + \underset{(0.031)}{0.354} \cdot TR$
Fiscal policy
$PS/Y = \underset{(0.005)}{0.224} \cdot Y + \underset{(0.016)}{0.518} \cdot P$

[a] Standard errors are reported in parentheses.

All the estimated coefficients are statistically significant and have the expected signs. In particular, the primary surplus increases if the level of economic activity rises and the price level increases. This happens because there are budget components, such as revenue and transfers, that depend on the level of economic activity and are expressed in nominal terms. The coefficients in the monetary policy rule show little change compared with those reported for the M-VAR in table 1.1.

We now examine the response of output and prices to an identified monetary policy shock. The response of output has the same shape as the one obtained with the VAR that considered only monetary policy. An increase of 1.0 per cent in the federal funds rate produces a maximum decline in real GDP of 0.2 per cent, against 0.4 per cent found in the M-VAR. Monetary policy still has real effects. With respect to price level, the response becomes significant after 5 quarters and remains so for more than 30 quarters (at .68 confidence level). After 8 years prices are 0.6 per cent below the initial level; there is a sharp difference with respect to the figures obtained in the M-VAR. The statistical significance of these differences will be tested in Section 1.5.

How can the simple introduction of a fiscal policy variable have such significant effects on the magnitudes of the impulse responses of output and prices? From an econometric point of view, it is essentially a problem of omitted variables and misspecification of the reduced form of the VAR, which leads to inconsistent estimates of all the coefficients. Since impulse responses and variance decompositions are highly non-linear functions of the coefficients of the reduced form VAR and the matrix A_0, they are also inconsistently estimated. The omission of an indicator of fiscal policy leads to the federal funds rate capturing the effects of fiscal policy on output and prices. The consequences of misspecifying vector autoregressions are analysed in detail in Braun and Mittinik (1993), who show that the omission of relevant variables produce inconsistent impulse responses and variance decompositions.

A contractionary fiscal shock, measured by an increase of 1.0 per cent in the primary surplus to real GDP ratio, produces a maximum decline in output of 0.7 per cent after 10 quarters. The response is not permanent since output goes back to its initial level after 20 quarters (see figure 1.2).

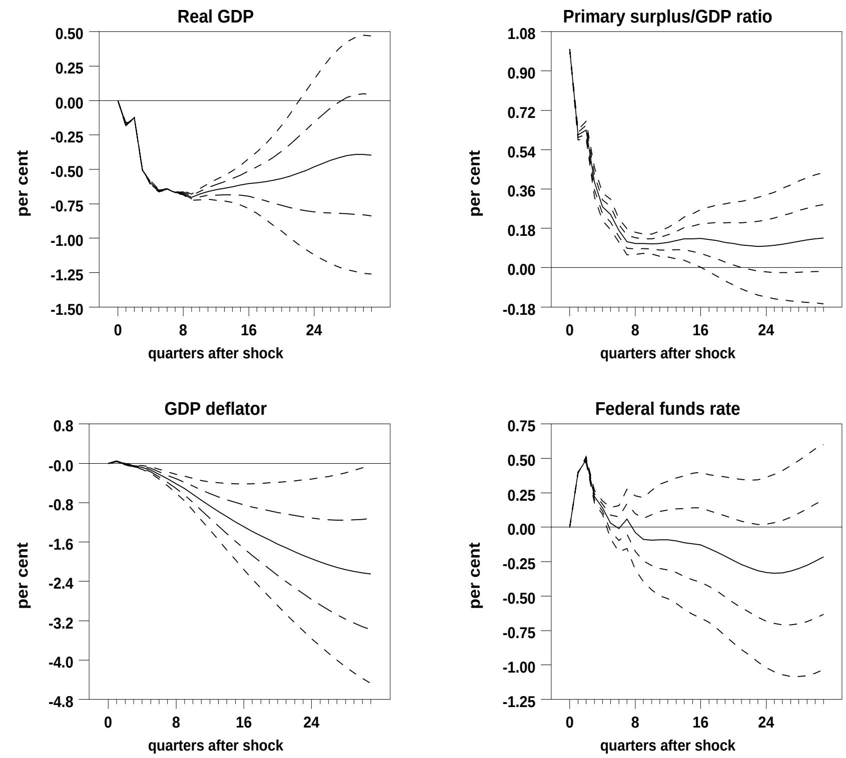

Fig. 1.2 Fiscal policy shock (PS-VAR)

The price level decreases persistently after a contractionary fiscal policy shock. The response is very slow: after 32 quarters prices are 2.0 per cent below their initial level. An increase in the surplus, due, for example, to an increase in taxation reduces disposable income and consumption. This decrease in aggregate demand causes the price level and output to decrease. The responses of prices and output to fiscal policy shocks are similar in shape to the responses to a monetary policy shock (see figure 1.1). Fiscal policy seems to be as effective as monetary policy.

We now evaluate whether the structural fiscal and monetary policy shocks we have observed capture the main fiscal and monetary events of the last 40 years. Structural shocks can be computed from

$$V_t = A_0^{-1} U_t \tag{1.3}$$

where U_t represents the vector of reduced form residuals. Fiscal shocks provide our measure of discretionary fiscal policy. The figure below reports the structural monetary and fiscal policy shocks.

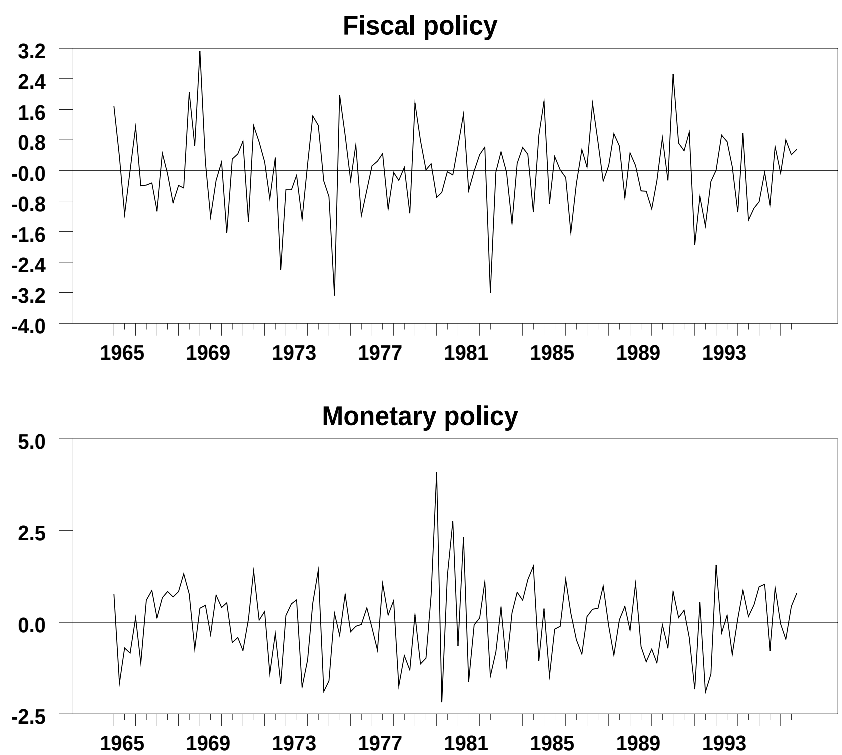

Fig. 1.3 Structural shocks (PS-VAR)

Several fiscal events can be identified: the strong adjustment of 1969 (the surtax approved in 1968:2, a temporary increase in taxation); the expansion of 1967 (this event is highlighted in Blanchard and Perotti (1999) as an expenditure shock); the tax rebate of the second quarter of 1975; the Reagan tax cut of 1981 (Economic Recovery Tax Cut) which was approved in August 1982, and the increase in military spending in 1980. Therefore it seems that the VAR is performing quite well in capturing the most important fiscal events in the post-war period in the U.S. We consider this an important criterion in the overall evaluation of the proposed VAR. It is important to underline that policy shocks are observed at the time of implementation because it is at this time that the budget is affected.

With respect to monetary policy shocks figure 1.3 clearly highlights the Volcker period in which the volatility of the federal funds rate increased because of the nonborrowed targeting regime. The anti-inflationary shock of 1979:2 is clearly detectable (Romer and Romer (1989)). The expansionary policy of 1983 and 1992 are also detectable (these events are highlighted in Bernanke and Mihov (1998) who compare their indicator with the Romers' dates and the Boschen-Mills index).

1.5 Disaggregating the federal budget into revenue and expenditure

One shortcoming of choosing the primary surplus as indicator of fiscal policy is that the effects of government expenditure and revenue shocks cannot be separated. This is equivalent to assuming that changes in taxation and expenditure have the same impact on macroeconomic variables.

In this section we therefore disaggregate the federal primary surplus into revenue minus transfers (T) and expenditure (G), following Blanchard and Perotti (1999). This new specification (RE-VAR henceforth) also allows to test the robustness of the results obtained with the PS-VAR.

The same identification scheme of the PS-VAR is used. Fiscal variables depend simultaneously on output and prices while these variables cannot respond contemporaneously to fiscal policy. However, the results are robust to assuming that these variables can respond, within a quarter, to fiscal policy shocks. In addition we assume that taxation decisions are taken once expenditure has been decided. This assumption is also made by Blanchard and Perotti (1999) who find that the results hold no matter which decision is assumed to be taken first. We have also tested the two specifications without obtaining any substantial differences in the results. The estimated policy rules of the RE-VAR are reported in the following table.

Table 1.3

Monetary and fiscal policy rules: RE-VAR[a]

Monetary policy rule
$R = \underset{(0.002)}{0.047} \cdot PC + \underset{(0.02)}{0.551} \cdot Y + \underset{(0.05)}{0.88} \cdot P + \underset{(0.044)}{0.362} \cdot TR$
Fiscal policy rule: taxes
$T = \underset{(0.11)}{1.853} \cdot Y + \underset{(0.234)}{6.384} \cdot P + \underset{(0.018)}{0.092} \cdot G$
Fiscal policy rule: expenditure
$G = \underset{(0.053)}{-0.122} \cdot Y - \underset{(0.118)}{0.062} \cdot P$

[a] Standard errors are reported in parentheses.

All the estimated coefficients are statistically significant, with the only exception of the price level in the expenditure equation; moreover, they all have the expected signs. Those of the monetary policy rule are similar to those of the benchmark model. Nominal revenue increases when real GDP, which can be assumed to be correlated with the tax base, increases and when the price level increases. The expenditure policy rule suggests that government expenditure increases when output decreases.

Figure 1.4 shows that an increase of 1.0 per cent in the federal funds rate produces a maximum decrease of real GDP of 0.26 per cent, which again is lower than the 0.4 of the benchmark case. For a comparison, the figure also presents the analogous responses for the two previous VARs. Error bands are not presented to make the comparison easier.

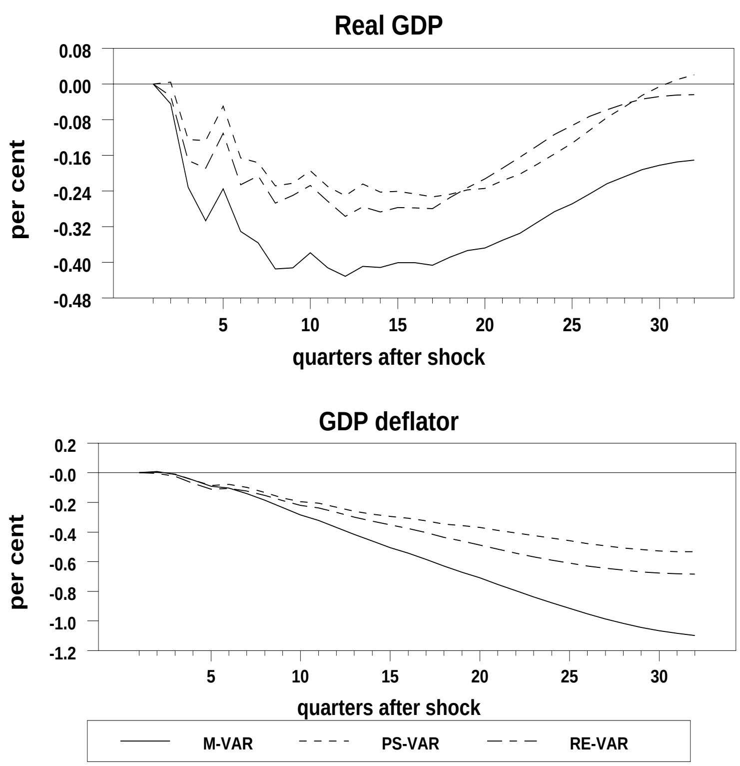

Fig. 1.4 Comparison of responses to a monetary policy shock

The result we have previously obtained with our VAR models is clearly confirmed, namely the omission of a fiscal policy indicator modifies the conclusion about the quantitative effects of monetary policy. Controlling for fiscal shocks significantly reduces the estimated magnitude of the effects of monetary policy: the maximum contraction of output is halved in the VAR that includes the fiscal variables. The response of the price level also changes significantly. For comparison purposes we report the impulse responses to an exogenous one per cent increase in the federal funds rate, obtained with the VAR described in Christiano *et al.* (1996a) VAR modified to include fiscal policy variables.

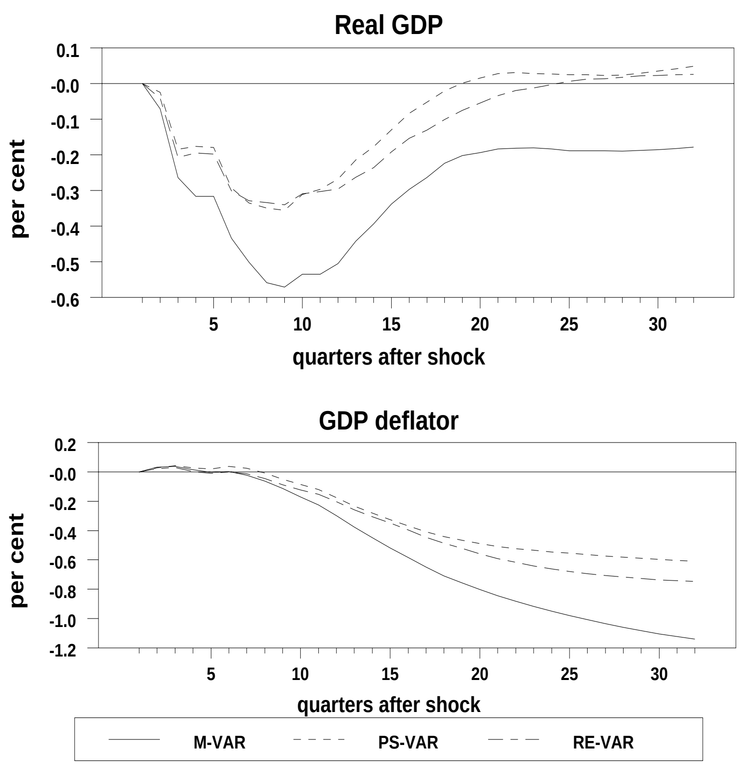

Fig. 1.5 Comparison of responses to a monetary shock: Christiano *et al.* (1996a)

The figure above reports the impulse responses of output and prices to a contractionary monetary policy shock obtained with and without fiscal variables. As it can be seen the omission of fiscal policy variables in the VAR increases the magnitudes of the effects of monetary policy on output and prices. The results are robust to the ordering between monetary and fiscal policy variables.

Figure 1.6 below shows in the first column the responses to a revenue shock and in the second one the responses to a government expenditure shock.

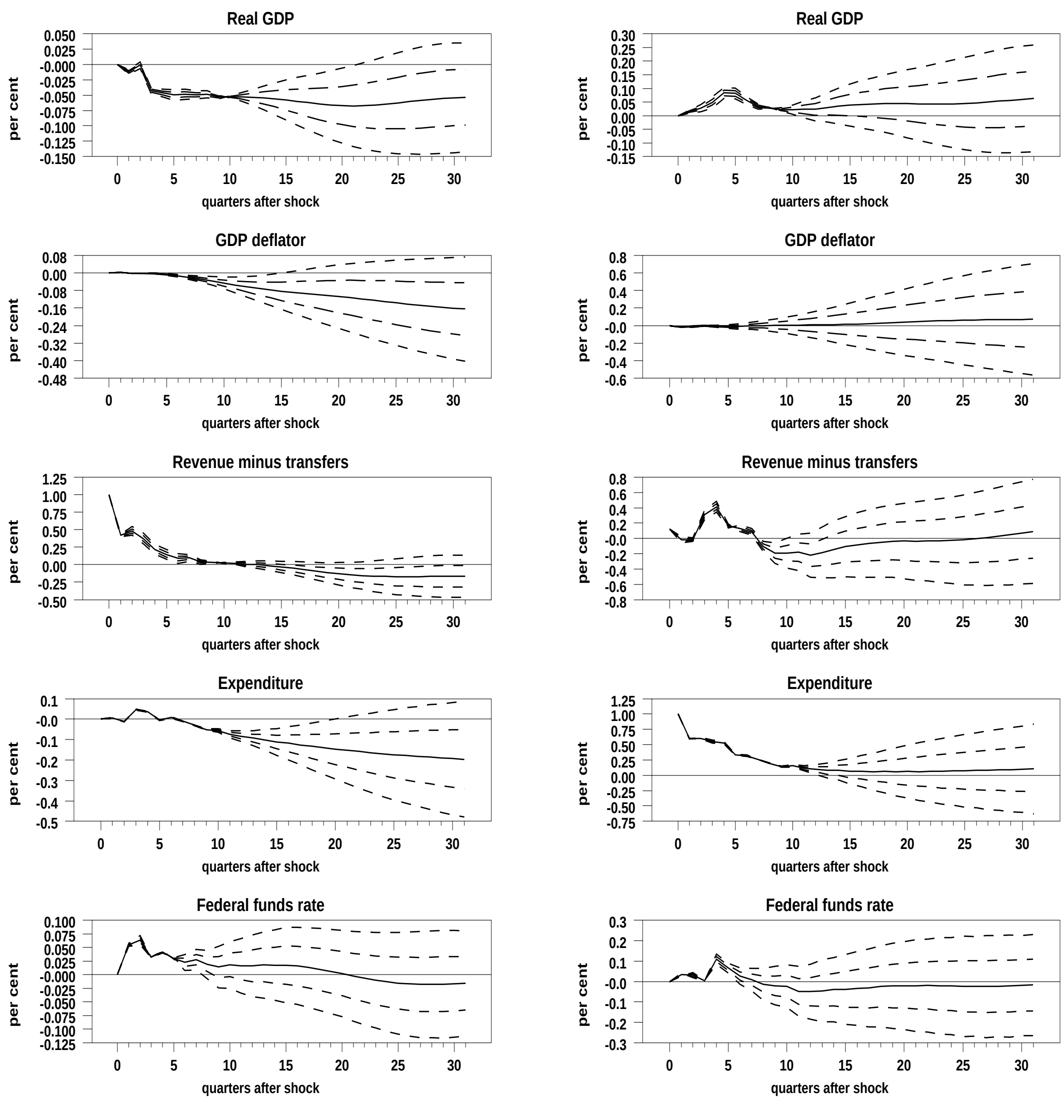

Fig. 1.6 Fiscal policy shocks (RE-VAR): revenue and expenditure

A one per cent increase in revenue induces a decrease in real GDP which is significatively different from zero. The maximum decline in output of around 0.06 per cent is reached after 15 quarters. The price level permanently decreases after the fiscal policy shock and after 32 quarters prices are 0.20 per cent below their baseline value. The response of the federal funds rate, although statistically significant, is very close to zero. This shows that monetary policy does not respond to significantly fiscal policy shocks. An increase in distorsionary taxation produces a decline in disposable income which reduces consumption and the price level.

An expansionary fiscal policy measured by a one per cent increase in government expenditure produces a positive but small (0.1 per cent) increase in output that lasts for less than two years. The figure suggests that the response of private-sector output is negative. This may be due to the increase in the interest rate and revenue, which are statistically significant for around 6 quarters. An expansionary expenditure shock causes the interest rate and revenue to increase which in turn lowers investment and consumption thus reducing the initial positive effect on output. This may suggest the existence of a crowding-out effect of government expenditure shocks. The response of the price level is never significant. The responses of output are in line with those obtained by Blanchard and Perotti (1999), at least from a qualitative point of view. However, our model suggests a smaller response of output which dies out more quickly. The reason for this difference may be that Blanchard and Perotti (1999) omitting a short-term interest rate. In principle, their VAR may suffer from the same omitted variable problem discussed above. As a check of this hypothesis, monetary policy variables are dropped from the RE-VAR. In this case a positive revenue shock has a severely negative impact on output and prices. An expansionary expenditure shock produces an increase in the price level and a small increase in output.[7] This result confirms that in order to correctly evaluate the effects of fiscal and monetary policy shocks, both policies should be considered in the same VAR.

The result that the responses of output and prices to a monetary policy shocks are smaller when revenues minus transfers and expenditure are introduced as measures of fiscal policy in the benchmark VAR is thus confirmed. The explanation is the same as the one we have given for the results obtained with the PS-VAR i.e. the omission of relevant variables produces inconsistent impulse responses and variance decompositions.

Figure 1.7 presents the fiscal and monetary policy shocks obtained with the RE-VAR.

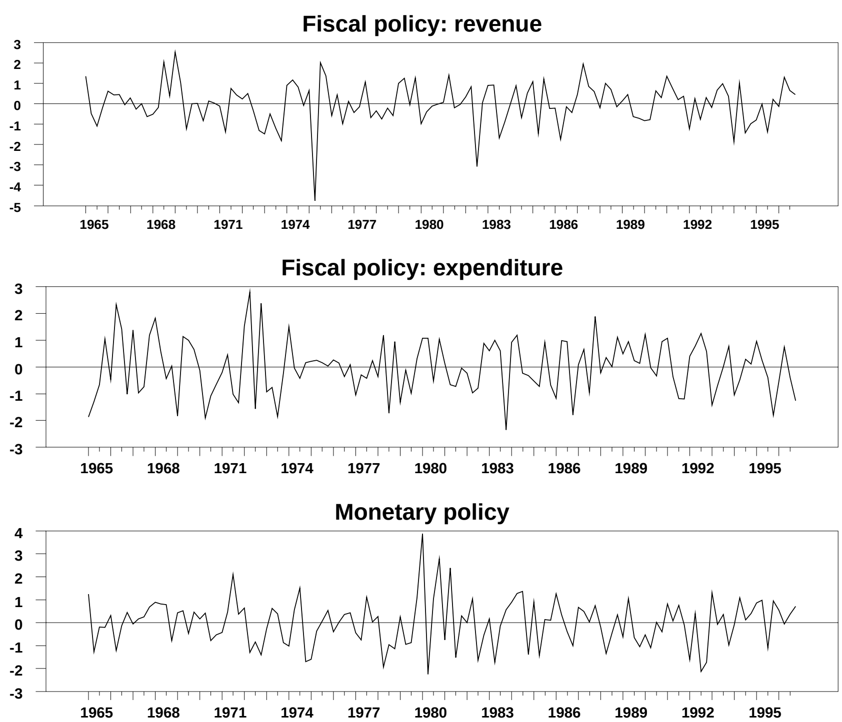

Fig. 1.7 Structural shocks (RE-VAR)

[7] These figures are not reported but can be found in Neri (2001).

With respect to tax shocks, the 1975:2 tax rebate is clearly detectable and represents the most important event in the post-war history of fiscal policies in the U.S. in terms of magnitude. The 1981 Reagan's tax reduction is also detectable together with the 1968 surtax. Expenditure shocks highlight the Vietnam war and an important increase in government expenditure in 1972 and a significative decrease in 1983. Large expenditure shocks also occurred before 1973. With respect to monetary policy, the anti-inflationary period under Volcker chairmanship, is clearly detectable. The expansionary episodes in 1974 and 1992 when the Federal Reserve cut interest rates to help the economy recover are also captured by the VAR.

1.6 Do we really need to model both fiscal and monetary policy?

In Sections 1.4 and 1.5 we have shown that the introduction of fiscal policy variables in the benchmark VAR affects the magnitude of the responses of output and the price level to a monetary policy shock without making significant alterations to the shapes. Up to now this conclusion has only been based on a qualitative comparison of impulse responses. In this section we will formally test the significance of the differences between the responses of output and prices to a monetary policy shock in the M-VAR and the two VARs that contain fiscal variables. The test will be based on the first, second and third principal component of the impulse responses.

For each quarter of the impulse response function, the following statistic (which is distributed asymptotically as a χ^2 with one degree of freedom) is computed:

$$\chi_i^2(k) = \frac{(\bar{c}_i^b(k) - \bar{c}_i^f(k))^2}{\sigma^2(\bar{c}_i^b(k)) + \sigma^2(\bar{c}_i^f(k))} \tag{1.4}$$

where $k = 1, .., K$ is the step at which the impulse responses are evaluated, $\bar{c}_i$ gives the average responses (b stands for benchmark and f for the two fiscal models, while i stands for output prices) and $\sigma^2(\bar{c}_i(k))$ is their variance. The responses are normalised so that in all the VARs a monetary shock increases the federal funds rate by 1.0 per cent. According to Sims and Zha (1999) the impulse responses can be represented in terms of the principal components of their estimated covariance matrix Ω

$$c_{ij}(t) = \hat{c}_{ij}(t) + \sum_{k=1}^{K} \gamma_k W_{\cdot k}(t) \tag{1.5}$$

where c_{ij} is the response of variable i to shock j, $\hat{c}_{ij}$ is the estimated mean response, γ_k is a random variable with a mean of zero and variance equal to the k^{th} eigenvalue of Ω, and $W_{\cdot k}$ the corresponding eigenvector. The advantage of using the principal components of the impulse response function is that the χ_i^2 statistics in (1.4) can be summmed up since they are indipendently distributed. The following tables report the results.[8]

[8]The first component accounts on average for 50 per cent and 90 per cent of the variance of the responses of, respectively, real GDP and the GDP deflator. The second component explains about 25 per cent of the variance of the response of real GDP and 9 per cent for the price level while the third component accounts for, respectively, 15 and 3 per cent.

Table 1.4

Distance test on first component of impulse responses[a]

quarters	distance Y		p-value		distance P		p-value	
1[b]	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)
2	0.048	(0.016)	0.000	(0.001)	0.003	(0.013)	0.445	(0.000)
3	0.106	(0.060)	0.000	(0.000)	0.003	(0.012)	0.639	(0.010)
4	0.178	(0.118)	0.000	(0.000)	0.001	(0.021)	0.875	(0.005)
5	0.183	(0.124)	0.000	(0.000)	0.006	(0.017)	0.718	(0.161)
6	0.163	(0.105)	0.000	(0.000)	0.023	(0.003)	0.364	(0.886)
7	0.178	(0.150)	0.000	(0.000)	0.042	(0.019)	0.280	(0.575)
8	0.185	(0.147)	0.000	(0.000)	0.052	(0.032)	0.356	(0.504)
9	0.185	(0.159)	0.000	(0.000)	0.065	(0.047)	0.399	(0.486)
10	0.181	(0.148)	0.001	(0.009)	0.087	(0.064)	0.390	(0.472)
11	0.181	(0.147)	0.019	(0.049)	0.113	(0.083)	0.377	(0.463)
12	0.180	(0.131)	0.075	(0.168)	0.134	(0.099)	0.394	(0.473)
13	0.183	(0.130)	0.142	(0.259)	0.154	(0.116)	0.413	(0.487)
14	0.167	(0.121)	0.261	(0.376)	0.177	(0.131)	0.422	(0.506)
15	0.158	(0.121)	0.364	(0.445)	0.205	(0.148)	0.416	(0.517)
16	0.151	(0.121)	0.443	(0.501)	0.231	(0.161)	0.418	(0.537)
17	0.150	(0.125)	0.491	(0.527)	0.253	(0.173)	0.426	(0.556)
18	0.138	(0.131)	0.555	(0.542)	0.278	(0.187)	0.429	(0.568)
19	0.133	(0.139)	0.589	(0.546)	0.306	(0.201)	0.425	(0.580)
20	0.131	(0.152)	0.610	(0.532)	0.332	(0.213)	0.424	(0.591)
21	0.131	(0.159)	0.619	(0.534)	0.356	(0.228)	0.426	(0.597)
22	0.131	(0.167)	0.622	(0.522)	0.379	(0.243)	0.428	(0.602)
23	0.130	(0.167)	0.623	(0.530)	0.403	(0.259)	0.428	(0.603)
24	0.130	(0.168)	0.618	(0.531)	0.426	(0.277)	0.428	(0.601)
25	0.137	(0.170)	0.589	(0.522)	0.446	(0.295)	0.430	(0.598)
26	0.144	(0.168)	0.558	(0.519)	0.464	(0.313)	0.431	(0.593)
27	0.150	(0.159)	0.521	(0.524)	0.482	(0.331)	0.431	(0.587)
28	0.158	(0.156)	0.474	(0.513)	0.499	(0.348)	0.430	(0.581)
29	0.167	(0.152)	0.419	(0.502)	0.514	(0.365)	0.428	(0.574)
30	0.178	(0.149)	0.355	(0.479)	0.528	(0.379)	0.426	(0.567)

Figures not in parentheses refer to the M-VAR against the PD-VAR.
Figures in parentheses refer to the M-VAR against the RE-VAR.
[a] The distance is the absolute value of the differences of the responses to a monetary policy shock.
[b] The impact response of output and prices is restricted to zero in all VARs.

Table 1.5

Distance test on second component of impulse responses[a]

quarters	distance Y		p-value		distance P		p-value	
1[b]	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)
2	0.048	(0.016)	0.000	(0.000)	0.003	(0.013)	0.621	(0.013)
3	0.106	(0.060)	0.000	(0.000)	0.003	(0.012)	0.846	(0.386)
4	0.178	(0.118)	0.000	(0.000)	0.001	(0.021)	0.950	(0.361)
5	0.183	(0.124)	0.000	(0.019)	0.006	(0.017)	0.879	(0.604)
6	0.163	(0.105)	0.011	(0.148)	0.023	(0.003)	0.676	(0.946)
7	0.178	(0.150)	0.041	(0.109)	0.042	(0.019)	0.570	(0.765)
8	0.185	(0.147)	0.114	(0.231)	0.052	(0.032)	0.579	(0.692)
9	0.185	(0.159)	0.187	(0.280)	0.065	(0.047)	0.567	(0.645)
10	0.181	(0.148)	0.258	(0.374)	0.087	(0.064)	0.513	(0.599)
11	0.181	(0.147)	0.311	(0.416)	0.113	(0.083)	0.460	(0.556)
12	0.180	(0.131)	0.341	(0.488)	0.134	(0.099)	0.429	(0.526)
13	0.183	(0.130)	0.352	(0.505)	0.154	(0.116)	0.394	(0.493)
14	0.167	(0.121)	0.391	(0.534)	0.177	(0.131)	0.345	(0.459)
15	0.158	(0.121)	0.389	(0.518)	0.205	(0.148)	0.277	(0.413)
16	0.151	(0.121)	0.363	(0.485)	0.231	(0.161)	0.214	(0.369)
17	0.150	(0.125)	0.298	(0.419)	0.253	(0.173)	0.152	(0.317)
18	0.138	(0.131)	0.233	(0.318)	0.278	(0.187)	0.086	(0.247)
19	0.133	(0.139)	0.116	(0.187)	0.306	(0.201)	0.033	(0.168)
20	0.131	(0.152)	0.007	(0.041)	0.332	(0.213)	0.006	(0.091)
21	0.131	(0.159)	0.000	(0.001)	0.356	(0.228)	0.001	(0.027)
22	0.131	(0.167)	0.000	(0.000)	0.379	(0.243)	0.000	(0.002)
23	0.130	(0.167)	0.010	(0.000)	0.403	(0.259)	0.000	(0.000)
24	0.130	(0.168)	0.096	(0.009)	0.426	(0.277)	0.000	(0.000)
25	0.137	(0.170)	0.176	(0.051)	0.446	(0.295)	0.000	(0.000)
26	0.144	(0.168)	0.234	(0.121)	0.464	(0.313)	0.000	(0.000)
27	0.150	(0.159)	0.261	(0.194)	0.482	(0.331)	0.000	(0.000)
28	0.158	(0.156)	0.269	(0.249)	0.499	(0.348)	0.000	(0.001)
29	0.167	(0.152)	0.253	(0.284)	0.514	(0.365)	0.000	(0.002)
30	0.178	(0.149)	0.221	(0.298)	0.528	(0.379)	0.001	(0.008)

Figures not in parentheses refer to the M-VAR against the PD-VAR.
Figures in parentheses refer to the M-VAR against the RE-VAR.
[a] The distance is the absolute value of the differences of the responses to a monetary policy shock.
[b] The impact response of output and prices is restricted to zero in all VARs.

Table 1.6

Distance test on third component of impulse responses[a]

quarters	distance Y		p-value		distance P		p-value	
1[b]	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)
2	0.048	(0.016)	0.000	(0.092)	0.003	(0.013)	0.582	(0.033)
3	0.106	(0.060)	0.000	(0.019)	0.003	(0.012)	0.839	(0.422)
4	0.178	(0.118)	0.000	(0.011)	0.001	(0.021)	0.950	(0.428)
5	0.183	(0.124)	0.002	(0.057)	0.006	(0.017)	0.882	(0.656)
6	0.163	(0.105)	0.035	(0.206)	0.023	(0.003)	0.672	(0.952)
7	0.178	(0.150)	0.060	(0.148)	0.042	(0.019)	0.542	(0.785)
8	0.185	(0.147)	0.103	(0.210)	0.052	(0.032)	0.520	(0.690)
9	0.185	(0.159)	0.120	(0.186)	0.065	(0.047)	0.468	(0.601)
10	0.181	(0.148)	0.125	(0.190)	0.087	(0.064)	0.357	(0.497)
11	0.181	(0.147)	0.094	(0.148)	0.113	(0.083)	0.222	(0.375)
12	0.180	(0.131)	0.054	(0.107)	0.134	(0.099)	0.111	(0.247)
13	0.183	(0.130)	0.010	(0.024)	0.154	(0.116)	0.029	(0.110)
14	0.167	(0.121)	0.000	(0.000)	0.177	(0.131)	0.000	(0.016)
15	0.158	(0.121)	0.000	(0.000)	0.205	(0.148)	0.000	(0.000)
16	0.151	(0.121)	0.000	(0.000)	0.231	(0.161)	0.000	(0.000)
17	0.150	(0.125)	0.004	(0.026)	0.253	(0.173)	0.000	(0.000)
18	0.138	(0.131)	0.059	(0.086)	0.278	(0.187)	0.000	(0.000)
19	0.133	(0.139)	0.135	(0.120)	0.306	(0.201)	0.000	(0.000)
20	0.131	(0.152)	0.175	(0.109)	0.332	(0.213)	0.000	(0.003)
21	0.131	(0.159)	0.173	(0.085)	0.356	(0.228)	0.000	(0.005)
22	0.131	(0.167)	0.132	(0.042)	0.379	(0.243)	0.000	(0.004)
23	0.130	(0.167)	0.061	(0.011)	0.403	(0.259)	0.000	(0.001)
24	0.130	(0.168)	0.003	(0.000)	0.426	(0.277)	0.000	(0.000)
25	0.137	(0.170)	0.000	(0.000)	0.446	(0.295)	0.000	(0.000)
26	0.144	(0.168)	0.000	(0.000)	0.464	(0.313)	0.000	(0.000)
27	0.150	(0.159)	0.002	(0.000)	0.482	(0.331)	0.000	(0.000)
28	0.158	(0.156)	0.050	(0.021)	0.499	(0.348)	0.000	(0.000)
29	0.167	(0.152)	0.125	(0.102)	0.514	(0.365)	0.000	(0.000)
30	0.178	(0.149)	0.178	(0.192)	0.528	(0.379)	0.000	(0.000)

Figures not in parentheses refer to the M-VAR against the PD-VAR.
Figures in parentheses refer to the M-VAR against the RE-VAR.
[a] The distance is the absolute value of the differences of the responses to a monetary policy shock.
[b] The impact response of output and prices is restricted to zero in all VARs.

Table 1.7

Overall distance test[a]

component	$\chi^2\,(Y)$		p-value		$\chi^2\,(P)$		p-value	
first	368.56	(409.08)	0.0	(0.0)	19.45	(54.30)	0.960	(0.008)
second	398.34	(165.54)	0.0	(0.0)	834.75	(825.67)	0.0	(0.0)
third	393.31	(569.86)	0.0	(0.0)	3292.18	(2001.58)	0.0	(0.0)

Figures not in parentheses refer to the M-VAR against the PS-VAR.
Figures in parentheses refer to the M-VAR against the RE-VAR.
[a] The distance is the absolute value of the differences of the responses to a monetary policy shock.

The response of output in the M-VAR is significantly larger than in the two other VARs for the first 11 quarters in both fiscal VARs while the differences in the response of prices are significantly different from zero only for the first 4 quarters in the RE-VAR. An overall evaluation of the significance of these differences can be obtained by summing up the χ^2 statistics over the number of steps in the response horizon: this sum is distributed as a χ^2 with as many degrees of freedom as the number of steps, K. There is a significant difference in the responses of both output and the price level to a monetary policy shock.

Overall, formal statistical tests have shown that the omission of fiscal variables from a benchmark monetary VAR can determine a bias in the responses to a monetary policy shock. This bias is greater for the response of output. Similar results, which are not shown, are obtained for the decomposition of the variance of the forecast errors.

1.7 Conclusions

In this chapter we have shown that fiscal and monetary policy have both small effects on output and the price level. A contractionary monetary policy shock decreases output and prices as well as does a contractionary fiscal policy shock, measured alternatively by an exogenous increase in revenue or in the ratio of primary surplus to GDP. Expenditure shocks have very small and short-lived effects on output and no effect at all on prices.

The analysis also provides another, perhaps more interesting, result. Using the structural VAR methodology, we have shown that the introduction of fiscal variables in a model that considers only monetary policy has important consequences on the magnitudes of the response of output and prices to a monetary policy shock. A statistical test on the significance of the differences between the mean responses has shown that the impact on output is significantly smaller in the VARs that include fiscal policy variables. This result is obtained either by using the ratio of the primary surplus to real GDP or by disaggregating the budget into expenditure and revenue minus transfers.

We think that analysing jointly fiscal and monetary policy in a VAR is the correct thing to do in order to evaluate the dynamic impact of these shocks on output and prices. However, if a researcher is concerned with evaluating qualitatively the dynamic responses of output and prices to a monetary policy shock, fiscal variables may be omitted. On the other hand, if the focus is on the quantitative effects of monetary policy, on its contribution to output and price fluctuations, and on the relative importance of fiscal and monetary policy shocks, then it would be desirable to specify a structural VAR that jointly considers the two policies. This result is in line with the suggestions of Leeper, Sims and Zha (1996) who underline the importance of correctly identifying structural shocks by setting up larger models that can trace the effects of policy shocks across a wider variety of variables. The authors identify serious problems in models that imply significant real effects of monetary policy and argue that correcting these problems lowers the implied size of these effects. This is exactly what we have done by taking into account fiscal policy in an otherwise standard small-scale monetary VAR.

Appendix A.1 Data sources and construction of fiscal variables

All the data come from NIPA (National Income and Product Account) and the FRED database of the Federal Reserve of Saint Louis.

"Y": gross domestic product, seasonally adjusted, billions 1992 $

"P": gross domestic product implicit price deflator (1992=100), seasonally adjusted

"PC": Dow Jones index of spot commodity prices, quarterly average of daily figures

"R": federal funds rate, quarterly average of daily figures in percentage annual terms

"TR": total reserves adjusted for changes in reserve requirements billions $

"PS": federal government primary surplus(+) or deficit(-) billions $

"T": federal revenue minus transfers billions, $ seasonally adjusted

"G": federal government current expenditure billions, $ seasonally adjusted

Transfers = social security benefits + social assistance grants + unfunded employee pension + transfers to the rest of the world + net casualty premium + other transfers

Revenue = direct taxes on households + direct taxes on business + indirect taxes + social security contributions received

Expenditure = consumption expenditure + grants to state and local governments + subsidies

Federal primary surplus = revenue - expenditure - transfers - consumption of fixed capital - net capital transfers received + property income - interest paid + interest received

Appendix A.2 Identification schemes

Identification matrix of the M-VAR.

$$A_0 = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ 0 & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} \begin{matrix} PC \\ P \\ Y \\ R \\ TR \end{matrix}$$

Identification matrix of the PS-VAR.

$$A_0 = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & a_{56} \\ 0 & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{matrix} PC \\ P \\ Y \\ PS/Y \\ R \\ TR \end{matrix}$$

Identification matrix of the RE-VAR.

$$A_0 = \begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 & 0 \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 & 0 \\ 0 & a_{52} & a_{53} & a_{54} & a_{55} & 0 & 0 \\ a_{61} & a_{62} & a_{63} & 0 & 0 & a_{66} & a_{67} \\ 0 & a_{72} & a_{73} & 0 & 0 & a_{76} & a_{77} \end{bmatrix} \begin{matrix} PC \\ P \\ Y \\ G \\ T \\ R \\ TR \end{matrix}$$

Chapter 2

Structural VARs: monetary policy and stock prices

2.1 Introduction[1]

From 1995 to 2000 financial markets have experienced a sustained increase in stock prices in many countries. Stock market indices have increased by 270 per cent in Spain, 200 per cent in France, Italy, Germany, and the U.S., more than 100 per cent in the U.K and Canada and only 10 per cent in Japan. A sudden inversion of the trend was recorded in March 2000. Since this peak, after one year stock market indices had dropped by around 25 per cent in Spain, 20 per cent in Germany, France, Italy, the U.S. and by almost 30 per cent in Canada and Japan. Indices continued to decrease throughout all 2001 and 2002.

Against this background, it should not be surprising that the relationship between

[1]This chapter builds up on a research project undertaken with Enrico Gisolo at the Research Department of the Bank of Italy during autumn 2000.

monetary policy and asset prices, in general, has recently known renewed interest among academics and policy-makers. Both have debated on whether monetary policy should respond to developments in financial markets (Bernanke and Gertler (2000) and Rigobon and Sack (2001)), the extent to which these might have been caused by monetary policy itself (Rapach (2001)) and, particularly, during the last two years, the role of stock market wealth in the transmission mechanism of monetary policy. In life cycle/permanent income models, changes in stock prices can affect households' consumption choices because these assets are an important component of households' wealth. Movements in interest rates can affect stock prices and consequently households' wealth: this effect can provide an additional channel, besides the traditional interest rate and credit ones, through which monetary policy can ultimatley affect output and inflation. However, there is little evidence on the contribution of the wealth channel to the monetary transmission mechanism. Lettau, Ludvigson and Steindel (2001) analysis for the U.S. is the only available evidence although the authors focus on the effects of changes in total wealth on consumption. The main finding is that the wealth channel is not a dominant source of monetary policy transmission to consumption. The reason for this result is that monetary policy shocks, measured by innovations in the federal funds rate, have only transitory effects on asset prices. The effects of changes in stock prices on households' financial wealth are likely to be larger in those countries where stock ownership is more widespread among households. With respect to the relationship between financial wealth and consumption, empirical analyses have shown that the effects of changes in stock prices on consumption are not large. Boone, Giorno and Richardson (1998) estimate that a 10 per cent fall in stock market prices reduces consumption by 0.45 to 0.75 per cent in the U.S. after one year. Similar results are obtained for Canada and the U.K (0.45) while for the other G-7 countries the estimated elasticities are on average smaller (less than 0.2).[2] These findings suggest that

[2]The authors assume the same marginal propensity to consume for all the countries.

the effects of changes in stock prices on aggregate demand and output are small. However, they may well be far from negligible in the light of the tremendous decline of stock prices in the last two years.

This chapter, by focusing on the effects of monetary policy on stock market indices, may be of help in giving an approximate assessment of the relevance of the "stock market" channel of the monetary transmission mechanism. For a given amount of stock holdings in households' portfolios, the finding of a small effect of monetary policy on stock prices would imply that the "stock market" channel is not a dominant source of transmission of monetary policy shocks in the economy. In the analysis we rely on structural VARs to identify monetary shocks and evaluate their effects on stock market indices in the G-7 countries and Spain. Structural VARs have been applied extensively in the literature to the analysis of the effects of monetary policy in many countries. A recent example is Kim (1999), who proposes a common specification to identify monetary policy shocks in the G-7 countries. Although the monetary authorities of these countries have been characterised by different operating procedures, the author shows that the proposed model fits well and does not present any puzzling responses of monetary aggregates and prices (the "liquidity" and "price" puzzles sometimes found in the literature).

It is found that contractionary monetary policy shocks, measured by exogenous increases in short-term interest rates, have small, negative and transitory effects on stock market indices. The persistence, the magnitudes and the timing of these effects differ significantly from country to country. These results are in line with previous analyses that have relied on an alternative identification of monetary policy shocks.

The chapter is organised as follows: Section 2.2 presents some of the existing literature, Section 2.3 describes the structural VAR methodology and Section 2.4 presents the estimation results and the impulse responses.

2.2 The existing literature

Surprisingly, notwithstanding the importance of the issue of the relationship between stock markets and monetary policy, to the best of our knowledge little empirical and theoretical research has focused on the effects of monetary policy on stock prices. Sellin (2001) provides an interesting survey on the interaction between monetary policy and stock prices. For what concerns the empirical analysis, few works have tried try to evaluate the effects of monetary policy on stock markets. All these analyses share the same methodology of structural VARs.

Thorbecke (1997) analyses how stock returns respond to monetary policy shocks in the U.S. The author finds that an expansionary monetary policy increases ex-post stock returns.[3] This result can be explained by the positive effect on economic activity and thus on future cash flows and by the reduction in the discount factor at which those flows are discounted.

Rapach (2001) provides another analysis, based on U.S. data, on the effects of money supply shocks on real stock prices. These shocks are identified by means of long-run restrictions under the assumption that they are neutral with respect to real variables and interest rates in the long-run. The main result is that each identified shock affects real stock prices. Expansionary monetary policy shocks have a positive effect on real

[3] In the VAR analysis monetary policy shocks are identified alternatively as innovations in the federal funds rate and nonborrowed reserves. Identification of structural shocks is achieved by means of a Cholesky decomposition of the covariance matrix of the residuals as in Christiano *et al.* (1996a).

stock prices, the response of which can be rationalised according to the standard present-value evaluation principle. The positive effect on output increases expected real dividends while the decrease in the interest rate reduces the discount factor at which future dividend payments are evaluated. Another interesting result is that aggregate supply and monetary policy shocks have contributed significantly to the surge in stock prices in the second half of the nineties.

Lastrapes (1998) analyses the response of asset prices - long-term bond yields and real stock price indices - to monetary policy shocks in eight industrialised countries. The identification of monetary policy shocks is achieved, as in Rapach (2001), by means of long-run restrictions under the assumption that money supply shocks does not permanently affect interest rates, real output, real stock prices and real money. The main finding is that real stock prices respond positively and significantly to unexpected increases in the supply of money.

2.3 The structural VAR analysis

In this section we present our proposed identification of the structural VARs. We will assume that the economies we consider can be described by a structural dynamic vector equation:

$$A\left(L\right)y_t + c = v_t \tag{2.1}$$

where y_t is a vector of N economic variables, v_t is a vector of structural shocks that can be given, at least for some of them, an economic interpretation, c is a vector of constants and $A(L)$ is an autoregressive polinomial of order p. This polinomial is given by:

$$A(L) = A_0 + A_1 L + A_2 L^2 + ... + A_p L^p$$

The variables in y_t are in order: a world commodity price index, the nominal exchange rate, industrial production, the consumer price index, a short-term interest rate, a monetary aggregate and the stock market index.[4] All the variables, with only exception of the interest rate, are in expressed in logarithms.

The structural shocks are assumed to be serially uncorrelated and mutually independent. The reduced form of the VAR is given by the following system of equations:

$$B(L) y_t + c = u_t \tag{2.2}$$

where u_t is the vector of reduced form innovations. These are related to the structural shocks by the following relationship:

$$v_t = A_0 u_t \tag{2.3}$$

We are interested in recovering the coefficients that link contemporaneously the variables of the y_t vector, that is the non-zero elements of the A_0 matrix in (2.1). There are

[4]The nominal exchange rate with the U.S. dollar is used for Japan, Germany, U.K and Canada and the nominal exchange rate with the Deutsche Mark for France, Italy and Spain. With respect to the choice of the monetary aggregate, M2 was used for all the countries with the only exception of Germany, for which M3 was used. Stock market indices are: Standard and & Poor 500 (U.S.), Tokyo NSE (Japan), FAZ general (Germany), FTSE all share (U.K), CAC 40 (France), MIB (Italy), Toronto Composite index (Canada) and IBEX (Spain). All the data come from the International Financial Statistics (IMF), Main Economic Indicators (OECD), BIS (Bank for International Settlements) and Datastream.

several ways of identifying these coefficients. All the different strategies need to impose enough restrictions to identify these coefficients. A simple way of achieving this is to orthogonalize the covariance matrix of the VAR residuals, Σ, using a Cholesky decomposition: this is equivalent to assuming a recursive structure of the model (2.1). More complex strategies use both short-run and long-run restrictions as in Galì (1992) and restrictions on the signs of impulse responses as in Uhlig (1999a) or restrictions on the signs and cross-correlations of impulse responses as in Canova and De Nicoló (2002). We will rely on a non-recursive structure of the A_0 matrix, therefore imposing restrictions only on the contemporaneous relationship among the VAR variables. As a result, the long-run behaviour of the models will be left completely unrestricted. Given an estimate of Σ, the coefficients of the matrix A_0 can be estimated by means of maximum likelihood. The proposed identification scheme is the following:

$$\begin{bmatrix} v_{cp} \\ v_{exc} \\ v_y \\ v_p \\ v_{ms} \\ v_{md} \\ v_s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 & 0 & 0 & 0 \\ a_{31} & a_{32} & 1 & 0 & 0 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & 1 & 0 & 0 & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & 1 & a_{56} & 0 \\ 0 & 0 & a_{63} & a_{64} & a_{65} & 1 & 0 \\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & 1 \end{bmatrix} \begin{bmatrix} u_{cp} \\ u_{exc} \\ u_y \\ u_p \\ u_r \\ u_m \\ u_s \end{bmatrix}$$

where the vector on the left-hand side contains the structual shocks while the vector on the right-hand side the reduced form innovations. It is important to underline that among the structural shocks, only money supply v_{ms} and, to a smaller extent, money demand shocks v_{md} have a clear economic interpretation: the others are loosely identified. The VARs are overidentified by one restriction, with the only exception of the U.S. model in which the exchange rate is not introduced. The money supply and the money demand equations have the following representation in terms of contemporaneous relationships among the residuals of the VAR equations:

$$v_{ms} = u_r + a_{51}u_{cp} + a_{52}u_{exc} + a_{53}u_y + a_{54}u_p + a_{56}u_m \tag{2.4}$$

$$v_{md} = u_m + a_{63}u_y + a_{64}u_p + a_{65}u_r \tag{2.5}$$

We expect to find respectively a positively-sloped money supply (2.4) and negatively-sloped money demand relationship (2.5) in the (m, r) space.

Equation (2.4) can be interpreted as a monetary policy rule that specifies the supply of money as a function of the monetary aggregate, the nominal exchange rate, industrial production, the consumer price index and the commodity price index. Equation (2.5) represents a money demand equation in which the monetary aggregate depends on the interest rate, the assumed opportunity cost, industrial production, the measure of economic activity, and the price level. This modelling of the policy block allows us to disentangle monetary policy shocks from money demand shocks and it can be considered as a general scheme that can be applied to different countries where different operating procedures have been implemented. The commodity price index and the exchange rate in the monetary policy rule (2.4) are meant to capture external shocks that may generate inflationary pressures. These variables helps solving the so-called “price puzzle”, after Sims (1992): the finding that a contractionary monetary policy shock generates an increase in the price level. The assumption that the central bank observes industrial production and the price index is not present in Kim (1999) who justifies it in terms of availability of the information at the time when decisions are taken. Given the (monthly) frequency of the data we use, we prefer not to make this assumption since we think that it is not possible to rule out a priori that contemporaneous information on these variables may be available to policy-makers when setting monetary policy.

The exchange rate index is usually introduced in small open economies VARs since in these economies it is useful for the monetary authorities to target also the exchange rate (the countries participating in the EMS are an example). Moreover, for these economies the exchange rate plays an important role in the transmission mechanism of monetary policy. Smets (1997) finds that for Germany, France and Italy monetary policy is better modelled when the exchange rate is taken into account. The introduction of the exchange rate is particularly justified for the European economies and Canada. However, we prefer to adopt the same model for all the countries, with the exception of the U.S., where the exchange rate is not introduced since they are usually considered a relatively closed economy.

We have assumed a Cholesky identification of the block containing the commodity price index, the nominal exchange rate, the consumer price index and industrial production. We differ from Kim and Roubini (2000) since we do not allow the exchange rate to react to monetary policy shocks.[5] With respect to the stock price equation we have chosen to leave it completely unrestricted, assuming that all the variables can have a contemporaneous impact on this variable. We think that the minimum identifying restrictions we have imposed represent a very general framework that may be able to explain the dynamics of

[5]We have experimented with alternative identifications in which the exchange rate responded to these shocks without substantial differences in the behaviour of stock prices. Given that we are not interested in accounting for the "exchange rate" puzzle we have assumed that this variable does not contemporaneously respond to monetary shocks.

nominal and real variables in a relative large number of industrial economies.

Our analysis differs substantially from Lastrapes (1998). First, with respect to the identification scheme, we used restrictions on the short-run relationships among the variables and left the long-run behaviour of the variables completely unrestricted. We think that monetary policy shocks are not the only shocks that have transitory effects on real variables: aggregate demand and money demand shocks are other examples. Therefore the long-run monetary neutrality assumption could be not sufficient to identify monetary policy shocks. Moreover it is well recognised in the literature on VARs that monetary policy shocks are usually identified as innovations in short-term interest rates, while monetary aggregates are usually driven by money demand shocks (e.g. Sims (1992)). Second, contrary to Lastrapes (1998), in order to correctly identify monetary shocks we introduce the nominal exchange rate since, for some countries, especially small open economies, monetary policy shocks are better identified when the exchange rate is taken into account (e.g. Smets (1997)). Finally, we differ with respect to the choice of the sample period used in estimating the VARs: Lastrapes (1998) used monthly data from 1960 to 1994 while we used more recent data from 1985 to 2000.

2.4 Estimation results and impulse responses

In this section we present the estimates of the free coefficients of the A_0 matrices and we comment the results from the impulse response analysis. The reduced form VAR in (2.2) is estimated consistently in levels by means of OLS.[6] Then the concentrated log-likelihood

[6]Data are monthly and the sample periods goes from 1985 to 2000. The selection of the lag number was made looking at the autocorrelation function of the reduced form residuals. This strategy led to choose a different number of lags for the eight VARs.

is maximised with respect to the free coefficients of the A_0 matrix. The following table reports the overidentifying restriction tests.

Table 2.1
Overidentifying restriction test

	Canada	Germany	France	Italy	Spain	U.K	Japan	U.S.
OIR test	0.297	3.645	0.023	2.618	0.012	1.273	0.665	-[a]
p-value	0.585	0.056	0.878	0.105	0.909	0.259	0.414	-[a]

[a] The model for the U.S. is exactly identified. See Section 2.3.

Our restrictions are not rejected at conventional 5 per cent significance level for all the countries. The following table reports the negative of the estimated coefficients of the policy block (equations (2.4) and (2.5) in Section 2.3) of the A_0 matrix.

Table 2.2
Estimated coefficients of the A_0 matrix

	Canada	Germany	France	Italy	Spain	U.K	Japan	U.S.
interest rate equation								
cp	-0.058	-0.032	-0.117	0.044	0.034	-0.110	0.023	0.010
exc	0.172	0.020	0.114	0.047	-0.009	-0.000	0.013	-[a]
y	0.100	0.007	-0.085	-0.012	-0.014	-0.189	0.041	0.077
p	-0.099	-0.039	0.136	0.228	-0.050	0.414	0.083	0.257
m	0.580	0.256	0.213	0.089	0.101	0.598	0.286	0.252
money equation								
y	-0.033	0.114	-0.090	0.043	0.114	0.064	-0.072	-0.014
p	0.212	-0.914	-0.348	0.121	0.934	0.780	-0.127	-0.000[b]
r	-0.204	-7.340	-0.348	-0.052[b]	-0.614	-1.314	-2.478	-0.211

[a] This coefficient is not present since the exchange rate is not included in the model. See Section 2.3.
[b] Not significant at 5 per cent confidence level.

The coefficient that measures the endogenous response of the short-term interest rate to the monetary aggregate has the correct sign in all the VARs: following an unexpected increase in money, which may generate inflationary pressures, the monetary authority increases the interest rate. The commodity price index enters with the correct positive sign in the monetary policy rule of Italy, Spain, Japan and the U.S. The coefficient on the nominal exchange rate has the correct sign in the policy rule equations of Canada, Germany, France, Italy and Japan: an unexpected depreciation, measured by an increase of the nominal exchange rate induces the monetary authority to raise interest rates. The price level enters significantly and with the expected positive sign in the interest rate equations of France, Italy, UK, Japan and the U.S. while industrial production has the correct sign in the model for the U.S., Japan, Germany and Canada. Overall the signs of these coefficients indicate that monetary authorities move to a contractionary stance when faced with inflationary pressures. In the estimated money demand equations, the interest rate semi-elasticity has the expected sign for all the countries, while this is not the case for output and the price level.

We now analyse the responses of the VAR variables to a contractionary monetary policy shock, measured by an exogenous one per cent increase in the short-term interest rate.[7] The figures below report the first and second principal component of the estimated responses of interest rates, monetary aggregates and stock market indices to a contractionary one per cent monetary policy shock.

[7]Error bands (68 and 95 per cent probability intervals) for the first and second principal components of the impulse responses are computed by means of Monte Carlo integration following Sims and Zha (1999). In this paper the authors show how to compute error bands for overidentified structural VARs.

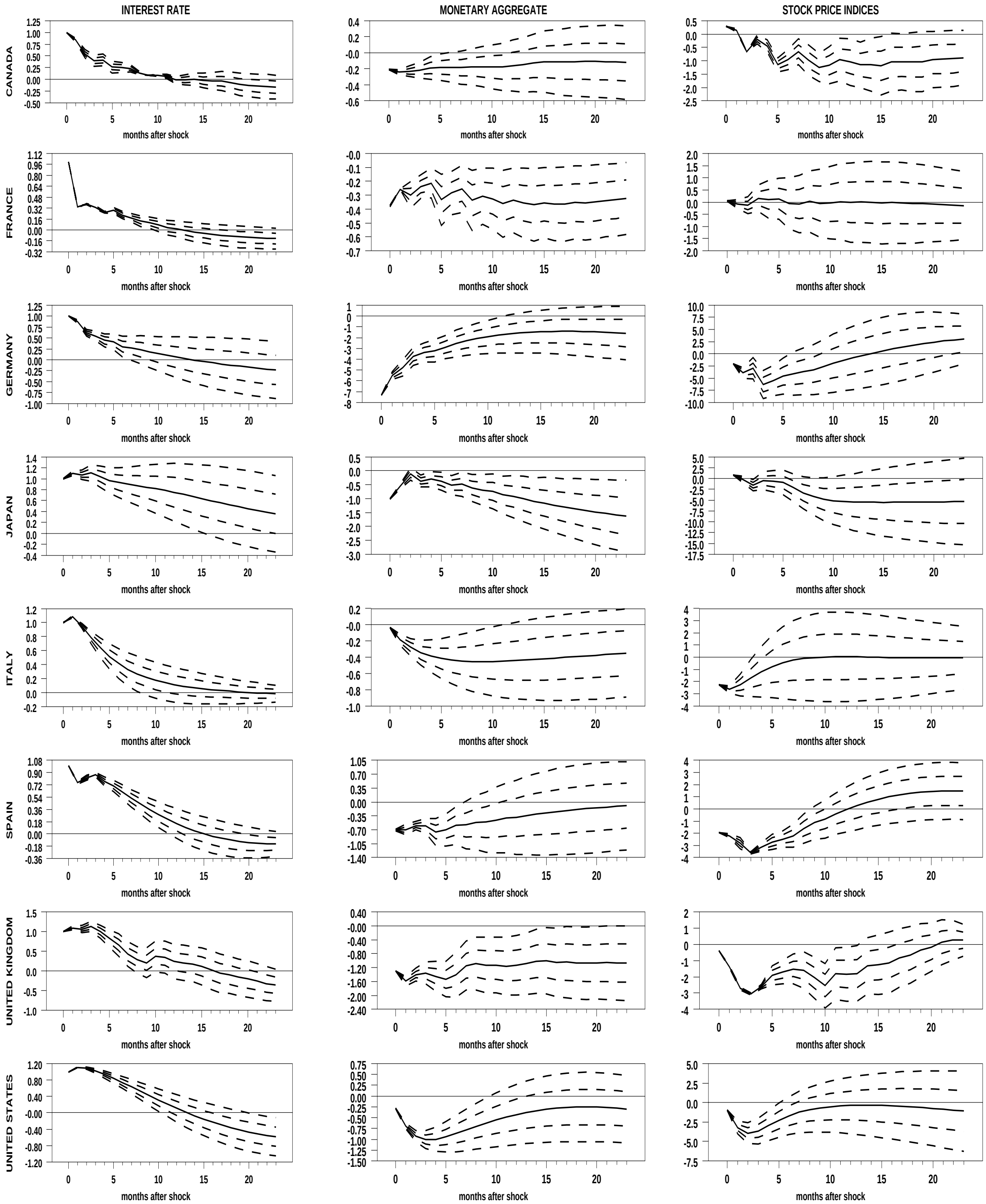

Fig. 2.1 Contractionary monetary policy shock: first principal component (68 and 95 per cent probability bands)

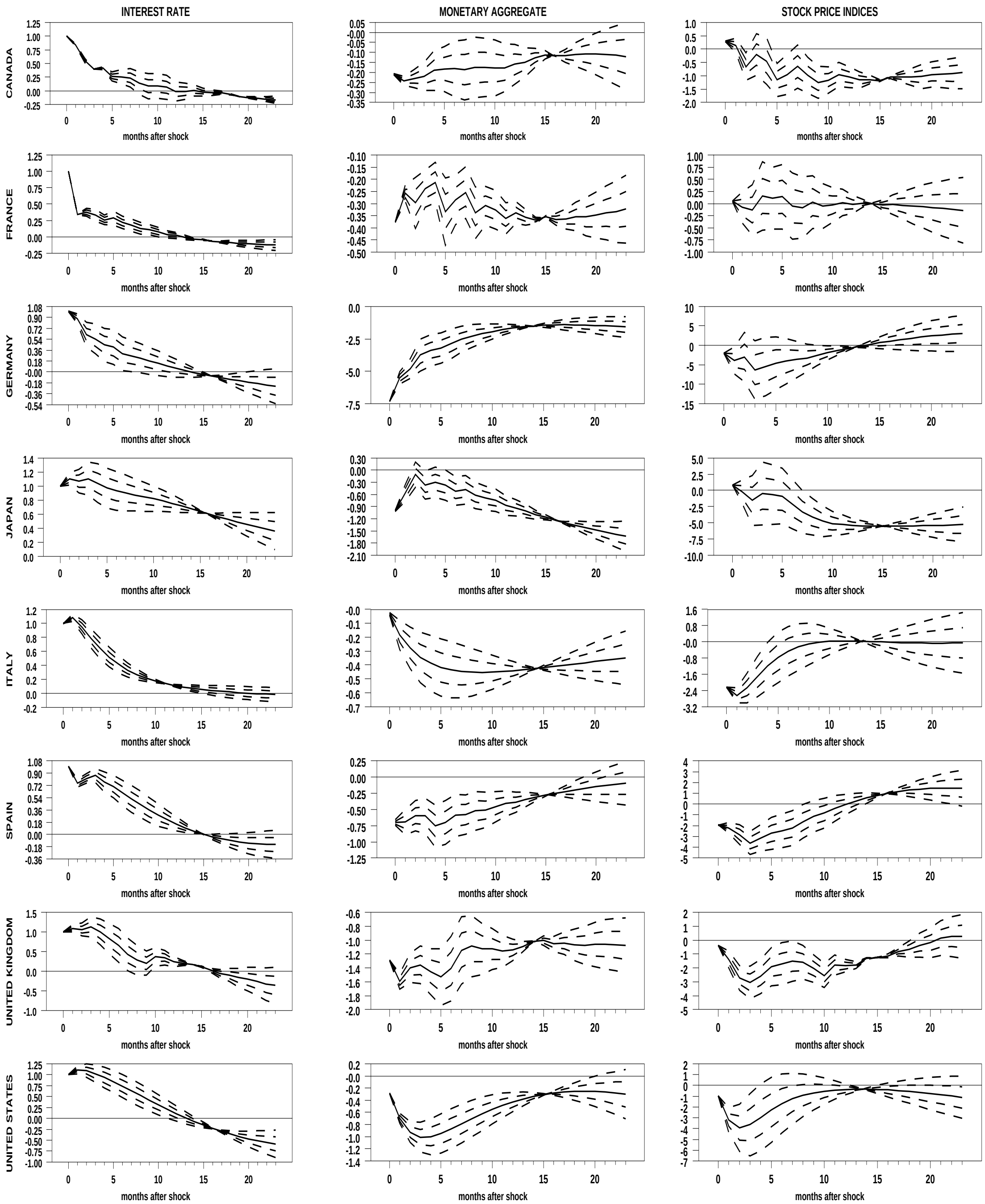

Fig. 2.2 Contractionary monetary policy shock: second principal component (68 and 95 per cent probability bands)

In all the countries, the initial increase in the interest rate is followed by a contraction of the monetary aggregate. The persistence of this liquidity effect differs from country to country. Almost every model in which policy shocks are identified with innovation in the interest rate shows a liquidity effect in the short run: an expansionary monetary policy shock, for example, is characterised by a decrease in a short-term interest rate and an increase in monetary aggregates (e.g. Gordon and Leeper (1994)). Industrial production and the consumer price index (these responses are not shown) decrease in all countries, with the responses differing in terms of persistence and magnitude. The price level responds smoothly in all VARs suggesting that prices may be sticky. A contractionary monetary shock produces a decrease in stock market indices in all the countries. As figure 2.1 shows, the responses differ in terms of magnitude, timing and persistence. With respect to the latter, we find a short-lived response in the U.S. and Germany and a more persistent in Italy, Canada, the U.K, Japan and Spain. Monetary shocks have no significant effects on the stock market in France. Lastrapes (1998) also finds no effects of monetary policy in France and small effects in the U.K. However, our results cannot be easily compared with those of Lastrapes (1998) since his models contains a long-term interest rate instead of a short-term one as it is done in this paper. Rapach (2001) reports for the U.S. a decrease on impact of about 6 per cent to a money supply shock that increases the short-term interest rate by one per cent.

The following table reports the responses of stock price indices to a one per cent contractionary monetary policy shock. For what concerns the maximum (significant) response of stock prices, in the U.S. it reaches nearly 4 per cent (in the fourth month), 1.0 per cent in Canada (twelfth month), 3.1 per cent in the U.K (fourth month), 6.3 per cent in Germany (fourth month), 2.7 per cent in Italy (second month), Japan 4.6 per cent (eighth month) and 3.6 per cent in Spain (fourth month).[8]

Table 2.3
Response of stock price indices to a one per cent contractionary monetary shock

months	Canada	Germany	France	Italy	Spain	U.K	Japan	U.S.
2	0.1	-3.9	-0.1*	-2.7	-2.2	-1.4	-1.1	-3.2
4	-0.2	-6.3	0.2*	-1.7	-3.6	-3.1	-2.0*	-3.6
8	-0.7	-3.6*	-0.1*	-0.8	-2.2	-1.5	-4.6	-1.2*
12	-1.0	-1.3*	0.0*	0.1*	-0.4*	-1.8	-6.0*	-0.4*
16	-1.2*	0.7*	0.0*	0.1*	0.8*	-1.3*	-6.0*	-0.4*
20	-1.0*	2.1*	-0.1*	0.0*	1.4*	-0.4*	-5.3*	-0.6*
24	-0.9*	3.0*	-0.1*	0.1*	1.5*	0.3*	-4.4*	-1.1*

* Not significant at 5 per cent confidence level. Significance is tested using the first component of the variance of the impulse responses.

Overall the table shows that the effects of monetary policy shocks on stock prices are not large. It is possible to evaluate the effect of monetary policy shocks on consumption that are due to changes in stock prices using the elasticities estimated by Boone, Giorno and Richardson (1998) and reported in Section 2.1. With respect to the U.S. and U.K, a one per cent increase in the short-term interest rate decreases consumption by around 0.14 per cent on average after one year. The effects are significatively smaller in Canada, France, Italy, Japan, Germany and Spain (around 0.05 on average). It must be noted that the effects of changes in policy interest rates on stock market indices are usually short-live: they become statistically not significant after 8 to 12 months. These figures suggest that the effects on consumption through the stock market are very small.

[8] As for the impulse responses, there is a significant cross-country heterogeneity account in the contribution of monetary shocks to fluctuations in stock market indices. It is important to underline that in the very short-run (up to 4 months) more than 70 per cent of the variability of stock market indices is due to shocks originating within these markets. This percentage is still around 50 per cent after 2 years.

Chapter 3

Structural VARs and DSGE models: monetary policy and stock prices

3.1 Introduction

In this chapter we present a limited participation model based on Christiano *et al.* (1997), Christiano and Gust (1999) and Christiano and Eichenbaum (1992) which is modified to include trading in the stock market. The model will be validated by comparing the impulse responses to monetary policy shocks in the model and in the data for the U.S. These shock will be identified in the model as i.i.d innovations to a monetary policy rule while in the data these shocks will be identified using a sign-restriction approach used in Canova (2001) and Uhlig (1999a).

Few papers in the literature have analysed the relationship between stock prices and monetary policy. Among them are Chami, Cosimano and Fullerkamp (1999), Cooley and

Quadrini (1999a), Lucas (1982) and Svensson (1985). In the first one the authors suggest the existence of a stock market channel of monetary policy besides the traditional interest rate and the credit ones. In their view, the inflation induced by a monetary expansion reduces the real value of firms' assets thus acting as a tax on the capital stock. This effect differentiates bonds and stocks and gives rise to the "stock market" channel of the monetary transmission mechanism. An expansionary monetary policy generates a decrease of real stock returns.

Cooley and Quadrini (1999a) develop a dynamic stochastic general equilibrium model in which financial factors play an important role in the decisions of firms and the transmission mechanism of monetary policy. Since firms are heterogeneous with respect to the size of their equity, the authors are able to construct a value-weighted stock market index and evaluate its response to monetary policy shocks. A contractionary one per cent monetary shock reduces the stock market index by nearly 0.2 per cent on impact.

Lucas (1982) and Svensson (1985) analyse cash-in-advance models in which households hold money and stocks. The pricing condition of these assets is the standard formula a la Lucas (1978) according to which the price of a stock is given by the discounted sum of future dividend payments. The model considered in this chapter delivers a similar pricing condition.

The organisation of the chapter is the following. In Section 3.2 the model is presented. Section 3.3 presents the first order conditions of the model and discusses them. Section 3.4 discusses the calibration of the parameters of the model and comment the impulse responses to monetary policy shocks. Section 3.5 validates the model.

3.2 A limited participation DSGE model

The choice of the limited participation model is motivated by the need to replicate the main aspects of the monetary transmission mechanism: a contractionary monetary policy shock generates an increase in the short-term interest rate and a decrease in money, output, inflation and profits. Moreover in this class of models an expansionary monetary shock, measured by an exogenous increase in the growth rate of money, generates a liquidity effect by decreasing the short-term interest rate. Standard cash-in-advance models of the type described in Lucas (1982) and Svensson (1985) are not able to generate a liquidity effect after a serially correlated shock to the growth rate of money. The reason is that in these models, monetary policy is able to affect interest rates only through expected inflation. Sticky price models of the type considered in Christiano *et al.* (1997) fail to account for the negative response of profits to a contractionary monetary policy shock. Therefore these models cannot be used to analyse the implications of monetary policy for stock prices, which depends crucially on the behaviour of profits.

3.2.1 The households sector

In this section we describe the model starting from the households sector. A representative household maximises the expected discounted flow of instantaneous utilities which are given by:

$$U\left(C_t, C_t^h, N_t, H_t\right) = \frac{\left(C_t - C_t^h\right)^{1-\gamma}}{1-\gamma} - \psi_0 \frac{(N_t + H_t)^{1+\psi}}{1+\psi} \tag{3.1}$$

where $1/\psi$ is the elasticity of labour supply, N_t, and C_t is consumption. The parameters

ψ_0, ψ and γ are all positive. We allow for habit formation in consumption as in Boldrin *et al.* (2001): C_t^h summarises past choices of consumption goods purchases. This feature is introduced in order to replicate the hump-shaped response of consumption to monetary shocks that is found in empirical VAR analyses. According to Boldrin *et al.* (2001), allowing for habits in consumption in a standard real business cycle model also helps in solving the equity premium puzzle without having to rely on high risk averse households. We use the following specifications of habits in consumption: $C_t^h = \chi C_{t-1}^h + bC_{t-1}$.[1] The parameter b determines the degree to which consumption is intertemporally substitutable. For simplicity, in solving the model we will assume that χ is equal to zero as in Christiano *et al.* (2001).

A monetary friction, according to which households adjust only gradually their holdings of cash is introduced in the model. This friction helps generating an excess of liquidity in the economy after a monetary policy shock (measured by an increase in the growth rate of money) that drives the interest rate down. We introduce a cost for adjusting the cash that is used by the representative household to purchase consumption goods: this cost is modelled in terms of hours, H_t, spent organising funds and withdrawing cash from bank accounts. We will model H_t as a function of cash holdings Q_t, as in Christiano and Eichenbaum (1992):

$$H_t = d\left\{exp\left[c\left(\frac{Q_t}{Q_{t-1}} - \mu_Q\right)\right] + exp\left[-c\left(\frac{Q_t}{Q_{t-1}} - \mu_Q\right)\right] - 2\right\} \tag{3.2}$$

where μ_Q is the steady state gross growth rate of cash holdings.[2] Both the function H_t

[1]Boldrin *et al.* (2001) have experimented with more general specifications of the habits function C_t^h without any significant effect on the behaviour of asset prices.

[2]Cooley and Quadrini (1999b) use quadratic adjustment costs for deposits.

and its first derivative, H_t', equal zero in the steady state. The marginal cost of adjusting cash is an increasing function of the two parameters c and d: the larger the value of their values, the larger will be the response of the interest rate to a change in the growth rate of money.

Households face a cash-in-advance constraint on the purchases of consumption goods:

$$P_tC_t \leq W_tN_t + Q_t \tag{3.3}$$

where P_t is the price of consumption goods, W_t is the wage paid by firms and Q_t is cash holding. An amount D_t, which is given by $M_t - Q_t$ is transferred to a representative financial intermediary. This receives a money injection X_t ($X_t = M_{t+1} - M_t$) from the central bank and lends the available funds $D_t + X_t$ to firms charging the interest rate R_t. Firms need to borrow in order to pay the workers before the products are sold. The loan market clearing condition requires the supply of loans to equal the demand

$$W_tN_t = D_t + X_t \tag{3.4}$$

The households' budget constraint is given by:

$$\begin{aligned} M_{t+1} = [W_tN_t + Q_t - P_tC_t] + r_tK_t + R_t\left[M_t - Q_t\right] + R_tX_t - P_tI_t + \\ + Z_t^{mf}\Pi_t^{mf} + Z_t^{mf}P_t^{mf} - Z_{t+1}^{mf}P_t^{mf} \end{aligned} \tag{3.5}$$

where the term in the first bracket is the cash that is not spent in the goods market, r_tK_t represents the payment received by the household for renting capital K_t to firms at the rental price r_t, $P_t I_t$ is the value of investment goods purchased, $R_t X_t$ are the profits of the financial intermediary, Z_t^{mf} and P_t^{mf} are respectively the beginning of period holding of stocks of a representative mutual fund and their price and Π_t^{mf} the dividends paid by the fund.[3] These are paid proportionally to the holding of stocks at the beginning of period. Investment is subject to an adjustment cost which we model as in Christiano *et al.* (2001): this implies that one extra unit of investment does not transform into one extra unit of capital. The law of motion of the stock of capital is given by

$$K_{t+1} = (1-\delta)K_t + F\left(I_t, I_{t-1}\right) \tag{3.6}$$

where δ is the depreciation rate, I_t is the amount of investment goods and F is a technology that transform past and current investment into productive capital K_{t+1}. The properties of the F function are crucial in determining the shape of the response of investment to monetary shocks. This modelling of the adjustment costs allows to obtain a hump-shaped response of investment to a monetary shock, a result that is well documented in the VAR literature on the macroeconomic effects of monetary policy. This function is given by:

$$F\left(I_t, I_{t-1}\right) = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t \tag{3.7}$$

Both the function S and its first derivative are equal to zero in the non-stochastic steady state, while the second derivative is equal to s ($s > 0$). The inverse of s measures the elasticity of investment to a one per cent increase in the current price of newly installed capital.

[3] We assume for simplicity that the stock of capital is owned by the households.

3.2.2 The stock market

We assume the existence of a financial market where stocks are traded.[4] A stock is defined as the right for the holder to receive a dividend payment. In this market a representative mutual fund (mf) buys and sells stocks of a continuum of firms j (which are presented later on). Its objective is to maximise the sum of expected discounted profits:

$$\sum_{i=0}^{\infty} E_t \left[\beta^{i+1} \frac{\Lambda_{t+i+1}}{\Lambda_t} \int_0^1 \left(Z^j_{t+i} \Pi^j_{t+i} + Z^j_{t+i} P^j_{t+i} - Z^j_{t+i+1} P^j_{t+i} \right) dj \right] \tag{3.8}$$

where Z^j_t is the holding of stocks of firm j, P^j_t is their price and Π^j_t is the dividend. The profits of the mutual fund are paid as dividends to the households'. The time index of the discount factor $\beta \frac{\Lambda_{t+i+1}}{\Lambda_t}$ reflects the fact that time t dividends of the mutual fund at time t can be used by households to purchase consumption goods only at $t+1$. Taking the first order condition of this maximisation problem with respect to Z_{t+i+1} and substituting forward we obtain the price for a stock of firm j

$$P^j_t = \sum_{i=1}^{\infty} E_t \left[\beta^i \frac{\Lambda_{t+i+1}}{\Lambda_{t+1}} \Pi^j_{t+i} \right] \quad \forall j \in (0,1) \tag{3.9}$$

It is important to underline that the mutual fund is only meant to be a descriptive device to model participation by households in stock markets and it does not play any role in the transmission mechanism of monetary policy shocks.

In a symmetric equilibrium, where the profits of all firms are equal, the prices of the

[4] We rule out speculative bubbles in the stock market: this implies that the prices of stocks are equal to their fundamental values.

stocks of these firms will be identical and the mutual fund will hold one stock for each firm.[5]

$$Z_t^j = 1 \quad \forall j \in (0,1) \tag{3.10}$$

The dividends paid by the mutual fund to the households are given by:

$$\Pi_t^{mf} = \int_0^1 \Pi_t^j = \Pi_t \tag{3.11}$$

where Π_t^j are the profits made by the j^{th} monopolistic firm. Since all firms are equal, as it will be shown later, they will achieve the same level of profits Π_t.

3.2.3 The firms sector

We assume the existence of a continuum of monopolists on the $(0,1)$ interval each producing an intermediate good using a constant return to scale technology that utilise capital and labour as inputs. We rule out entry and exit in the firm sector and assume that these firms are owned by the mutual fund. All these firms face the same problem which consists of maximising period t profits which are defined as

$$\Pi_t^j = P_t^j Y_t^j - C\left(r_t, R_t W_t, Y_t^j\right) \tag{3.12}$$

where Y_t^j is the demand by households for good sold by firm j at price P_t^j, given by

[5]We assume, for simplicity, a fixed supply of stocks normalised to one.

$$Y_t^j = Y_t \left(\frac{P_t}{P_t^j} \right)^{\frac{\mu}{\mu-1}} \tag{3.13}$$

and $\frac{\mu}{(\mu-1)}$ is the constant elasticity of demand. The first order condition of the problem of choosing the price P_t^j that maximises time t profits is given by the standard pricing formula:

$$P_t^j = \mu MC_t^j \tag{3.14}$$

where in equilibrium the marginal costs MC_t^j are equal for all firms since they have access to the same production technology and they face the same factor prices W_t and r_t. Marginal costs are given by:

$$MC_t = Ar_t^{\alpha} \left(W_t R_t \right)^{1-\alpha} \tag{3.15}$$

where A is a constant.[6] The production technology is a standard Cobb-Douglas function with capital share α and fixed cost of production ϕ. Since we focus on a symmetric equilibrium, we set $P_t^j \equiv P_t$, where P_t is the price of the consumption good (produced by the competitive firm described below).

Finally, intermediate goods are combined into a final good by a competitive firm with the following CES technology:

[6]The expression for marginal costs can be derived from minimisation of total costs $w_t R_t N_t + r_t K_t$.

$$Y_t = \left[\int_0^1 \left(Y_t^j \right)^{1/\mu} dj \right]^{\mu} \tag{3.16}$$

where goods are indexed by $j \in (0,1)$, Y_t is the output of the competitive firm and Y_t^j is the output of the j^{th} monopolistic firm.

3.2.4 Monetary policy

In this section we specify how monetary policy is conducted in order to close the model. Rules that set the level of a short-term interest rate have become very popular in the literature on monetary policy: the most famous is the "Taylor rule" according to which the interest rate responds to contemporaneous inflation and output gap. We will specify a general class of interest rate feedback rules of the type analysed in Clarida, Galí and Gertler (1998). A target for the short-term interest rate is set by the central bank. The target is given by:

$$R_t^* = \overline{R} + \rho_Y \left(Y_t - \overline{Y} \right) + \rho_\pi \left(\pi_t - \overline{\pi} \right) + \rho_m \left(m_t - \overline{m} \right) \tag{3.17}$$

where $\overline{R}$, $\overline{Y}$, $\overline{\pi}$ and $\overline{m}$ are respectively the steady state values of the short-term nominal interest rate, output, inflation and real balances. Potential output $\overline{Y}$ is assumed to be constant since shocks, such as technology, that can produce fluctuations in this variable are not considered. The rule is referred to as partial accommodation if ρ_m is different from zero: a positive value identifies an upward sloping supply of real money. The actual short-term interest rate is adjusted according to the following partial adjustment mechanism:

$$R_t = (1 - \rho_R) R_t^* + \rho_R R_{t-1} + \epsilon_t \tag{3.18}$$

where ρ, measuring the speed of adjustment, belongs to the $[0, 1]$ interval and ϵ_t is the monetary policy shock. The Taylor rule is obtained by setting ρ_Y to 0.5, ρ_π to 1.5, ρ_m to 0 and ρ_R to 0. Under these rules, the central bank provides, through money injections X_t to the financial intermediary, whatever amount of money is demanded by the households.

Alternatively monetary policy can be defined in terms of a money growth rule, according to which the gross growth rate of the money supply $g_t = \frac{M_{t+1}}{M_t}$ is adjusted in response to the monetary policy shock. Therefore the rule is given by:

$$A(L) g_t = B(L) \epsilon_t \tag{3.19}$$

where $A(L)$ and $B(L)$ are two lag operators and ϵ_t is the monetary policy shock. For simplicity we will assume an autoregressive process of order one for g_t with coefficient ρ_g.

3.3 The first order conditions of the model

We now briefly present and discuss the first order conditions of the representative household's maximisation problem. The first order condition for money holding is given by:

$$\Lambda_t - \beta E_t (\Lambda_{t+1} R_{t+1}) = 0 \tag{3.20}$$

where R_t is the interest rate on deposits and Λ_t is the multiplier of the representative household's budget constraint which measure the marginal utility of one extra dollar in the asset market. The first order condition for cash holdings is given by:

$$U_{t,H_t} H_{t,Q_t} - \beta E_t \left(U_{t+1,H_{t+1}} H_{t+1,Q_t} \right) + \mathcal{V}_t + \Lambda_t - \Lambda_t R_t = 0 \tag{3.21}$$

The term $\mathcal{V}_t + \Lambda_t$ measures the benefit of increasing Q_t by one dollar, which is given by the marginal utility of $1/P_t$ extra units of consumption goods while $\Lambda_t R_t$ gives the cost in terms of utility of reducing deposits. The multiplier $\mathcal{V}_t$ measures the value for the household of an extra dollar to the household to be spent in the goods market that is the value of the liquidity services of money. The remaining terms represent the cost of adjusting cash holding, respectively at time t and $t+1$. The term H_{t,Q_t} denotes the derivative of H_t with respect to Q_t and U_{t,H_t} the derivative of period t utility with respect to H_t.

The first order condition for stock holdings is given by:

$$-\Lambda_t P_t^{mf} + \beta E_t \left(\Lambda_{t+1} P_{t+1}^{mf} + \Lambda_{t+1} \Pi_{t+1}^{mf} \right) = 0 \tag{3.22}$$

where P_t^{mf} is the price of a stock and Π_t^{mf} is the dividend paid by the mutual fund. Substituting forward equation (3.22) we obtain the usual pricing equation for an asset paying dividends:

$$P_t^{mf} = \sum_{i=1}^{\infty} E_t \left(\beta^i \frac{\Lambda_{t+i}}{\Lambda_t} \Pi_{t+i}^{mf} \right) \tag{3.23}$$

A similar pricing condition is derived by Lucas (1982) and Svensson (1985). The price of a stock at time t is given by the sum of the discounted (by the marginal utility of wealth) flow of future dividends. The discount factor is given by $\beta^i \frac{\Lambda_{t+i}}{\Lambda_t}$. The price of a stock of the mutual fund can be seen as a stock market index where individual firms' prices are averaged with equal weights.

The first order condition for consumption and hours worked together imply the following labour supply equation:

$$\frac{U_{t,C_t} + \beta E_t U_{t+1,C_t}}{P_t} + \frac{U_{t,N_t}}{W_t} = 0 \tag{3.24}$$

The first order conditions for the choice of capital is

$$-\Lambda_t P_{K',t} P_t + \beta E_t \left[\Lambda_{t+1} r_{t+1} + \Lambda_{t+1} P_{K',t+1} P_{t+1} (1-\delta)\right] = 0 \tag{3.25}$$

where $P_{K',t}$ is the price at time t of an extra unit of installed capital and $r_{t+1} + P_{K',t+1}(1-\delta)$ is the corresponding benefit. The price $P_{K',t}$ is given by the ratio of of the lagrange multiplier of cash-in-advance constraint (3.3) and the households budget constraint (3.5). It is an arbitrage condition according to which the cost of giving up one unit of consumption must be equal, in terms of utility, to the benefit of the extra unit of capital in the following period. If there were no adjustment costs for investment, the price of new capital, $P_{K',t}$, would be equal one. The first order condition for investment implies

$$-\Lambda_t P_t + \Lambda_t P_{K',t} F_{1,t} + \beta E_t \left(\Lambda_{t+1} P_{K',t+1} F_{2,t+1}\right) = 0 \tag{3.26}$$

The term in brackets is the value, in terms of utility, of an extra unit of investment: this unit produces $F_{1,t}$ units of installed capital at time t and $F_{2,t+1}$ units at time $t+1$. The cost of one extra unit of investment is equal to the price of consumption goods.

3.4 Calibration of parameters and impulse responses

The first order conditions for the households, the cash-in advance constraint (assumed to be binding due to local non-satiation), the intermediate firms pricing condition, the loan market clearing conditions and the resource constraint are linearised around the steady state after having normalised all nominal variables by P_{t-1} to achieve stationarity. The system consisting of the linearised equilibrium conditions is solved with the method described in Christiano (1998).

The following table reports the calibrated parameters of the benchmark model.

Table 3.1
Calibrated parameters: benchmark model

utility function	β	γ	ψ	ψ_0 [a]	b	c	d
	0.9975	2.0	0.57	0.51	0.6	1000	0.00005
others	α	μ	ϕ	s	δ	$\overline{\pi}$ [b]	
	0.36	1.25	0.94	5.0	0.0083	1.002	

[a] The parameter is chosen so that N is equal to 1 in the nonstochastic steady state.
[b] The value of the steady state annual inflation rate is equal to 2.5 per cent

The calibration of the parameters is based on different sources. The value of the discount factor, β, is chosen so that the steady state value of the real interest rate is equal to 3 per cent per year. The value of b, which measures the degree of habits in consumption, is close to the estimate in the benchmark model in Christiano *et al.* (2001). The parameter ψ, measuring the inverse of the elasticity of the labour supply, is taken from Christiano *et al.* (1996b): it implies an elasticity of 1.75. The parameters c and d, that affect the marginal cost of adjusting cash holdings, are taken from Christiano and Eichenbaum (1992). These parameters are crucial in determining the persistence of the liquidity effect when monetary policy is defined in terms of a money growth rule. On the other hand, they have a smaller effect when an interest rate rule is assumed. With respect to the capital share in the production function, α, we have chosen the standard value of 0.36 used in the literature on real business cycle models. The parameter s of the investment adjustment cost function is set close to the average of the values estimated in Christiano *et al.* (2001). The parameter μ, measuring the mark-up of prices over marginal costs, is set to 1.25, close the benchmark value used in Christiano *et al.* (1997). The value of the fixed cost ϕ is calibrated assuming that the ratio of real profits to output is equal to 6 per cent as it is found in the U.S. data for the period 1985-2000.[7] Finally, the steady state annual inflation rate is set to 2.5 per cent.

The following table reports the responses on impact and after two years of stock prices to a contractionary one per cent monetary policy shock.

[7] The fixed cost is given by $\phi = \frac{\mu(1-s_\pi)\overline{K}^\alpha - \overline{K}^\alpha}{\mu(1-s_\pi)}$ where s_π is the share of profits, in real terms, relatively to output. We have set $\overline{N}$ equal to 1. The steady state level of capital is denoted with $\overline{K}$.

Table 3.2
Monetary policy rules and response of stock prices[a]

monetary policy rule	coefficients					response[b]	
	ρ_Y	ρ_π	ρ_m	ρ_R	ρ_g	$k = 1$	$k = 24$
1. Taylor	0.5	1.5	0	0	0	-5.0	-0.2
2. Taylor	0.5	1.5	0	0.75	0	-6.7	-0.7
3. partial accommodation	0.5	1.5	0.3	0.75	0	-6.6	0.4
4. inflation targeting	0	1.5	0	0.75	0	-9.9	-7.7
5. money growth	0	0	0	0	0.3	-6.6	-0.4

[a] Responses, in nominal terms, to a contractionary one per cent policy shock.
[b] Percent deviation from unshocked path after k periods.

Under all the rule, a contractionary monetary shock determines an increase in the short-term interest rate and a decrease in nominal stock prices and money. Inflation targeting rules produce persistent effects on stock prices, while this is not the case for those rules where the coefficient of the output gap is different from zero. The reason is that these latter rules have a stabilising effect on the economy: when the output gap becomes negative, the central bank reduces the target and the actual short-term interest rate and this has a positive effect on production, inflation and profits. In these cases, the level of nominal variables is not permanently affected by monetary policy: nominal profits, which are a determinant of stock prices, return to the baseline value after a monetary policy shock and this produces a transitory effect on nominal stock prices. The same results are obtained if a positive coefficient is assumed for real money and the coefficient for the output gap is set to zero. The following figure reports the responses of the interest rate, money and stock prices to a contractionary monetary policy shock under the different rules specified in Section 3.2.4.

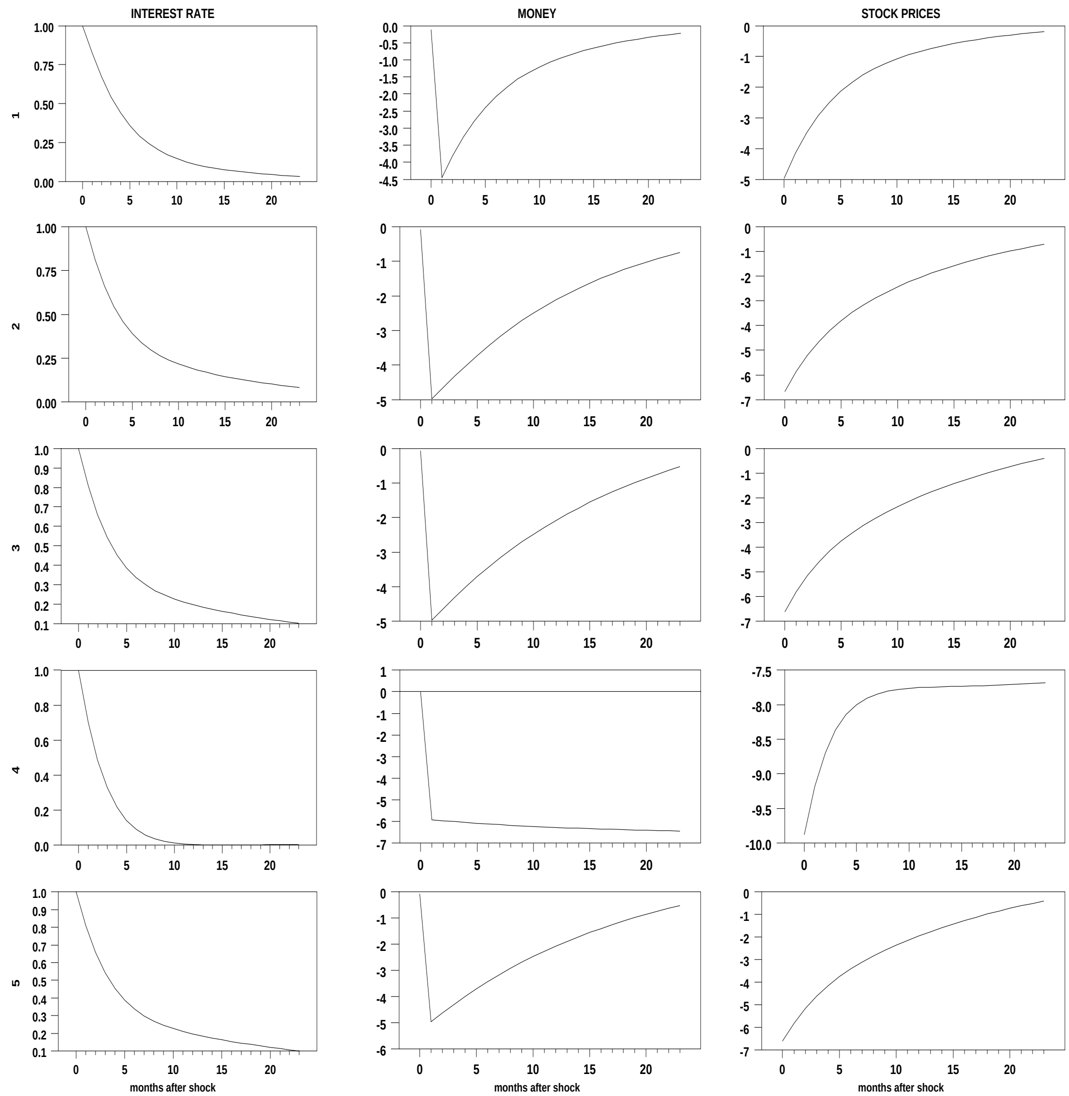

Fig. 3.1 Response of nominal stock prices to a contractionary monetary policy shock under different rules

The interpretation of the response of stock prices to a monetary policy shock can be based on the pricing condition (3.23), according to which the price of a stock is equal to the sum of future discounted dividends, given the information available at time t. Monetary policy shocks influence stock prices either through the discount factor $\beta^i \frac{\Lambda_{t+i}}{\Lambda_t}$ or future dividends Π_{t+i}^{mf}. In the model a contractionary monetary shock, measured either by an exogenous decrease in the growth rate of money or an increase in the short-term interest rate, produces an increase in firms' marginal costs and a decrease in production and profits. As a consequence of the decrease in labour and capital income, households' decrease deposits, investment and stock holdings in order to smooth consumption. The returns to these assets are linked by no-arbitrage conditions (as it can be seen by staring at equations (3.20), (3.21), (3.22), (3.25) and (3.26)). Therefore the decrease in stock prices is the consequence of lower future dividends and a lower demand for stocks for a given supply.

A sensitivity analysis of the response of stock prices to a contractionary monetary shock shows that, in the benchmark calibration and under a partial adjustment Taylor rule (rule 2 in table 3.2), the value of the mark-up μ and of the fixed cost ϕ play an important role in shaping the response. These parameters affects both the steady state of the model and the dynamics of dividends as it can be seen from the following equation:

$$\hat{\pi}_t^{mf} = \frac{1}{\overline{\pi}^{mf}} \left(\overline{\pi}\overline{Y} - \frac{\overline{\pi}\overline{Y}}{\mu} - \phi\frac{\overline{\pi}}{\mu} \right) \hat{\pi}_t + \frac{\overline{\pi}\overline{Y}}{\overline{\pi}^{mf}} \left(1 - \frac{1}{\mu} \right) \hat{Y}_t \tag{3.27}$$

where a hat denotes percentage deviation from steady state of real dividends π_t^{mf}, output, Y, and inflation, π. The fixed cost ϕ, when different from zero, and the mark-up μ determine the dynamics of profits and consequently stock prices. This is not the case when ϕ is equal to zero[8], in which case the above equation becomes:

$$\hat{\pi}_t^{mf} = \hat{\pi}_t + \hat{Y}_t \tag{3.28}$$

[8]This can be seen by noting that $\overline{\pi}^{mf} = \overline{\pi}\overline{Y} \left(1 - \frac{1}{\mu} \right)$.

As it can be seen from figure 3.2, setting the fixed cost equal to zero determines a smaller and less persistent response of nominal stock prices with respect to the benchmark calibration. The reason is that, as it can be seen from (3.27), the presence of fixed costs implies a higher dependence of real profits to output (the coefficient on $\hat{Y}_t$ is equal to 3.3 compared with a coefficient of 1). The choice of the mark-up μ is not relevant when the fixed cost is calibrated as it is described in footnote 7. On the other hand, it becomes relevant when the fixed cost is set to zero by affecting the steady state of the economy. A smaller mark-up (1.05) implies a larger response of stock prices mainly reflecting a larger impact of monetary policy on inflation partially compensated by a smaller effect on output. The opposite happens for a larger mark-up (1.8). The higher is the degree of monopolistic competition in the intermediate firm sector, which implies a lower elasticity of demand, the smaller is the response of dividends and nominal stock prices.

The parameter c that affects the magnitude of adjustment costs for changing cash holdings is also important in determining the behaviour of stock prices. A low value of c (200) implies a quicker adjustment of cash and deposits and consequently, by an arbitrage condition, stock holdings. For a given supply of stocks, this implies larger movements in stock prices. A larger c (2000) does not yield significatively different responses from the benchmark calibration. Changing the degree of risk aversion (γ) (from 1.01 to 4), the degree of habits in consumption (setting b equal to zero), the elasticty of labor supply ($\frac{1}{\psi}$) (from 0.057 to 10.57) and the cost for adjusting investment (from 1 to 10) have a small effect on the response of stock prices. The following figure reports the responses of nominal stock prices under different calibration of parameters.

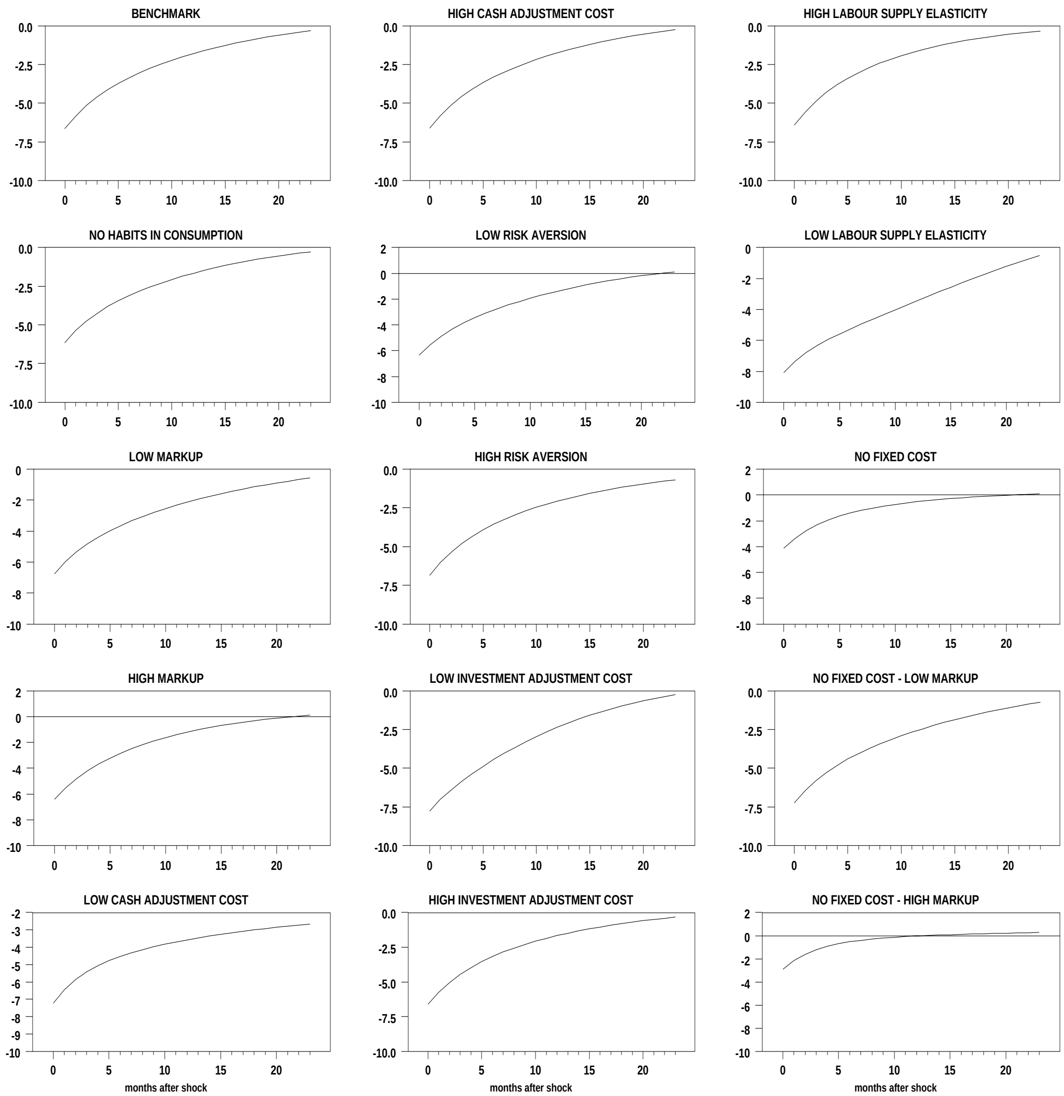

Fig. 3.2 Sensitivity analysis of the response of stock prices

3.5 Validating the model

In this section we will proceed in validating the proposed model applying the methodology described in Canova (2001) to U.S. data. This approach takes seriously the objection that all the models represent an approximation to the true data generating process (DGP) and the idea that economic theory should be used in validating these models. The proposed approach to validation combines calibration of dynamic stochastic general equilibrium (DSGE) models and VARs.

We now describe the approach. The first step consists of finding robust implications of the model. These are implications that are robust to different sets of parameters, different functional forms of the primitives and, as in our case, different monetary policy rules. In the second step, these implications, in the form, for example, of the signs of the impulse responses or their cross-correlations, are used to identify shocks in the data. An argument in favour of this identification strategy for VARs can be found in Canova and Pina (1999). The authors find that the zero restrictions generally used in the VAR literature can be inconsistent with the dynamic relationships among variables predicted by DSGE models.

In the third step, a qualitative comparison is carried out by comparing the responses of variables to identified shocks in order to examine whether and to what extent the dynamics of the model and the data are similar. In the last step the validation process uses the quantitative implications (e.g. impulse responses and variance decompositions) of the model and the data to test for the significance of their equality. Canova (2001), for example, compares the value of the half-life of output predicted by sticky price and limited participation models to evaluate whether they are able to generate sufficient persistence in the response of output to shocks.

The responses of money, stock price, output and prices to a monetary shock are used as a robust implication of the limited participation model we have set up. To evaluate the robustness of the signs of the responses we have used different sets of calibrated parameters and different monetary policy rules (see figures 3.1 and 3.2). A contractionary monetary shock always increases the short-term interest rate and decreases nominal stock prices and nominal money. The signs of the responses of output and prices are also robust to different policy rules and calibration of parameters.

The signs of the responses are used as restrictions to be imposed on U.S. monthly data running from 1985 to 2000. The covariance matrix of the reduced form VAR residuals, Σ, is decomposed into PDP' where D is the matrix of eigenvalues and P the matrix of corresponding eigenvectors.[9] The designed algorithm searches along all possible rotation matrices $Q_{m,n}$ and angles ν for the identifications that satisfy the sign restrictions on the first twelve steps of the impulse response horizon. A brief description of the algorithm is available in appendix B.2. The identifications that imply implausible magnitudes for the responses of stock prices and output are discarded when computing the median and the 5 and 95 percentiles. The response obtained imposing the sign restrictions on a different number of steps (k) of the impulse response function can be found in appendix B.3 of this chapter.

The following figure reports the responses of the short-term interest rate, money and stock prices to a contractionary monetary policy shock. Error bands (5 and 95 percentiles) are computed by means of Monte Carlo integration. For comparison we report the responses obtained with the model under a partial adjustment Taylor rule (rule 2 in Table 3.2).

[9]The reduced form VAR has three lags and a complete set of seasonal dummies. The number of lags has been selected in order to achieve serially uncorrelates residuals.

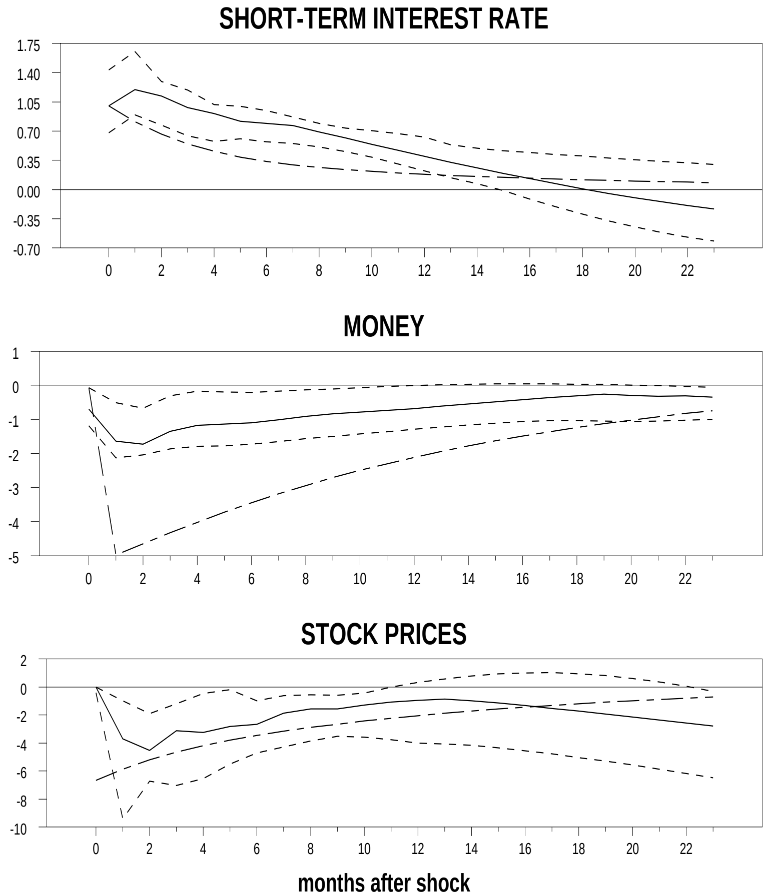

Fig. 3.3 Monetary policy shock: partial adjustment Taylor rule (k=12)

(— median – – 5, 95 percentiles — – — data)

The responses of the short-term interest rate and stock prices fall within the 90 per cent confidence interval while the response of nominal money M2 falls outside the interval. The model is able to replicate, at least qualitatively, the responses found in the data. The following figure compares the impulse responses in the data with those predicted by the model under an inflation targeting rule (rule 4 in table 3.2).

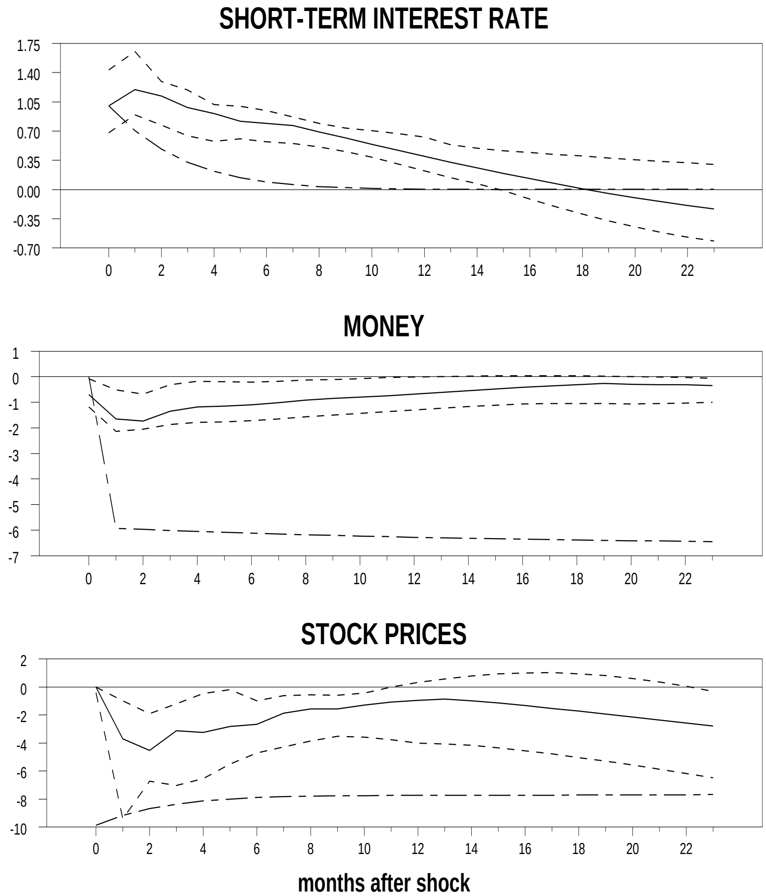

Fig. 3.4 Monetary policy shock: inflation targeting rule (k=12)

(— median – – 5, 95 percentiles — – — data)

The model with an inflation targeting rule predicts a persistent decline in nominal money which is not present in the data. The response of nominal stock prices is larger and more persistent in the model than in the data.

Overall, the responses in the data are robust to choosing different number of steps over which evaluating the sign of the responses as it can be seen from the figures reported above and in appendix B.3. However, the model with a partial adjustment Taylor rule seems to represent better the responses of stock prices and nominal money. The limited participation model, modified to allow households trading in stocks, which we have set up is able to replicate, at least from a qualitative point of view, the empirical responses of stock price indices to monetary policy shocks under a variety of monetary policy rules and calibration of parameters.

Appendix B.1 The model linearised equilibrium conditions

In this section we report all the linearised first order conditions together with the market-clearing conditions and the monetary policy rules for the model described in Section 3.2.

We define the following variables: $q_t = \frac{Q_t}{P_{t-1}}$, $m_t = \frac{M_t}{P_{t-1}}$, $w_t = \frac{W_t}{P_{t-1}}$, $\tilde{r}_t = \frac{r_t}{P_{t-1}}$, $\pi_t^{mf} = \frac{\Pi_t^{mf}}{P_{t-1}}$, $p_t^{mf} = \frac{P_t^{mf}}{P_{t-1}}$, $\lambda_t = \Lambda_t P_{t-1}$ and $\nu_t = \mathcal{V}_t P_{t-1}$. A bar denotes steady state values.

Consumption

$$-\{\gamma\left(1+\beta b^2\right)\left[\overline{C}\left(1-b\right)\right]^{-\gamma-1}\}\hat{C}_t+\{\gamma b\left[\overline{C}\left(1-b\right)\right]^{-\gamma-1}\}\hat{C}_{t-1}+\{\gamma b\beta\left[\overline{C}\left(1-b\right)\right]^{-\gamma-1}\}E_t\hat{C}_{t+1} =$$

$$\overline{\pi}\left(\overline{\lambda}+\overline{\nu}\right)\hat{\pi}_t+\overline{\pi}\,\overline{\lambda}\,\hat{\lambda}_t+\overline{\pi}\,\overline{\nu}\,\hat{\nu}_t$$

Labour supply condition

$$-\psi\overline{N}^{\psi}\hat{N}_t = \left(\overline{\lambda}+\overline{\nu}\right)\overline{\pi}\hat{\pi}_t+\overline{\lambda}\,\overline{\pi}\,\hat{\lambda}_t+\overline{\nu}\,\overline{\pi}\hat{\nu}_t$$

Euler equation for money

$$\hat{\lambda}_t = E_t\left(\hat{\lambda}_{t+1}+\hat{R}_{t+1}-\hat{\pi}_t\right)$$

Euler equation for cash

$$\left[2\overline{U}_N\frac{\overline{\pi}^2}{\overline{q}^2}c^2d\left(1+\beta\right)\right]\hat{q}_t-\left[2\overline{U}_N\frac{\overline{\pi}^2}{\overline{q}^2}c^2d\right]\hat{q}_{t-1}\left[2\overline{U}_N\frac{\overline{\pi}^2}{\overline{q}^2}c^2d\left(1+\beta\right)\right]E_t\hat{q}_{t+1}$$

$$+\left[2\overline{U}_N\frac{\overline{\pi}^2}{\overline{q}}c^2d\left(1+\beta\right)\right]\hat{\pi}_{t-1}-\left[2\overline{U}_N\frac{\overline{\pi}^2}{\overline{q}}c^2d\left(1+\beta\right)\right]\hat{\pi}_t+\overline{\nu}\hat{\nu}_t+\overline{\lambda}\left(1-\overline{R}\right)\hat{\lambda}_t-\overline{\lambda}\,\overline{R}\hat{R}_t = 0$$

Euler equation for investment

$$\hat{P}_{K',t} = -s\hat{I}_{t-1} + s\left(1+\beta\right)\hat{I}_t - s\beta E_t\hat{I}_{t+1}$$

Euler equation for capital

$$\hat{\lambda}_t + \hat{\pi}_t + \hat{P}_{K',t} = E_t\{\hat{\lambda}_{t+1} + \left[1-\beta\left(1-\delta\right)\right]\hat{\tilde{r}}_{t+1} + \beta\left(1-\delta\right)\hat{\pi}_{t+1} + \beta\left(1-\delta\right)\hat{P}_{K',t+1}\}$$

Euler equation for stock holdings

$$\hat{\lambda}_t + \hat{p}_t^{mf} = E_t\left[\hat{\lambda}_{t+1} + \beta\hat{p}_{t+1}^{mf} + \left(1-\beta\right)\hat{\pi}_{t+1}^{mf}\right]$$

Pricing condition of intermediate-goods producing firms

$$\hat{\pi}_t = \alpha\hat{\tilde{r}}_t + \left(1-\alpha\right)\hat{w}_t + \left(1-\alpha\right)\hat{R}_t$$

Production function of intermediate-goods producing firms

$$\overline{Y}\hat{Y}_t = \left[\left(1-\alpha\right)\overline{N}^{(1-\alpha)}\overline{K}^{\alpha}\right]\hat{N}_t + \left[\alpha\overline{N}^{(1-\alpha)}\overline{K}^{\alpha}\right]\hat{K}_t$$

Definition of rental price of capital

$$\hat{\tilde{r}}_t - \hat{w}_t - \hat{R}_t = \hat{N}_t - \hat{K}_t$$

Aggregate resource constraint

$$\overline{Y}\hat{Y}_t = \overline{C}\hat{C}_t + \overline{I}\hat{I}_t$$

Capital accumulation law

$$\hat{K}_{t+1} = (1-\delta)\,\hat{K}_t + \delta\hat{I}_t$$

Loan market clearing condition

$$\overline{w}\overline{N}\hat{w}_t + \overline{w}\overline{N}\hat{N}_t = \overline{\pi}\,\overline{m}\,\hat{m}_{t+1} - \overline{q}\hat{q}_t$$

Cash-in-advance constraint

$$\overline{\pi}\,\overline{C}\,\hat{\pi}_t + \overline{\pi}\,\overline{C}\,\hat{C}_t = \overline{w}\,\overline{N}\,\hat{w}_t + \overline{w}\,\overline{N}\,\hat{N}_t + \overline{q}\hat{q}_t$$

Definition of profits (once marginal costs have been substituted with inflation)

$$\hat{\pi}_t^{mf} = \frac{1}{\overline{\pi}^{mf}}\left(\overline{\pi}\overline{Y} - \frac{\overline{\pi}\overline{Y}}{\mu} - \phi\frac{\overline{\pi}}{\mu}\right)\hat{\pi}_t + \frac{\overline{\pi}\overline{Y}}{\overline{\pi}^{mf}}\left(1 - \frac{1}{\mu}\right)\hat{Y}_t$$

Objective short-term interest rate

$$\hat{R}_t^* = \rho_Y\hat{Y}_t + \rho_\pi\hat{\pi}_t + \rho_m\hat{m}_t$$

Short-term interest rate adjustment

$$\hat{R}_t = (1 - \rho_R)\,\hat{R}_t^* + \rho_R \hat{R}_{t-1} + \epsilon_t$$

Money growth rule

$$\hat{g}_t = \rho_g \hat{g}_{t-1} + \epsilon_t$$

Appendix B.2 The sign restriction approach to the identification of shocks

In this appendix we present the identification of shocks in VARs by means of restriction on the signs of the impulse responses of a selected set of variables.

The reduced form covariance matrix of the VAR residuals Σ is decomposed into PDP' where D is the matrix of eigenvalues and P the matrix of corresponding eigenvectors. The designed algorithm searches along all possible rotation matrices $Q_{m,n}$ and angles ν that satisfy the sign restrictions we have imposed using the following decomposition:

$$\Sigma = PD^{\frac{1}{2}}Q_{m,n}Q'_{m,n}D^{\frac{1}{2}}P'$$

The inverse of the matrix $PD^{\frac{1}{2}}Q_{m,n}Q'$ is used to compute the impulse responses to a monetary policy shock. The matrices $Q_{m,n}$ are orthonormal, that is they imply that $QQ' = I$ where I is the identity matrix.

Appendix B.3 Figures

Fig. 3.5 Monetary policy shock: partial adjustment Taylor rule (k=6)

(— median – – 5, 95 percentiles — – — data)

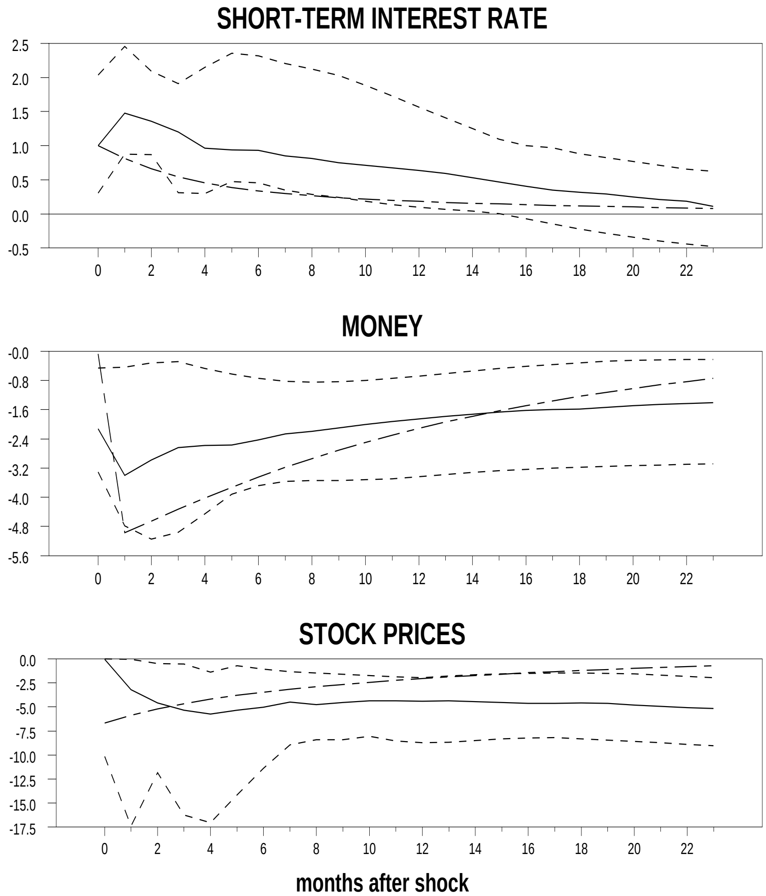

Fig. 3.6 Monetary policy shock: partial adjustment Taylor rule (k=16)

(— median – – 5, 95 percentiles — – — data)

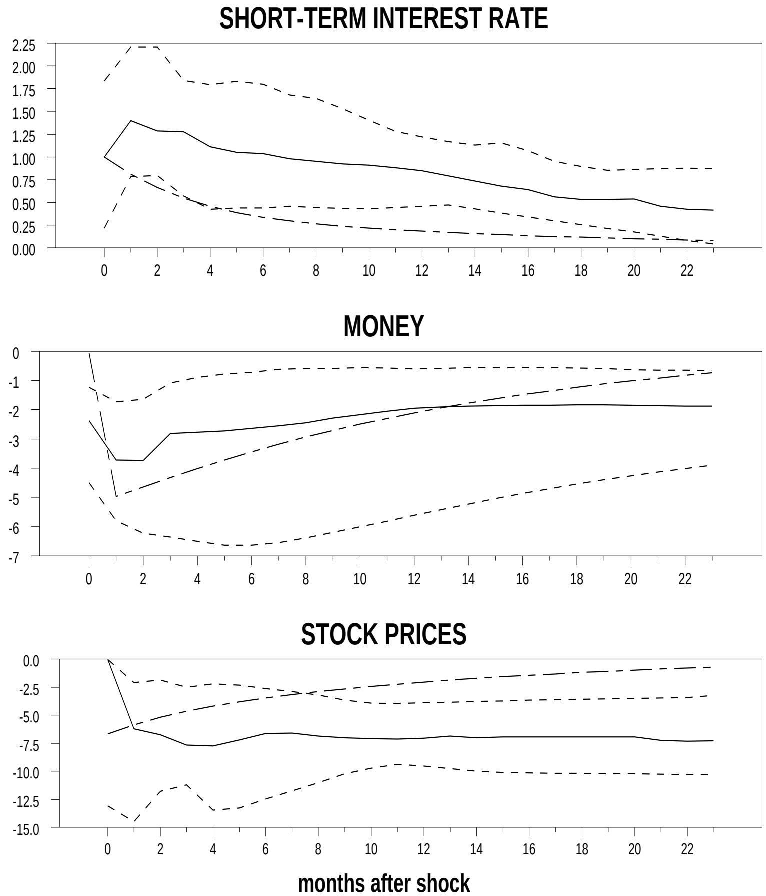

Fig. 3.7 Monetary policy shock: partial adjustment Taylor rule (k=24)

(— median – – 5, 95 percentiles — – — data)

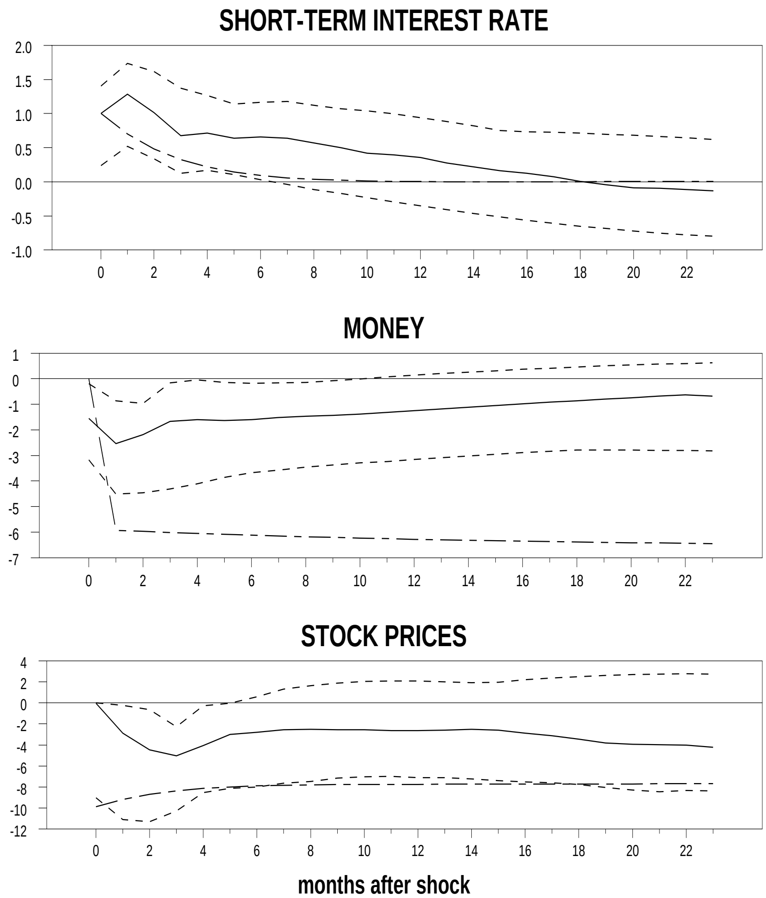

Fig. 3.8 Monetary policy shock: inflation targeting rule (k=6)

(— median – – 5, 95 percentiles — – — data)

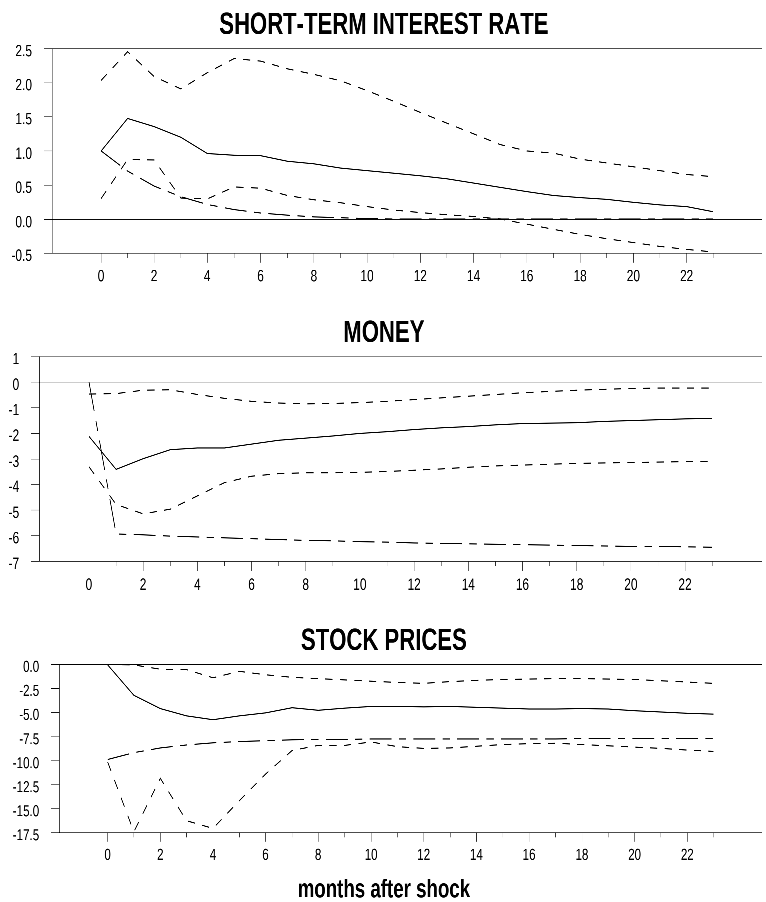

Fig. 3.9 Monetary policy shock: inflation targeting rule (k=16)

(— median – – 5, 95 percentiles — – — data)

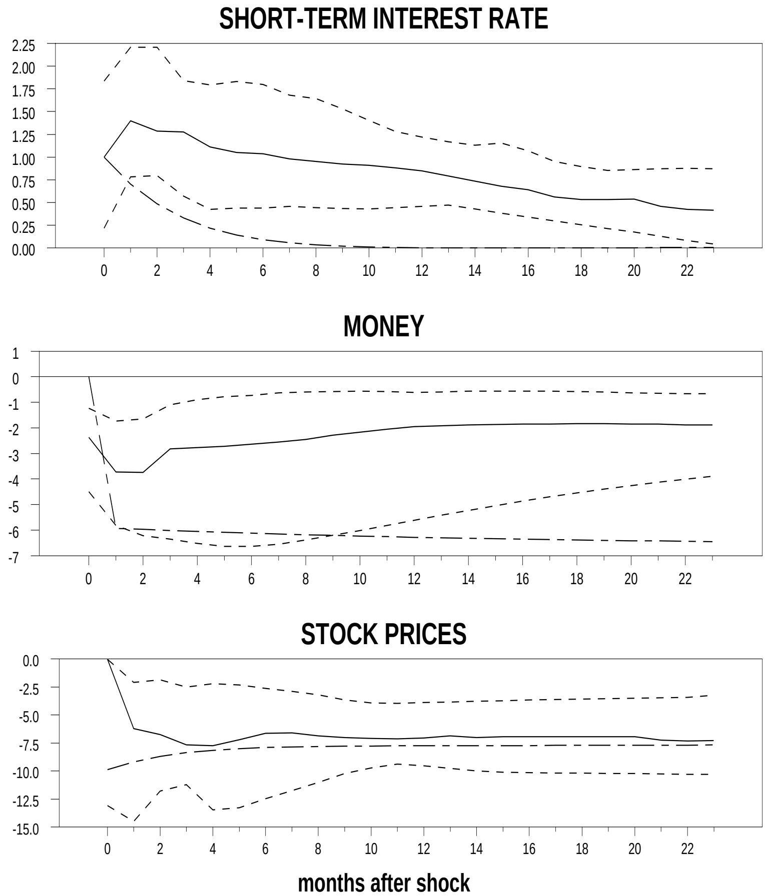

Fig. 3.10 Monetary policy shock: inflation targeting rule (k=24)

(— median – – 5, 95 percentiles — – — data)

Chapter 4

Estimation of DSGE models: agency costs or adjustment costs models

4.1 Introduction

In the literature on DSGE models it is common practice to introduce some sort of rigidity in the accumulation of capital either by households or firms. Besides other type of frictions (e.g. nominal wage and price rigidity), several papers impose adjustment costs on capital accumulation to improve the propagation mechanism of structural shocks and help the models in matching some key features of the data.

The presence of adjustment costs gives rise to a wedge between the price of investment goods and the price of newly installed capital and allows to study the relationship between Tobin'q and investment (e.g. Abel (1982)). Some examples of the papers that introduce adujstment costs on the accumulation of capital are Kim (2000), Ireland (2001b), Christiano *et al.* (2001), Altig *et al.* (2002) and Smets and Wouters (2002). Other papers such as Kydland and Prescott (1982) and McGrattan (1994) use a "time to build" constraint on the accumulation of capital to obtain more persistent dynamics for investment.

However an interesting and appealing alternative for modelling the costs for adjusting the capital stock has recently become available in the literature on the business cycle. Carlstrom and Fuerst (1997) have developed a real business cycle model in which adjustment costs for the capital stock arise endogenously as the result of agency costs associated to the production of investment goods. The existence of asymmetric information between lenders (capital mutual funds) and borrowers (entrepreneurs) of funds give rise to an agency problem the solution to which is a standard debt contract (Gale and Hellwig (1985)). The authors show that the model, contrary to a standard real business cycle (RBC) one, is able to match the empirical fact that output growth is serially correlated in the short-run (amplification). This amplification effect is the result of the optimising behaviour of entrepreneurs who accumulate net worth (internal funds) to lower agency costs. Another important result is the relationship between agency costs and adjustment costs models. While in these two class of models the supply of capital goods is an increasing function of their aggregate price, it is only in the agency costs model that this supply curve depends positively on the level entrepreneurs' net worth. Carlstrom and Fuerst (2001) conclude that the existence of these costs does not amplify the response of variables to monetary policy shocks.

In this chapter we investigate whether an agency cost type of model is an empirically valid alternative to models in which capital adjustment costs are imposed exogenously. By valid alternative we mean a model that is able to match some key features of the data such as first and second moments and impulse responses to shocks. To answer this question we estimate the agency cost model and two models with exogenous adjustment costs on investment via maximum likelihood using post-war data for the U.S. We then proceed to evaluate to what extent they are able to account for some of the features of the business cycle and the empirical response of a selected set of variables to identified technology and monetary policy shocks. The estimated agency cost model will also allow to quantify the welfare costs associated to agency costs.

The following results emerge from the analysis. First, the estimated agency cost model is not able to match the means and standard deviations of selected variables. The reason for this result may be the strong restriction the model imposes on the relation between internal funds and investment. The model with adjustment cost on the stock of capital seems to provide the best representation of business cycle fluctuations. Second, by comparing the likelihood at the maximum of the alternative models with that of an unconstrained first-order VAR for the data it results that all the three models perform worst than the VAR. One possible reason for this result is that other frictions, such wage rigidity, variable capacity utilisation and habits formation in consumption, which are not introduced in our models, may be of help in accounting for the dynamics of the data. Finally, an evaluation by means of impulse responses to technology and monetary policy shocks suggests that all the models are able to replicate, at least qualitatively, the data, with the adjustment cost models performing slightly better.

The remainder of the chapter is organised as follows. Section 4.2 review some of the existing literature. Section 4.3 presents the models, Section 4.4 describe their maximum likelihood estimation while Section 4.5 presents their evaluation. Section 4.6 presents the conclusions.

4.2 Links to the existing literature

In this section we review some of the papers that have developed and estimated dynamic stochastic models with adjustment costs on investment. Most of these models, in their state-space representation, have been estimated by means of maximum likelihood. Some examples are Kim(2000), Ireland (2001b) and Keen (2002) for the U.S., Smets and Wouters (2002) for the euro area and Dib (2001) for Canada. An alternative to maximum likelihood estimation can be found in Christiano *et al.* (2001) and Altig *et al.* (2002).

Kim (2000) develops and estimates a model with sticky prices and wages and finds that the interaction between nominal rigidities and adjustment costs for capital is crucial in generating a liquidity effect of monetary policy. The fit of the model is comparable to that of an unconstrained first-order VAR. A similar model is set up and estimated by Dib (2001) using data for Canada.

Ireland (2001b) investigates whether the correlations between nominal and real variables are the result of price rigidity or they reflects the way in which monetary policy is conducted. Ireland's model includes capital adjustment costs.

Keen (2002) estimates a model with sticky prices and limited participation in financial markets using data for the U.S. and finds that the estimated model is able to replicate some important key characteristics of the data.

Christiano *et al.* (2001) consider a model with nominal rigidities, variable capacity utilisation and adjustment costs on the changes in investment. The parameters are estimated minimising the distance between the model and the data impulse responses to identified monetary policy shocks. The estimated model is able to account for the observed persistence in both inflation and output. Recently, Altig *et al.* (2002) have shown that the same model is also able to account for the responses of a set of variables to technology shocks. In these two papers the introduction of adjustment costs on the changes in the level of investment is crucial in generating a hump-shaped response of this variable following a monetary and technology shocks.

Smets and Wouters (2002) develop and estimate using Bayesian techniques a dynamic stochastic general equilibrium model for the euro area with both nominal and real rigidities. Similarly to Christiano *et al.* (2001) the adjustment costs are imposed on the changes in the level of investment. The authors find that the estimated model performs better than a standard VAR and does at least as well as a Bayesian VAR.

All the works that have been described in this section are characterised by models in which monetary policy has real effects. However, other papers have developed and estimated via maximum likelihood dynamic stochastic equilibrium models in which monetary policy plays no role. McGrattan (1994), for example, finds that incorporating fiscal shocks in a real business cycle model with a "time to build" constraint on the accumulation of capital reduces the contribution of technology shocks to fluctuations in output, consumption and hours worked.

4.3 The models

In this section we describe three models that have been proposed in the literature. The first one is a model in which capital adjustment costs arise endogenously as the result of asymmetric information and agency costs (Carlstrom and Fuerst, 1997, 2001). In the second model adjustment costs on the level of investment are exogenously imposed following Ireland (2001b). In the last model adjustment costs are imposed on the changes in investment following Christiano *et al.* (2001) and Smets and Wouters (2002). In all the models prices are sticky because monopolistic competitive firms face a cost for changing the prices of their products. The common setup of the models differ from Ireland (2001b) with respect to the choice of the utility function, the way in which the productivity shock enters in the production function and for the absence of a shock to the marginal efficiency of investment.

4.3.1 The households sector, the production sector and monetary policy

We now discuss the maximisation problem of the representative households and monopolistic competitive firms which are common to all the models. We also describe how the interest rate is set by the monetary authority.

A representative household maximise the expected stream of discounted istantaneous utilities by choosing the amount of consumption goods to buy, labor to supply and real balances to hold. The utility is given by:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\eta_t \frac{1}{(1-\gamma)} c_t^{(1-\gamma)} - \psi_0 \frac{1}{(1+\psi)} L_t^{(1+\psi)} + \theta_0 \frac{1}{(1-\theta)} \left(\frac{M_t}{P_t e_t} \right)^{(1-\theta)} \right]$$

where η_t is a consumption preference shock and e_t is a money demand shock. These two shocks follow independent first-order autoregressive processes with coefficients ρ_η and ρ_e and i.i.d normally distributed innovations with standard deviations σ_η and σ_e.

The budget constraint the representative household faces is given by:

$$\frac{M_{t-1} + B_{t-1} + W_t L_t + r_t k_t + D_t}{P_t} \geq c_t + k_{t+1} - (1-\delta)\, k_t + \frac{B_t / R_t + M_t}{P_t}$$

where M_t is nominal money holdings, B_t is nominal bond holdings, R_t is the gross interest rate on bonds, D_t are the profits of firms that produce consumption goods, r_t is the rental price of capital k_t and P_t is the price level.

We now describe the production sector of the economy. A competitive firm aggregates intermediate goods into a final good using the following constant-returns-to-scale technology

$$y_t = \left[\int_0^1 y_t\,(i)^{\frac{\vartheta}{\vartheta-1}}\, di \right]^{\frac{\vartheta}{\vartheta-1}}$$

where $\vartheta > 1$ is the constant elasticity of demand.

Each intermediate monopolistic competitive firm produces a good indexed by i using the following Cobb-Douglas production technology:

$$a_t k_t\,(i)^{\alpha}\, L_t\,(i)^{1-\alpha} \geq y_t\,(i)$$

and hiring labour and capital from households. The aggregate productivity shock a_t follows an autoregressive process of order one with coefficient ρ_a and i.i.d normally distributed innovations with standard deviation σ_a.

Price rigidity is introduced in the model as in Rotemberg (1982) and Ireland (2001a, 2001b) assuming that intermediate firms face a quadratic cost for changing their prices $P_t\,(i)$

$$\frac{\phi_p}{2}\left[\frac{P_t\left(i\right)}{\overline{\pi}P_{t-1}\left(i\right)}-1\right]^2 y_t\left(i\right)$$

which is paid in terms of finished goods. The parameter $\phi_p \geq 0$ determines the size of adjustment costs while $\overline{\pi}$ denotes the steady state gross rate of inflation. The presence of costs for adjusting prices makes the problem of monopolistic competitive firms dynamic. These firms maximise the expected discounted stream of real profits by choosing the amount of labour and capital to hire from households and the price of the goods they sell. The way price rigidity is introduced in the model implies that the aggregate resource constraint is given by

$$y_t + \frac{\phi_p}{2}\left(\frac{\pi_t}{\overline{\pi}}-1\right)^2 y_t = c_t + i_t$$

To close the models we need to specify the rule according to which the monetary authority sets the nominal short-term interest rate R_t. The monetary policy rule is defined as in Ireland (2001b): the interest rate is adjusted in response to deviations of current inflation, output and nominal money growth from their steady state levels:

$$\hat{R}_t = \rho_y \hat{y}_t + \rho_\pi \hat{\pi}_t + \rho_g \hat{g}_t + v_t$$

The shock v_t follows an autoregressive process of order one with coefficient ρ_v and i.i.d normally distributed innovations with standard deviation σ_v.

4.3.2 The agency costs (AG) model

In this section we briefly describe the model of Carlstrom and Fuerst (1997) starting from the entrepreneurs sector. The entrepreneurs, who are responsible for the production of investment goods, have access to a stochastic linear technology that transforms $i_{i,t}$ units of consumption goods into $\omega_{i,t} i_{i,t}$ units of investment goods (the index i stands for the i^{th} entrepreneur). It is assumed that only these agents can costlessly observe the productivity shock $\omega_{i,t}$: it is exactly this assumption that give rise to agency issues in the model. Entrepreneurs need external financing to produce capital goods since absent this assumption, the issue of asymmetric information would not play any role in the model.

The lenders of funds, the capital mutual funds (CMFs) that receive resources from households, must pay a monitoring cost $\mu i_{i,t}$ in order to observe the productivity shock $\omega_{i,t}$. This shock has an i.i.d lognormal distribution with a mean of unity and cumulative distribution function Φ. As a result of the asymmetric information, a moral hazard problem arises since the entrepreneur would misreport the true value of $\omega_{i,t}$ to the lender. The optimal contract between capital mutual funds and entrepreneurs, which Gale and Hellwig (1985) and Williamson (1987) have shown to be a standard debt contract, is such that the borrower always report the true value of $\omega_{i,t}$. If $n_{i,t}$ is the amount of internal funds that the entrepreneur has available, he will borrow $i_{i,t} - n_{i,t}$ and agree to repay an interest rate R_t^k to the lenders. However, if the realisation of $\omega_{i,t}$ is low, the entrepreneur will default. This will happen whenever the productivity shock is such that $\omega_{i,t} \leq \left(1 + R_t^k\right) \frac{(i_{i,t} - n_{i,t})}{i_{i,t}} \equiv \overline{\omega}_{i,t}$. In case of default, the lender will get the outcome of the project $\omega_{i,t} i_{i,t}$ net of the monitoring cost $\mu i_{i,t}$. For simplicity, we drop the index i from all the entrepreneur-specific variables since all agents face the same optimisation problem.

The optimal contract, which is described by the pair (i_t, ω_t) can be derived from maximising the expected return of the entrepreneur subject to a participation constraint, which implies that the lender must be able to recoup the investment. The maximisation problem is described by

$$\text{Maximise } q_t i_t f_\omega(\overline{\omega}_t) \quad \text{subject to} \quad q_t i_t g_\omega(\overline{\omega}_t) \geq (i_t - n_t)$$

where q_t is the aggregate price of capital goods.[1] The two functions $f_\omega(\overline{\omega}_t)$ and $g_\omega(\overline{\omega}_t)$, which are described in appendix C.1, measure the fraction of expected income received respectively by the entrepreneur and the lender. The optimal contract is characterised by:

$$q_t\{1 - \Phi(\overline{\omega}_t)\mu + \phi(\overline{\omega}_t)\mu\left[\frac{f_\omega(\overline{\omega}_t)}{f'_\omega(\overline{\omega}_t)}\right]\} = 1 \tag{4.1}$$

and

$$i_t = \frac{1}{[1 - q_t g_\omega(\overline{\omega}_t)]} n_t \tag{4.2}$$

From (4.1) it can be seen that the cut-off for the productivity shock, which characterises the optimal contract, is the same for all the entrepreneurs, since it depends only on the aggregate price of capital goods. By substituting (4.1) into (4.2) and aggregating across all the entrepreneurs we obtain a positive relationship between investment and,

[1]An additional constraint, $q_t i_t f_\omega(\overline{\omega}_t) \geq n_t$ which will always be binding, ensures that the entrepreneur will participate in the project. See Carlstrom and Fuerst (1997).

respectively, internal funds and the price of capital goods. In all the models we consider investment depend positively on the price of capital goods. However, an important difference between the agency cost model and models with costly capital adjustments is that in the former case the internal funds of entrepreneurs act as shifters of the supply curves of capital goods: for given price of capital, an increase in internal funds determines an increase in investment. The details of this result can be found in Carlstrom and Fuerst (1997).

The amount of internal funds, or net worth, of entrepreneurs is given by the market value of their accumulated stock of capital. Entrepreneurs rent their capital and then sell their remaining undepreciated capital to capital mutual funds receiving, respectively, $z_t r_t$ and $z_t q_t (1-\delta)$ units of consumption goods. This net worth is used as a basis for the lending contract:

$$n_t = z_t \left[q_t (1-\delta) + r_t \right] \tag{4.3}$$

With respect to the behaviour of the entrepreneurs in terms of consumption and saving decisions we will assume that entrepreneurs behave as permanent income consumers as in Carlstrom and Fuerst (2001).

4.3.3 The capital adjustment costs (CADJ) model

In this section we present a modification to the model presented in Section 4.3.1 which is based on Ireland (2001b). In this model an extra term, measuring the cost for changing the capital stock, will be introduced in the households' budget constraint.

This term is given by:

$$\frac{\phi_k}{2}\left(\frac{k_{t+1}}{k_t}-1\right)^2 k_t$$

As in Ireland (2001b) the costs for adjusting the capital stock are paid by the households: the presence of this cost gives them an incentive to change investment gradually.

The presence of adjustment costs implies that, out of the steady state, the price of newly installed capital differs from the price of investment goods (i.e. Tobin's q is different from 1). The first order condition for the choice of capital is given by the following equation:

$$\lambda_t P_{k',t} = \beta E_t \left[\lambda_{t+1}\left(r_{t+1} + P_{k,t+1}\right)\right] \tag{4.4}$$

where λ_t is the lagrange multplier of the budget constraint described in Section 4.3.1, which measures the utility of an extra unit of consumption good to the representative households. The price at time t in terms of consumption goods of one unit of newly installed capital, $P_{k',t}$ is given by

$$P_{k',t} = 1 + \phi_k\left(\frac{k_{t+1}}{k_t}-1\right)$$

while the price of the same good at the end of period $t+1$ is

$$P_{k,t+1} = 1 - \delta + \phi_k\left(\frac{k_{t+2}}{k_{t+1}}-1\right)\frac{k_{t+2}}{k_{t+1}} - \frac{\phi_k}{2}\left(\frac{k_{t+2}}{k_{t+1}}-1\right)^2$$

According to equation (4.4) the cost, in terms of utility, of investing in one unit of capital must be equal to the expected return, in terms of utility, which is given by the rental price of capital and the next period price of capital.

4.3.4 The investment adjustment costs (IADJ) model

In this section we present an alternative modification to the model described in Section 4.3.1 based on Christiano *et al.* (2001) and Smets and Wouters (2002) which consists of imposing adjustment costs on the changes in investment rather than on the level. Consequently the capital accumulation law becomes

$$k_{t+1} = (1 - \delta) k_t + F(i_t, i_{t-1})$$

where the function F transforms current and past investment in productive capital ready to be used in the next period production process. This specification of the adjustment cost for investment introduces a richer dynamic in the investment equation and it also produces a hump-shaped response of investment to the different shocks. The function F is given by:

$$F(i_t, i_{t-1}) = \left[1 - S\left(\frac{i_t}{i_{t-1}}\right)\right] i_t$$

and is such that its value and its first derivative are both zero in the steady state while the second derivative is equal to s. This parameter turns out to be crucial in shaping the dynamics of investment and capital.

The budget constraint of the representative household is not affected by this specification of the adjustment cost function for investment as it is the case in the capital adjustment model. In the model presented in this section the costs are paid in terms of investment goods. As in the model described in Section 4.3.3, the steady state value of the price of newly installed capital in terms of investment goods (Tobin's q) is equal to 1.

The first order conditions for the choice of investment and capital are given by the following Euler equations:

$$\lambda_t P_{k',t} = \beta E_t \lambda_{t+1} \left[r_{t+1} + P_{k',t+1} \left(1 - \delta \right) \right] \tag{4.5}$$

$$\lambda_t = P_{k',t} \lambda_t F_1 \left(i_t, i_{t-1} \right) + \beta E_t \left[\lambda_{t+1} P_{k',t+1} F_2 \left(i_{t+1}, i_t \right) \right] \tag{4.6}$$

where F_i denotes the derivative of the F function with respect to the i^{th} argument and λ_t is the multiplier of the representative households budget constraint. In these equations $P_{k',t}$ denotes the price in terms of consumption goods, as of time t, of one unit of capital which can be used for production at $t+1$. According to (4.5), the cost of investing in one unit of capital, in terms of utility, must be equal to the expected return, which is given by the rental price of capital and the price of the same unit of capital net of depreciation, evaluated at the marginal utility of the households. According to (4.6), the price of one unit of investment, in terms of utility, must be equal to the value of installed capital at $t+1$ and the value at $t+2$: the reason is that an increase in i_t affects the stock of capital at $t+1$ and $t+2$ via the technology described by the function F.

4.4 Maximum likelihood estimation

All the models we have described are the equal under the assumption that agency costs are zero and that capital and investment are not subject to any adjustment cost.

The first order conditions of the models together with the market-clearing conditions are linearised around the steady state. All the equations are reported in appendix C.1. The system that consists of the linearised equations and the law of motions of the exogenous shocks is solved with the method described in Uhlig (1999b) and the solution is expressed in the following form:

$$s_t = Ps_{t-1} + Qx_t \tag{4.7}$$

$$f_t = Rs_{t-1} + Sx_t \tag{4.8}$$

$$x_{t+1} = Nx_t + \epsilon_{t+1} \tag{4.9}$$

where s_t is the vector of endogenous state variables, x_t is the vector of exogenous state variables (the structural shocks) and f_t consists of all the other endogenous variables. All the variables are expressed as percentage deviation from respective steady state values.

Using equations (4.7), (4.8) and (4.9) we can derive a state-space model which can be estimated by means of maximum likelihood using the method described in Hamilton

(1994). In order to estimate as precisely as possible the aggregate default probability that characterises the agency cost model, we will exploit the information contained in both internal funds and investment.

Before proceeding with the estimation, we define the vector of observables $\tilde{f}_t$:

$$\tilde{f}_t = [\ m_t \quad i_t \quad n_t \quad c_t \quad \pi_t \quad R_t\ ]'$$

which consists of the variables we will use in estimating the models. In the agency cost model consumption is defined as the sum of households' and entrepreneurs' consumption.

Since the models are driven by four structural shocks, a maximum number of four variables can be used in the estimation to avoid stochastic singularity. A possible solution to this problem is to add measurement errors to some of the observed variable. The measurement errors are attached to the following variables: investment, consumption and internal funds. The measurement error in internal funds is motivated by the fact that in the agency cost model this variable measure the internal funds of the firms producing investment goods, while in the data it refers to all (nonfarm nonfinancial) firms. The measurement error in investment is introduced for the following reason: in all the models this variable represents productive capital which in the data is measured by nonresidential fixed investment while we use the time series for gross private investment for which the data are available for a longer period. Similarly, consumption is assumed to be measured with error because in the models it represents nondurable consumption expenditures while data on personal consumption expenditures are used in the estimation. The other variables, real money, inflation and the short-term interest rate, are assumed to be measured without errors. As in Ireland (2000), measurement errors can be interpreted as a way of capturing all the movements in the variables that the model is not able to account for.

Thus they help the model in fitting the data by providing extra sources of randomness. The model is therefore augmented with a vector of measurement errors ξ_t. The system of equations for the selected variables becomes

$$f_t = \tilde{R}s_{t-1} + \tilde{S}x_t + \xi_t$$

where the matrices denoted with a hat are obtained selecting the appropriate rows of the matrices P, Q, R and S in (4.7), (4.8) and (4.9). The measurement error ξ_t, which is assumed to be independent from the structural shocks, follows the process

$$\xi_{t+1} = D\xi_{t-1} + \varsigma_t$$

$$E\varsigma_t\varsigma_t' = \Sigma_\varsigma$$

where the matrices D and Σ_ς are both diagonal.

The data we use for the estimation of the model consists of the empirical counterparts of the variables contained in $\tilde{f}_t$: real consumption (c_t), real investment (i_t), real internal funds (n_t), real money M2 (m_t), the three-month nominal interest rate (R_t) and the inflation rate (π_t). The sample period goes from 1966:1 to 2001:4. For a description of the data see appendix C.2. Since the model predicts per capita variables and in order to eliminate the trend in real variables due to population growth, consumption, investment, real balances and real internal funds are normalised by the civilian noninstitutional population age 16 and over. The logs of these variables are detrended. The reason for using data starting from 1966 is that monetary policy implementation in the U.S. begun to resemble its modern equivalent only in the second half of the 1960s (Strongin (1995)). A different trend is estimated for the post-1991 period for investment and consumption, while a different one is estimated for real money for the post-1979 period. A figure with the logs of the detrended variables is reported in appendix C.2.

The likelihood function of the models is given by:

$$lnL = -\frac{NT}{2} ln\left(2\pi\right) - \frac{1}{2}\sum_{t=1}^{T} ln|\Omega_t| - \frac{1}{2}\sum_{t=1}^{T} u_t' \Omega_t^{-1} u_t \tag{4.10}$$

where N is the number of variables, T the number of observations and Ω_t is the covariance matrix of the vector of prediction errors u_t which are obtained using

$$u_t = \tilde{f}_t - \tilde{f}_{t|t-1} = \tilde{f}_t - E\left(\tilde{f}_t | \tilde{f}_{t-1}, ..., \tilde{f}_1\right)$$

where E is the expectation operator.

As it has been argued in Section 4.3.2, internal funds do not play any role in shaping the dynamics of the variables in the capital and investment adjustment costs models. Therefore in estimating these two models we assume that internal funds are explained completely by the measurement error.[2] This allows estimating all the models using the same set of variables.

[2] An alternative way to proceed could consist of nesting the different specification for adjustment costs into a single model. We leave this possibility for future research.

The results of the maximum likelihood estimation are reported in table 4.1.[3] The values of some parameters that are common to all models are calibrated since they are unidentified without information on other variables. These are: the depreciation rate δ, which is fixed to 0.025 (10 per cent per year), the steady state price-marginal cost markup (1.2), as in Ireland (2001b) and the parameter ψ in the households' utility function (0.57 as in Christiano *et al.* (1996b), implying an elasticity of the labour supply of 1.57).

In the agency cost model other parameters must be calibrated. These are the entrepreneurs propensity to consume and the monitoring cost are set, respectively, to 0.053 and 0.25 following Carlstrom and Fuerst (1997, 2001). Preliminary attempts to estimate the value of the monitoring cost led to an unreasonable value for this parameter. Moreover, the likelihood function shows little variation with respect to the monitoring cost μ which could depend on its weak identification. For this reason we decided to calibrate the value of the monitoring cost to the value used in Carlstrom and Fuerst (1997). The standard deviation of the firm-specific productivity shock ω_t is only a scale variable. Having calibrated the monitoring cost, we can assess the existence of agency costs by looking at the significance of the estimated default probability. Monitoring costs are given by $\Phi(\overline{\omega})\,\mu$: therefore a positive and significant value of $\Phi(\overline{\omega})$, for given μ, implies the existence of agency costs.

[3] The likelihood function is maximised using the algorithm csminwel.m written by C. Sims. This routine is robust to discontinuities in the objective function although being a gradient-based method.

Table 4.1

Models' parameter estimates

	AG		CADJ		IADJ	
	Estimates	Std. error	Estimates	Std. error	Estimates	Std. error
β	0.9982	0.0001	0.9944	0.0008	0.9945	0.0003
α	0.1156	0.0085	0.2343	0.0106	0.2103	0.0389
$\overline{\Phi}$	0.0217	0.0064	-	-	-	-
σ	3.8336	0.3776	4.9227	0.3409	5.6316	0.3815
θ	8.9869	0.4095	4.8401	0.3052	4.9381	0.3663
ϕ_p	0.1833	0.0518	0.0358	0.0212	0.0028	0.0006
ϕ_k	-	-	28.5230	0.0322	-	-
s	-	-	-	-	5.9319	1.0677
ρ_y	-0.0574	0.0084	-0.0365	0.0048	-0.0467	0.0072
ρ_π	0.7613	0.0292	0.6286	0.0600	0.4105	0.0789
ρ_g	0.2685	0.0328	0.4082	0.0573	0.6607	0.0640
$\overline{z}$	2181.7880	197.7049	579.7518	68.0571	764.9420	333.2766
$\overline{e}$	0.1872	0.0006	0.2315	0.0083	0.0721	0.0054
$\overline{n}$	-	-	220.6990	5.9046	220.6990	5.4257
$\overline{\pi}$	1.0155	0.0003	1.0195	0.0018	1.0134	0.0003
ρ_a	0.9705	0.0192	0.9851	0.0054	0.9686	0.0047
ρ_η	0.9947	0.0104	0.9906	0.0003	0.9831	0.0176
ρ_v	0.3424	0.0326	0.4302	0.0471	0.4453	0.0482
ρ_e	0.9816	0.0017	0.9522	0.0002	0.9447	0.0420
σ_a	0.0130	0.0017	0.0254	0.0022	0.0455	0.0051
σ_η	0.0046	0.0014	0.0149	0.0039	0.0219	0.0056
σ_v	0.0032	0.0002	0.0038	0.0004	0.0054	0.0006
σ_e	0.0159	0.0009	0.0179	0.0025	0.0229	0.0025
ρ_c	0.9701	0.0115	0.9139	0.0002	0.9706	0.0001
ρ_i	0.9936	0.0155	0.8758	0.0044	0.8743	0.0042
ρ_n	0.9968	0.0121	0.9384	0.0067	0.9721	0.0026
σ_c	0.0067	0.0006	0.0000	0.0017	0.0000	0.0020
σ_i	0.0424	0.0028	0.0403	0.0022	0.0403	0.0024
σ_n	0.0417	0.0031	0.0439	0.0026	0.0522	0.0031

The households' discount factor, β, in the agency cost model is equal to 0.9982 while it is only slightly smaller for the other two models. The estimate of the capital share in the production function, α, is equal to 0.2343 and 0.2103 respectively for the capital adjustment cost and the investment adjustment cost. The value estimated for the agency cost is significatively smaller. All the estimates are below the value of 0.36 conventionally used in the literature on the real business cycle. McGrattan (1994), for example, reports a value of α of 0.397 for a model with perfect competition in the production sector. On the other hand, Keen (2002) reports a value of α of 0.1656 which is closer to our estimate than to the conventional RBC value. The estimate of the parameter that measures the cost of adjusting the prices of the intermediate goods producing firms is 0.18335 in the agency model. Smaller values are estimated for the other two models (0.0358 and 0.0028 for respectively the CADJ and the IADJ models). The risk aversion coefficients for real money and consumption, respectively denoted with θ and σ, are significatively larger than one, thus ruling out logarithmic-type of preferences which are sometimes used in the literature.

The estimates of $\overline{a}$, $\overline{e}$ and $\overline{\pi}$, which measure the steady state levels of the technology and money demand shocks and inflation, allow the model to match the average values in the data of detrended consumption and investment, real money and inflation.

With respect to the monetary policy rule, the coefficients that measures the response of the short-term nominal interest rate to inflation and nominal money growth are significant not far from the values in Ireland (2001b) for the pre-Volcker period. The coefficient measuring the response of the interest rate to output is negative in all the models.

The autoregressive parameters of the structural shocks are all significant and the same is true for the standard errors. The autoregressive coefficients of the structural shocks, which are close to one, imply very persistent shocks. The only exception is the coefficient for the monetary policy shock process. The estimates for the measurement error processes suggest that all the models have some difficulties in accounting sufficiently well for the fluctuations in real internal funds and investment while they seem to provide a better representation of the dynamics of consumption.[4]

Turning now to the parameter of interest which characterises the agency cost model, the default probability Φ, our estimate suggests that agency costs matter. The estimated default probability, 2.17 per cent (which implies an annual probability of 8.7), is larger than the calibrated value (0.974 per cent) of Carlstrom and Fuerst (1997, 2001). The estimated steady state values of real internal funds and investment implies an internal financing ratio of 34 per cent, close to 38 per cent used in Carlstrom and Fuerst (1997, 2001). The fraction of expected investment, net of the monitoring cost, received the entrepreneurs is equal to 38 per cent (39 in Carlstrom and Fuerst (1997)) while the fraction received by lenders is 61 per cent. The estimated default probability implies that on average 0.54 per cent of investment is destroyed by monitoring. The implied steady state estimate for the price of newly installed capital goods (in terms of consumption goods), Tobin's q, is equal to 1.073 a value which is larger than the one in Carlstrom and Fuerst (1997, 2001). It is worth remembering that both the adjustment cost models have a different implication for the price of capital goods: they imply a steady state value of Tobin's q of 1, since no cost is paid for adjusting the capital stock. The presence of agency costs implies a reduction in the steady state level of the capital stock of 7.7 per cent (3.6 in Carlstrom and Fuerst (1997)) and in the steady state level of output (0.9 per cent). The estimated welfare loss in steady state for the households is equal to 0.86 per cent while it is significantly smaller for the entrepreneurs (0.39 per cent). These values

[4] The standard deviation of the measurement error is statistically not different from zero.

seem to suggest that the welfare costs associated to agency costs are not large.[5]

The parameter measuring the cost for adjusting the capital stock in the CADJ model, ϕ_k, is equal to 28.52, which is in between the values estimated by Ireland (2001b) for the pre-1979 and the post-1979 periods. Using the estimated capital stock obtained via the Kalman filter we can compute the costs associated to changes in the capital stock. These costs amount, on average, to 0.23 per cent of the level of investment, a value which is half the cost estimated in the agency cost model.

The parameter measuring the cost for adjusting investment in the IADJ model, s, is equal to 5.93, which is in the range of values estimated in Christiano *et al.* (2001). Using the estimated value for s we can compute the costs associated to changes in the level of investment. These costs amount, on average, to 0.74 per cent of the level of investment, a value which is larger than the costs estimated in the agency costs and capital adjustment costs models.

4.5 Models' evaluation

In the literature on DSGE models, summary statistics such as first and second moments have been used to validate models. To evaluate the fit of the models we have considered we start by comparing the means of the data with the corresponding values for the models, as in Kim (2000) and McGrattan (1994). The means of the data are computed using logged and detrended data. The means, standard deviations and correlations for the three models are computed as averages across 5000 simulations of the log of time series of length 200

[5]Assuming that the fraction of entrepreneurs over total population is equal to 10 per cent yields an overall welfare loss of 0.82 per cent.

quarters. The first 56 simulated data are dropped to remove any dependence on the initial conditions and to obtain time series of the same length as the data. Throughout all the simulations measurement errors are assumed to be zero. At each simulation the parameters of the models are drawn from a multivariate normal distribution with mean equal to the estimated coefficients and covariance matrix equal to the inverse of the estimated hessian matrix. The differences between the means, the standard deviations and the correlations predicted by the models and the corresponding values of the data will tested below using an appropriate statistic. The results are reported in table 4.5.

Table 4.2

Models and data means

	m	i	n	c	π	R
data	7.4604	6.0420	5.3953	7.6328	0.0105	0.0147
AG	7.4707	5.2681*	4.1806*	7.6625	0.0153	0.0171
CADJ	7.3989	5.9825	5.3967	7.6625	0.0180	0.0232
IADJ	7.4608	5.8198	5.3952	7.6234	0.0129	0.0185

* Statistically different from the corresponding value in the data.

The table shows that overall the models are able to match the average values of the variables. The agency cost model predicts significantly lower averages of real internal funds and investment, which are statistically different at 95 per cent from the corresponding values in the data. The same model predicts a larger value for the means of inflation and the short-term nominal interest rate. The other two models seem to replicate better the means of the data.

The next two tables compares the standard deviations and the contemporaneous correlations of detrended data and the models' variables.

Table 4.3

Models and data standard deviations

	m	i	n	c	π	R
data	0.0461	0.0936	0.0840	0.0348	0.0061	0.0053
AG	0.0572	0.1565	0.1550	0.0170*	0.0091	0.0092
CADJ	0.1374	0.1795	0.1065	0.0465	0.0137	0.0133
IADJ	0.1218	0.2703	0.1545	0.0346	0.0083	0.0090

* Statistically different from the corresponding value in the data.

The adjustment cost models overpredict significantly the volatility of real balances. The agency cost model underpredicts the volatility of consumption while all the models overpredicts that of investment, real internal funds, the short-term interest rate and inflation.

Table 4.4

Models and data correlations

	data	AG	CADJ	IADJ
$\rho(m_t, i_t)$	0.29	0.39	0.66	0.50
$\rho(m_t, n_t)$	-0.10	0.45*	-	-
$\rho(m_t, c_t)$	0.50	0.69	0.54	0.65
$\rho(m_t, \pi_t)$	-0.24	-0.46	-0.59	-0.60
$\rho(m_t, R_t)$	-0.34	-0.56	-0.75	-0.83*
$\rho(i_t, n_t)$	0.60	0.98*	-	-
$\rho(i_t, c_t)$	0.57	0.76	0.96*	0.66
$\rho(i_t, \pi_t)$	0.20	0.01	-0.19	0.00
$\rho(i_t, R_t)$	0.16	-0.16	-0.37	-0.29
$\rho(n_t, c_t)$	0.21	0.73*	-	-
$\rho(n_t, \pi_t)$	0.17	-0.04	-	-
$\rho(n_t, R_t)$	0.27	-0.18	-	-
$\rho(c_t, \pi_t)$	-0.24	-0.13	-0.12	-0.33
$\rho(c_t, R_t)$	-0.06	-0.27	-0.24	-0.46
$\rho(\pi_t, R_t)$	0.75	0.88*	0.80	0.66

* Statistically different from the corresponding value in the data.

The table shows that all the models are able to match sufficiently well the signs of the correlations between inflation, the interest rate and real money. All the models also predict a positive correlation between real money, consumption, investment and inflation. The agency cost model overpredicts the correlation between investment and real internal funds. Overall all the models seem to provide a good representation of the business cycle properties of the data.

Following Canova and Ortega (2000) and Cogley and Nason (1994) we compute the statistic that allows to compare the first and second moments of the models with the corresponding values for the data. This statistic, which measures the distance between the moments of the models and the data, is given by the following quadratic form:

$$d_j = (H_j - H)\, V\left[(H_j - H)\right]^{-1} (H_j - H)' \tag{4.11}$$

where H_j is the vector of statistics for the model j, H is the corresponding statistic for the data and $V(H_j - H)$ is the covariance matrix of the distance vector $H_j - H$. This statistic is asymptotically distributed as a χ^2 with degrees of freedom equal to the number of elements in H_j.

In measuring the distance between the models and the data we consider, similiarly to Canova and De Nicoló (1995), both the sampling variability of the data and the uncertainty in simulated data. Following Canova (1994) we will compute the model's statistics drawing parameters from the estimated distribution and simulating time series for the structural shocks. The values reported in the table correspond to the fraction of simulations in which the statistic is larger than the critical value of the χ^2 distribution: therefore it represents the probability of rejecting the null hypothesis that the model's statistics match the values of the data.

Table 4.5

Distance tests of summary statistics

	mean	standard deviation	correlation
AG	1.000	0.109	0.988
CADJ	0.017	0.002	0.909
IADJ	0.093	0.136	0.739

The table shows that the agency cost model is rejected by the data in terms of both first and second moments. The failure of the model to account for the means of the data is due to the values for investment and real internal funds which are lower than the corresponding values in the data. These differences are statistically significant (see table 4.2). This result may be explained by the restriction imposed by the agency model between the dynamics of these two variables as it can be seen from equation (4.2) in Section 4.3.2. This restriction is also likely to be responsible for the failure of the model in accounting for the standard deviations of real internal funds and investment. All models fail to account for the observed correlations in the data. The capital adjustment cost model seem to provide the best representation of business cycle fluctuations, both in terms of means and standard deviations. The investment adjustment model fails to account for the variability of the data since it predicts a larger standard deviation for investment.

Alternatively we can evaluate the fit of the three models by comparing their likelihood value at the maximum with that of an unconstrained first order VAR with a constant term for the same variables employed in the maximum likelihood estimation. The agency costs and the adjustment costs models have, respectively, 26 and 27 parameters to be estimated while the VAR has 42 coefficients. The likelihood value of the agency cost model is equal to 2793 while the corresponding values for the other two models are 2845 (CADJ) and 2819 (IADJ). The agency costs model fits the data significantly worse than the VAR, which has a likelihood of 2867. A likelihood ratio test for each of the models against the VAR shows that they are all rejected at conventional 5 per cent confidence level.

All the methods that we have presented have been used extensively in the real business cycle literature. However, new approaches to models' validation have appeared in the last few years. Recently, Canova (2001) has proposed a strategy for validating from an economic point of view dynamic stochastic general equilibrium models using VARs and impulse responses. This approach differs substantially from standard model validation which relies on first and second moments since it focuses on conditional rather than unconditional moments. The proposed approach consists, as first step, of finding robust implications of the model: these are implications that are robust to different sets of parameters, different functional forms of the primitives and different specifications of the monetary policy rule. In a second step, these implications, in the form, for example, of the signs of impulse responses, are used to identify shocks in the data by means of a VAR. An argument in favour of this strategy for identifying structural shocks can be found in Canova and Pina (1999). The authors find that the zero restrictions generally used in the VAR literature can be inconsistent with the dynamic relationships implied by DSGE models. In a third step, a qualitative comparison is carried out by comparing the responses of other variables to identified shocks. This step aims at examining whether and to what extent the dynamics of the model and the data are similar. In the last step the validation process uses the quantitative implications (e.g. impulse responses and variance decompositions) of the model and the data and tests for the significance of their equalities. Canova (2001) compares, for example, the value of the half-life of output to evaluate whether a sticky price and a limited participation models are able to generate sufficient persistence in the response of this variable to a monetary shock.

Relying on this approach to models validation we set up a VAR for the data and impose restrictions on the signs of the impulse responses to identified technology and monetary policy shocks. We selected these two shocks since these are the ones for which we know most. Moreover, the effect of these shocks have been extensively documented in the literature, both theoretical and empirical. A recent example is Altig *et al.* (2002).

The restrictions we impose on the signs of the impulse responses are derived from the estimated agency costs and adjustment costs models. In all the models a positive technology shock increases investment, consumption and real money while it drives down the inflation rate and the interest rate. Similarly, a positive monetary policy shock increases the interest rate and decreases the inflation rate, consumption, investment and real money. We do not impose any restriction on the sign of the response of real internal funds since only the agency cost model has an implication for it. These restrictions are imposed for the first 10 steps of the impulse response horizon. However we allow for the possibility that the responses do not satisfy the imposed restriction on 2 steps out of 10 steps in order to capture some situations such as an increase in the inflation rate following a contractionary monetary policy shock ("price puzzle").[6] The following figures report the median responses for the VAR for the data and the corresponding values for the three estimated models together with 5 and 95 percentiles.[7] The first column reports the responses of selected variables to a positive (one standard deviation) technology shock and the second column the responses to a (one standard deviation) positive monetary shock.

[6]See appendix B.2 in Chapter 3 for a brief description of the methodology.

[7]The VAR for the data has two lags and a constant term.

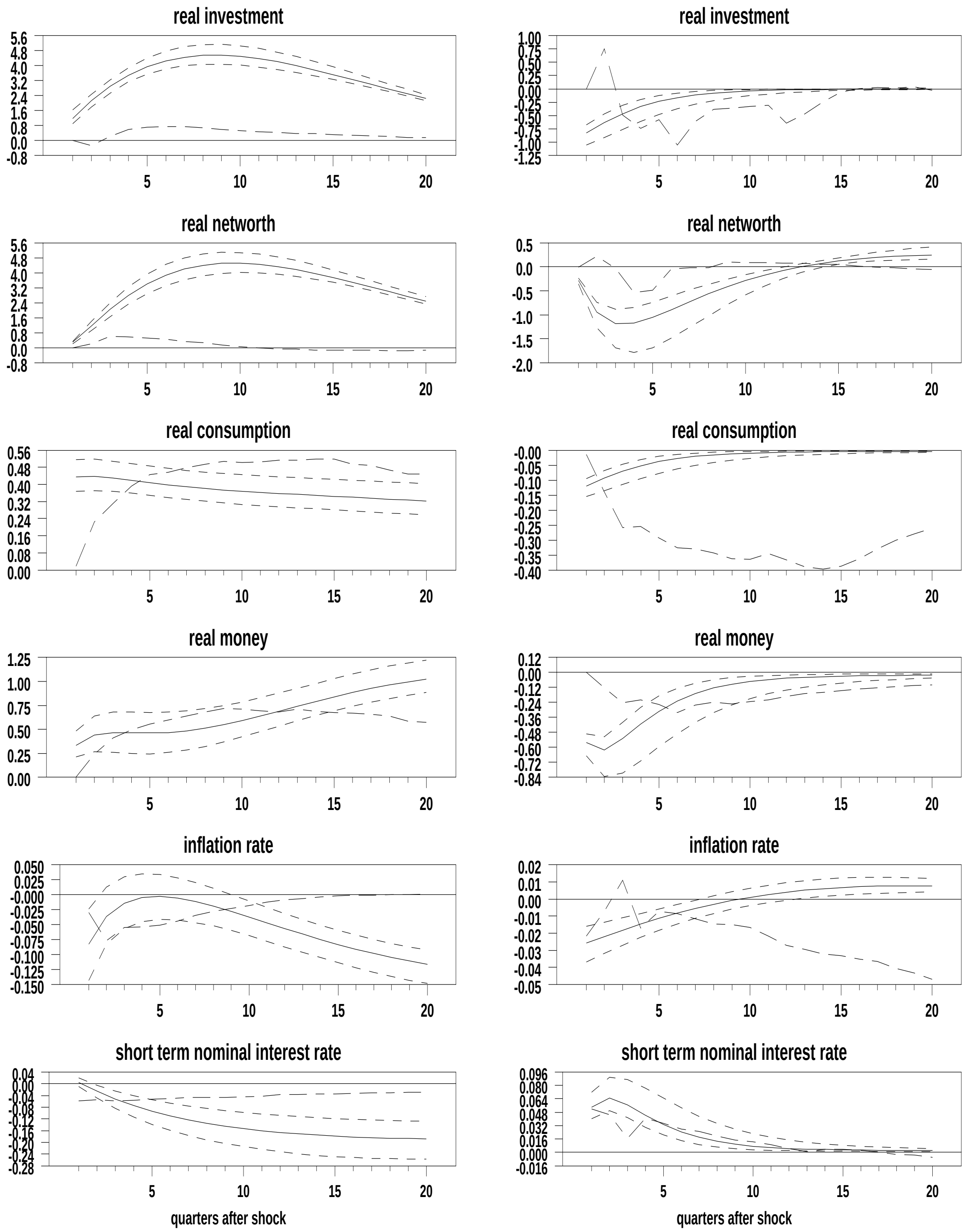

Fig. 4.1 Impulse responses: agency cost model and data

(— median – – 5, 95 per cent — – — data)

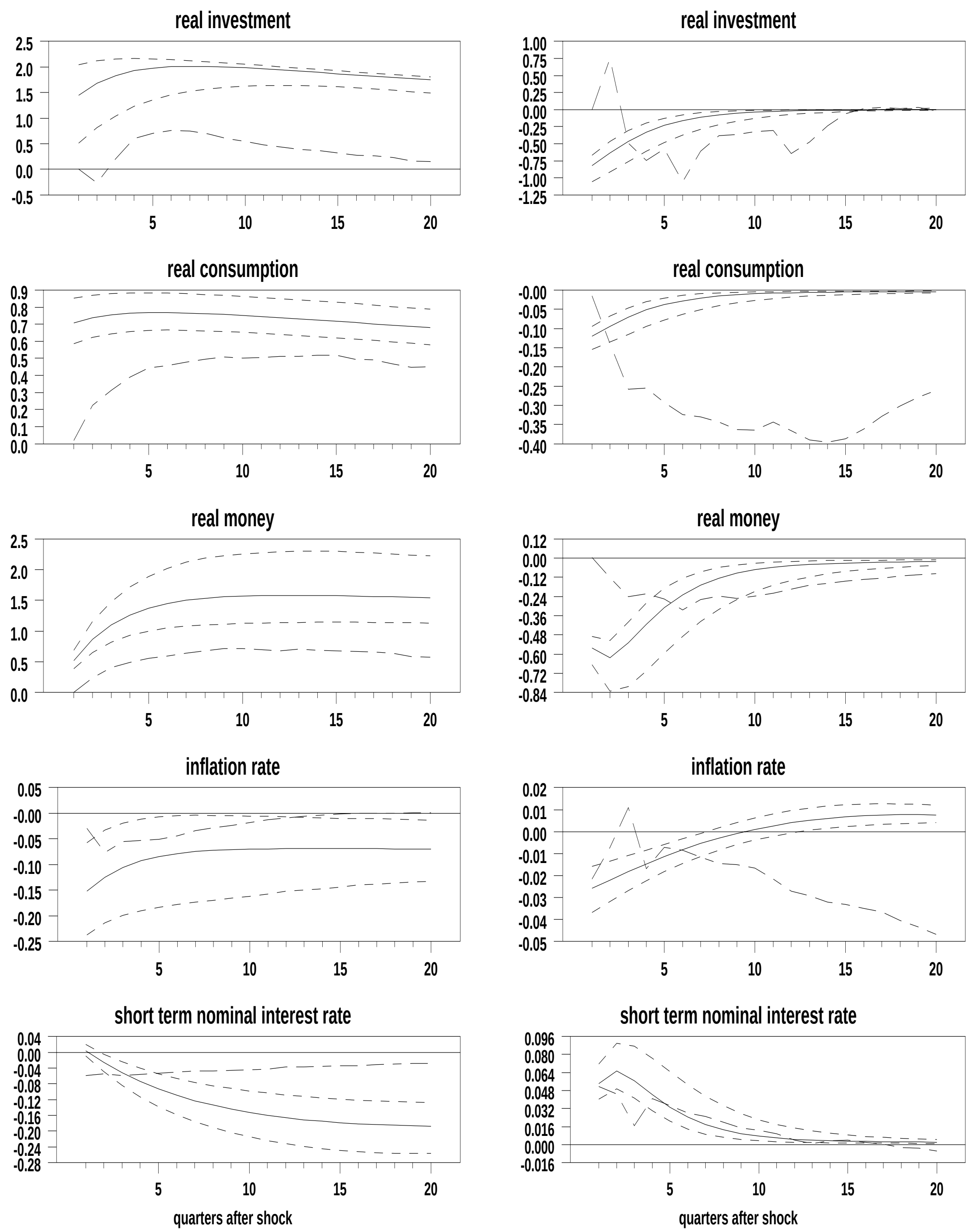

Fig. 4.2 Impulse responses: capital adjustment cost model and data

(— median – – 5, 95 per cent — – — data)

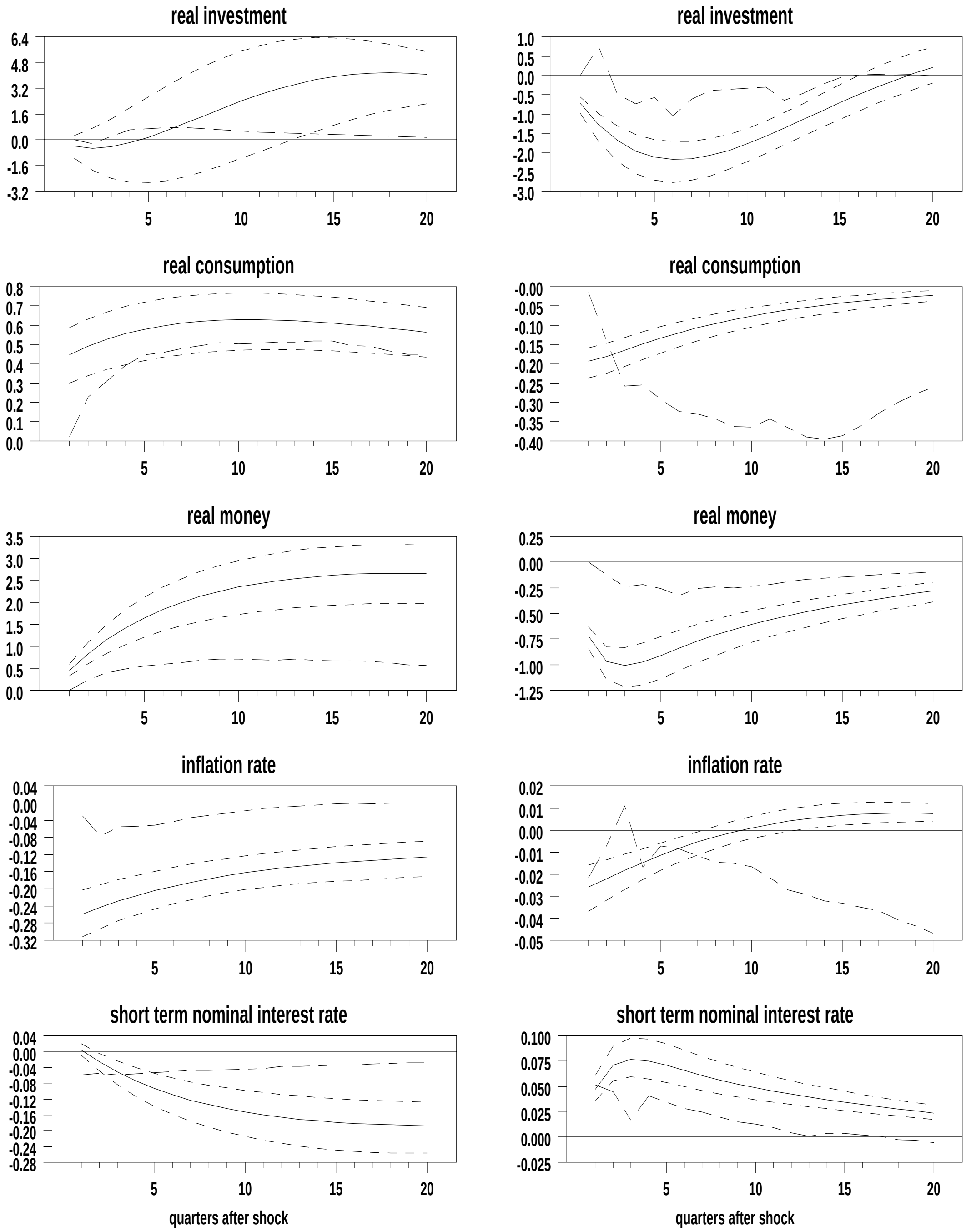

Fig. 4.3 Impulse responses: investment adjustment cost model and data

(— median – – 5, 95 per cent — – — data)

All the figures show that the models qualitative implications for the impulse responses are satisfied by the data, as it has to be expected given the identifying restrictions we have imposed. The only exception is the response of real internal funds to a positive technology shock in the agency cost model. The data suggest a negative response of this variable while the model predicts an increase. The model predicts a different (from the data) path for the response of real money and consumption following a positive technology shock. The model also implies a large response of investment which is smaller than what the data seem to suggest. With respect to monetary policy shocks, the model is not able to generate a hump-shaped response of investment as it is the case for the data. The model does not seem to provide sufficient amplification to monetary policy shocks while this is the case for technology shocks. These results are in line with the findings in Carlstrom and Fuerst (1997, 2001). Other type of frictions, such as wage or employment rigities, may be useful to provide amplification to the responses of variables to monetary policy shock. Christiano *et al.* (2001) and Smets and Wouters (2002) are two examples of models with such features.

The capital adjustment cost model is able to replicate sufficiently well the responses of real money, the interest rate and inflation to a positive technology shock while it predicts a larger (than in the data) response for investment. With respect to a contractionary monetary policy shock, the model does not generate a hump-shaped response and it predicts a short-lived response for inflation. As for the agency cost, the capital adjustment cost model does not provide sufficient amplification to monetary shocks.

With respect to a positive technology shock, the investment adjustment cost model yields responses which are similar to the capital adjustment model. However in the former the response of consumption is more similar to what is found in the data while this is not the case for investment, for which the model predicts a more delayed response. The model is able to provide sufficient amplification to monetary shocks for what concerns investment being able to generate a hump-shaped response as in the data. Again, as it has been stressed for the other two models, adjustment costs on the changes in investment do not provide amplification to the responses of consumption and inflation to monetary policy shocks.

4.6 Conclusion

The main contribution of this chapter is to estimate and compare three alternative dynamic stochastic general equilibrium (DSGE) models of the U.S. economy in which capital accumulation is subject to adjustment costs. The models, evaluated at the estimated parameters, are validated in terms of different statistics which have been commonly used in the real business cycle literature and in terms of their ability to replicate the responses to shocks identified in the data. The analysis leads to the following conclusions.

First, all the values of the parameters estimates are all reasonable. The agency cost model suggests that the aggregate default probability in the U.S. economy is around 2.2 per cent per quarter (8.7 per cent per annum). This value is larger than the one used in the literature and shows that agency costs matter. Expected loss from monitoring amounts to around 0.54 of the level of investment. The estimated welfare loss in steady state due to the existence of agency costs is equal to 0.82 per cent, which is not large. The adjustment costs models suggest that costs related to variations in the capital stock are between 0.23 and 0.74 per cent of the level of investment.

Second, all the models are able to explain, at least partially, the means, the standard deviations and the correlations among the selected variables. Overall it seems that the capital adjustment cost model is able to provide the best representation of U.S. business cycle fluctuations. However, by comparing the likelihood at the maximum of the alternative models with that of a VAR for the data it results that all the models are rejected. The reason for this result may be that other nominal rigidities, such as staggered wages, and real rigidities (e.g. variable capacity utilisation and habits formation in consumption) are needed to provide amplification to shocks and a better representation of business cycle fluctuations. An evaluation by means of impulse responses to technology and monetary policy shocks suggests that all the models are able to replicate, at least qualitatively, the data, with the adjustment cost models performing slightly better from a qualitative point of view.

Appendix C.1 The models linearised equilibrium conditions

In this section we report all the linearised first order conditions together with the market-clearing conditions and the stochastic processes for the structural shocks of the estimated model for the two models presented in Sections 4.3.2, 4.3.3 and 4.3.4. The following equations are common to all the models. A bar denotes steady state values.

Labour supply condition

$$\psi\hat{l}_t + \gamma\hat{c}_t - \hat{\eta}_t = \hat{w}_t$$

Euler equation for bonds holdings

$$-\gamma\hat{c}_t + \hat{\eta}_t = -\gamma E_t\hat{c}_{t+1} + \hat{R}_t - E_t\hat{\pi}_{t+1} + E_t\hat{\eta}_{t+1}$$

Households' money demand

$$\hat{m}_t = \frac{\gamma}{\theta}\hat{c}_t - \left[\frac{1}{\theta}\frac{1}{\left(\overline{R}-1\right)}\right]\hat{R}_t + \left(\frac{\theta-1}{\theta}\right)\hat{e}_t$$

Pricing condition of intermediate-goods producing firms

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \phi_\pi\left[\alpha\hat{r}_t + (1-\alpha)\,\hat{w}_t - \hat{a}_t\right]$$

with $\phi_\pi = \frac{(\vartheta-1)}{\phi_p}$;

Production function of intermediate-goods producing firms

$$\hat{y}_t = \hat{a}_t + \alpha \hat{k}_t + (1 - \alpha)\,\hat{l}_t$$

Definition of rental price of capital

$$\hat{r}_t = \hat{l}_t - \hat{k}_t + \hat{w}_t$$

Monetary policy rule

$$\hat{R}_t = \rho_y \hat{y}_t + \rho_\pi \hat{\pi}_t + \rho_g \hat{g}_t + \hat{v}_t$$

where $\hat{g}_t$ is the growth rate of nominal money defined as

$$\hat{g}_t = \hat{m}_t - \hat{m}_{t-1} + \hat{\pi}_t$$

Technology shock

$$\hat{a}_t = \rho_a \hat{a}_{t-1} + \epsilon_t^a$$

Preference shock

$$\hat{\eta}_t = \rho_\eta \hat{\eta}_{t-1} + \epsilon_t^\eta$$

Money demand shock

$$\hat{e}_t = \rho_e \hat{e}_{t-1} + \epsilon_t^e$$

Monetary policy shock

$$\hat{v}_t = \rho_v \hat{v}_{t-1} + \epsilon_t^v$$

The following equations close the agency cost model.

Aggregate resource constraint

$$\hat{y}_t = \frac{\overline{c}}{\overline{y}}\hat{c}_t + \frac{\overline{i}}{\overline{y}}\hat{i}_t + \frac{\overline{c}^e}{\overline{y}}\hat{c}_t^e$$

Capital accumulation law

$$\hat{k}_{t+1} = (1-\delta)\,\hat{k}_t + \delta\hat{i}_t + \left[\frac{\overline{i}}{\overline{k}}\phi\left(\overline{\omega}\right)\mu\overline{\omega}\right]\hat{\omega}_t$$

Euler equation for capital

$$\hat{q}_t - \gamma\hat{c}_t + \hat{\eta}_t = \beta\left(1-\delta\right)E_t\hat{q}_{t+1} - \gamma E_t\hat{c}_{t+1} + \left[1-\beta\left(1-\delta\right)\right]E_t\hat{r}_{t+1} + E_t\hat{\eta}_{t+1}$$

Optimal contract:

$$\hat{i}_t = \hat{n}_t + \frac{g_\omega\left(\overline{\omega}\right)\overline{q}}{\left[1-\overline{q}g_\omega\left(\overline{\omega}\right)\right]}\hat{q}_t + \frac{g_\omega'\left(\overline{\omega}\right)\overline{q}\,\overline{\omega}}{\left[1-\overline{q}g_\omega\left(\overline{\omega}\right)\right]}\hat{\omega}_t$$

and

$$\frac{1}{\overline{q}}\hat{q}_t = -\mu\overline{\omega}\left[-\phi + \frac{(\phi' f_\omega + f'_\omega \phi)\, f'_\omega - f''_\omega \phi f_\omega}{(f')^2}\right]\hat{\omega}_t$$

where the functions f and g are given by

$$f_\omega\left(\overline{\omega}_t\right) = \int_{\overline{\omega}_t}^{\infty} \omega_t \phi\left(\omega_t\right) d\omega_t - \left[1 - \Phi\left(\overline{\omega}_t\right)\right]\overline{\omega}_t$$

$$g_\omega\left(\overline{\omega}_t\right) = \int_0^{\overline{\omega}} \omega_t \phi\left(\omega_t\right) d\omega_t + \left[1 - \Phi\left(\overline{\omega}_t\right)\right]\overline{\omega}_t - \Phi\left(\overline{\omega}_t\right)\mu$$

and f'_ω and f''_ω denote, respectively, the first and second derivative of f_ω.

Definition of net worth or internal funds

$$\hat{n}_t = \hat{z}_t + \left[\frac{\overline{q}\,\overline{z}\,(1-\delta)}{\overline{n}}\right]\hat{q}_t + \left(\frac{\overline{z}\,\overline{r}}{\overline{n}}\right)\hat{r}_t$$

Entrepreneurs' capital accumulation law

$$\hat{z}_{t+1} = \hat{i}_t + \left[\frac{f'_\omega\left(\overline{\omega}\right)\overline{\omega}}{f_\omega\left(\overline{\omega}\right)}\right]\hat{\omega}_t$$

Entrepreneurs' consumption

$$\hat{c}^e_t = \hat{q}_t + \hat{i}_t + \left[\frac{f'_\omega\left(\overline{\omega}\right)\overline{\omega}}{f_\omega\left(\overline{\omega}\right)}\right]\hat{\omega}_t$$

The following equations close the capital adjustment costs model.

Aggregate resource constraint

$$\hat{y}_t = \frac{\overline{c}}{\overline{y}}\hat{c}_t + \frac{\overline{i}}{\overline{y}}\hat{i}_t$$

Capital accumulation law

$$\hat{k}_{t+1} = (1-\delta)\,\hat{k}_t + \delta\hat{i}_t$$

Prices of capital goods

$$\hat{P}_{k',t} = \phi_k\left(\hat{k}_{t+1} - \hat{k}_t\right)$$

$$\hat{P}_{k,t+1} = \frac{\phi_k}{(1-\delta)}\left(\hat{k}_{t+2} - \hat{k}_{t+1}\right)$$

Euler equation for capital

$$\hat{P}_{k',t} - \gamma\hat{c}_t + \hat{\eta}_t = \beta E_t\hat{P}_{k',t+1} - \gamma E_t\hat{c}_{t+1} + [1-\beta(1-\delta)]\,E_t\hat{r}_{t+1} + E_t\hat{\eta}_{t+1}$$

The following equations close the investment adjustment costs model.

Aggregate resource constraint

$$\hat{y}_t = \frac{\overline{c}}{\overline{y}}\hat{c}_t + \frac{\overline{i}}{\overline{y}}\hat{i}_t$$

Capital accumulation law

$$\hat{k}_{t+1} = (1-\delta)\,\hat{k}_t + \delta\hat{i}_t$$

Euler equation for capital

$$-\gamma\hat{c}_t + \hat{\eta}_t + \hat{P}_{k',t} = \beta\,(1-\delta)\,E_t\hat{P}_{k',t+1} + [1-\beta\,(1-\delta)]\,E_t\hat{r}_{t+1} - \gamma E_t\hat{c}_{t+1} + E_t\hat{\eta}_{t+1}$$

Euler equation for investment

$$\hat{P}_{k',t} = -s\hat{i}_{t-1} + s\,(1+\beta)\,\hat{i}_t - s\beta E_t\hat{i}_{t+1}$$

Appendix C.2 Data

c_t: real personal consumption expenditures

i_t: real gross private domestic investment

y_t: real gross domestic product

n_t: real internal funds for nonfarm nonfinancial corporate business

R_t: three-month Treasury Bill rate (percentage per annum)

m_t: real M2 money stock deflated with the implicit GDP price deflator

Real consumption, real investment and real GDP come from the National Income and Product Accounts and are expressed in billions of chained (1996) dollars. The money stock, M2, and the three-month Treasury Bill rate comes from the Federal Reserve of St. Louis while internal funds are taken from the Flow of Funds from the Federal Reserve. Investment, consumption, output, internal funds, real money are converted to per-capita terms by dividing them by the civilian noninstitutional population, age 16 and over (Bureau of Labour Statistics).

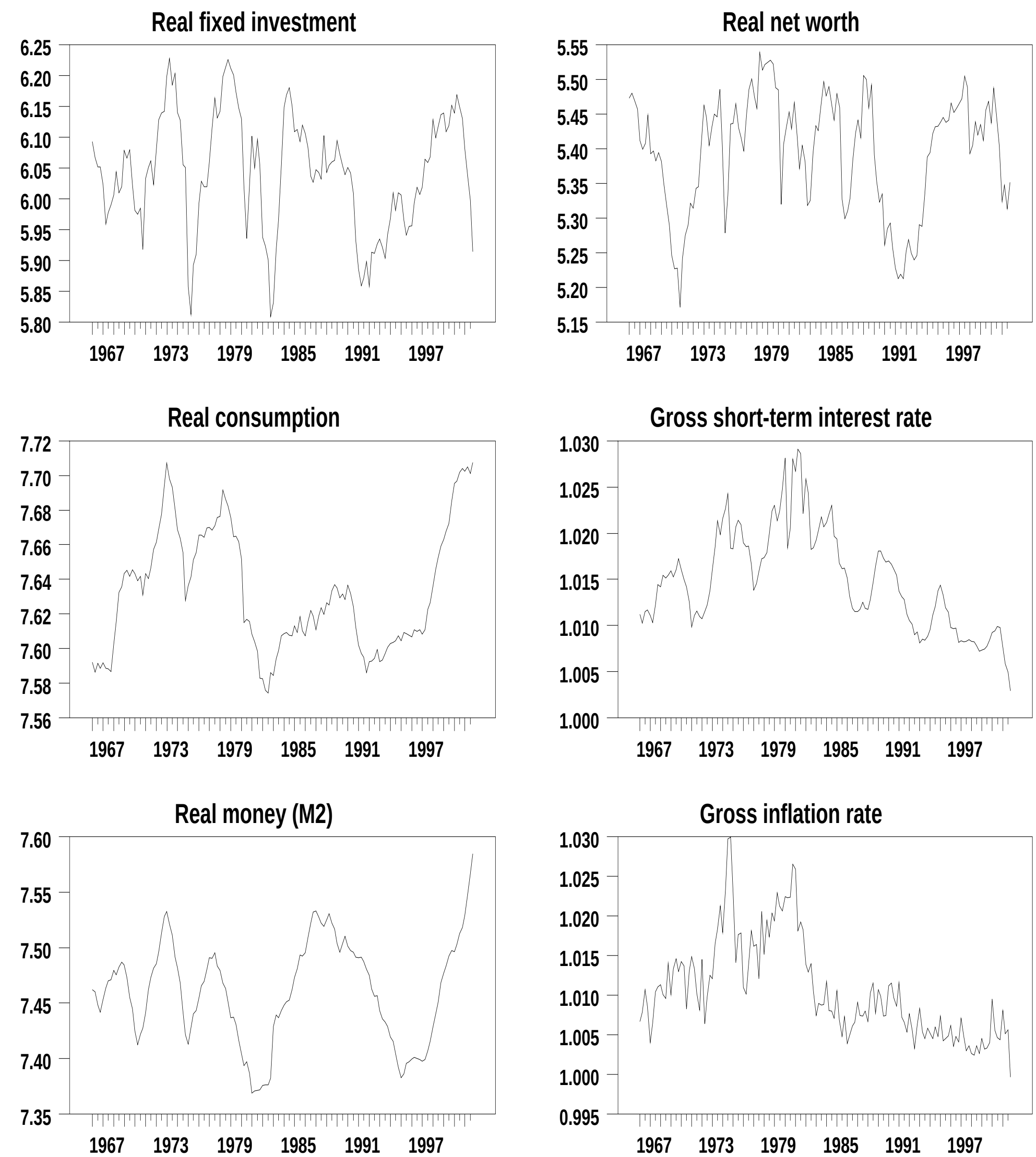

Fig. 4.4 Detrended variables (in logarithms)

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