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Résumé

Cette thèse est constituée de trois essais portant sur l'étude du cycle économique. Les deux premiers chapitres examinent les mécanismes endogènes de propagation dynamique, alors que le troisième étudie la dynamique de l'inflation et les causes de la Grande Modération.

Le premier chapitre examine les effets de la politique monétaire et des chocs technologiques dans le cadre d'un modèle d'équilibre général dynamique qui contient: i) des rigidités nominales de prix, ii) une structure input-output, iii) quelques rigidités réelles, et iv) une politique monétaire réaliste sous forme de règles de Taylor. Le modèle est en mesure de produire une réponse négative des heures travaillées à court terme suivant un choc technologique, ainsi qu'une réponse positive à moyen terme, ce qui est en accord avec les résultats empiriques de Basu, Fernald et Kimball (2006). Contrairement au modèle de Dotsey (1999), le présent modèle prédit une baisse à court terme des heures suivant un choc technologique positif sous différentes spécifications de la règle de Taylor. La clé pour comprendre la différerence entre nos résultats et ceux de Dotsey est la prise en compte de la formation d'habitude de consommation dans notre modèle. On démontre aussi que le facteur principal derrière nos principaux résultats est l'interaction entre les rigidités de prix et la structure input-output. Par exemple, celle-ci permet de générer des sentiers de réponse des variables réelles en forme de cloche suivant un choc monétaire.

Le second chapitre développe et estime un modèle d'équilibre général dynamique capable de reproduire des faits saillants du cycle économique américain. Ces faits incluent les autocorrélations positives du taux de croissance de l'output, de la consommation, de l'investissement et des heures travaillées, la quasi-absence d'autocorrélation du taux de croissance du salaire réel et la faible corrélation entre la productivité moyenne du travail et les heures travaillées. Le modèle parvient à produire de la persistence au moyen de ses mécanismes endogènes de propagation. Nos résultats suggèrent qu'un modèle satisfaisant incorpore une rigidité nominale des salaires, une faible externalité d'emploi, un degré modéré dans la formation d'habitude de la consommantion, et des coûts d'ajustement d'investissement qui sont modestes. Les contrats de salaires qui influent habituellement sur les effets réels des chocs monétaires ont également une incidence importante sur l'impact des effets des chocs technologiques.

Le troisième chapitre développe et estime un modèle d'équilibre général de la Grande Modération qui inclut des rigidités de prix, une élasticité variable de la demande, ainsi qu'une hypothèse de spécificité du travail à la firme. Tout en réconciliant les preuves microéconomiques et macroéconomiques concernant l'ajustement des prix, le modèle explique de façon satisfaisante l'accroissement de la stabilité macroéconomique de la période dite de Grande Inflation à celle de la Grande Modération. Le modèle identifie les chocs à l'offre de travail comme étant la source principale de la réduction de volatilité de la croissance de l'output. Toutefois, des changements dans le comportement du secteur privé, une politique monétaire moins accommodante, et des chocs plus petits expliquent d'une manière à peu près égale la réduction de la variabilité de l'inflation.

Mots-clés: Rigidités nominales, rigidités réelles; grande modération.

Abstract

This dissertation includes three essays on business cycle and monetary economics. The first two chapters are concerned with endogeneous propagation mechanisms, while the third chapter is about inflation dynamics and the "Great Moderation".

The first chapter looks at the effects of monetary policy and technology shocks from the perspective of a dynamic general equilibrium model that features: i) sticky nominal prices, ii) a roundabout input-output structure, iii) a few real frictions and iv) a realistic monetary policy in the form of a Taylor rule. The model is able to generate a short-run negative response of hours worked following a positive technology shock and a positive response in the medium run, consistent with the evidence reported in Basu, Fernald and Kimball (2006). Unlike Dotsey (1999), the model predicts a short-run decline in hours following a positive technology shock under alternative specifications of the Taylor rule. The difference in results is explained by the omission of habit formation in consumption in Dotsey's model. This chapter also shows that a key feature of the model is the interaction between sticky prices and the input-output structure which gives rise to typical hump-shaped responses of real variables to a monetary policy shock.

The second chapter develops and estimates a dynamic general equilibrium model that captures the salient features of postwar U.S. business cycles. These include the positive serial correlation in the growth rates of output, consumption, investment and hours worked, the near-zero serial correlation in real wage growth and the near-zero correlation between hours worked and return to working. Thus, the model meets the challenge of producing a plausible business-cycle persistence via its internal structure. Our findings suggest that a successful model is one that features sticky nominal wages, a relatively small employment externality, mild consumption habit, and relatively modest investment adjustment costs. Wage contracts which are usually seen as affecting mostly the effects of monetary shocks on the real side of the economy, also have a significant impact on the effects of technology shocks.

The third chapter develops and estimates a dynamic stochastic general equilibrium model of the U.S. Great Moderation that features sticky prices, a variable elasticity of demand facing firms and firm-specific labor. While reconciling to a good extent the microeconomic and macroeconomic evidence about the behavior of nominal prices, the model accounts very well for the dramatic increase in macroeconomic stability from the Great Inflation to the Great Moderation. Reminiscent of the evidence in Shapiro and Watson (1988) and Hall (1997), labor-supply shocks are found to be the key source of the sharp reduction in the volatility of output growth. However, changes in the behavior of the private sector, a less accommodative monetary policy and smaller shocks explain almost evenly the large decline in the variability of inflation.

Keywords: Nominal rigidities; real rigidities; great moderation.

Introduction

The last decade has witnessed a rapid development in monetary business cycle models. These models build on the generation of business cycle models that have followed Kydland and Prescott (1982). In the RBC literature, monetary policy is not relevant. However, empirical evidence supports the hypothesis that monetary policy shocks have significant real effects. General equilibrium models with sticky prices and/or wages are consistent with this evidence, which makes them very popular and suitable for monetary policy analysis.

In this thesis, I use this last generation of dynamic stochastic general equilibrium (DSGE) models to examine several issues. In a few words, the first two chapters are concerned with endogeneous business-cycle propagation, while the third chapter examines inflation dynamics and studies the sources of the "Great Moderation". In what follows I describe the main findings of the chapters and their contributions to the literature.

The first chapter develops a DSGE model that explains the macroeconomic consequences of the interactions between a roundabout input-output structure, sticky prices, a few plausible real frictions and Taylor-type of rules. The model is used to address the following issues. First, the predictions of the model concerning the adjustment of several variables to a technology improvement are confronted with the empirical findings from a structural vector autoregression (SVAR) where the technology shock is identified along the lines suggested by Galí (1999). Second, following Dotsey (1999), the model serves the purpose of analyzing the conditions under which a technology improvement leads to a short-run decline in hours worked in the presence of Taylor rules. Third, based on the empirical evidence that a monetary policy shock generates a persistent, hump-shaped response of output (e.g., Galí, 1992; Bernanke and Mihov, 1998; Christiano, Eichenbaum and Evans (2005), we assess whether the interaction between the input-output structure and sticky prices gives rise to this typical pattern in the response of output.

There exists a vast literature on the effects of technology shocks on aggregate fluctuations. A recent SVAR literature identifies a technology shock as the only one that has a permanent effect on output and labor productivity (e.g. Galí, 1999; Francis and Ramey, 2005a). Under this identification strategy, Galí (1999) shows that hours worked decline in the short run following a technology improvement shock. Using annual data, Basu, Fernald and Kimball (2006) construct a direct and "purified" measure of technology that controls for non-technological factors that may affect measured total factor productivity. They find that when thechnology improves, the response of hours is negative in the short run and positive in the medium run. We corroborate this pattern in the response of hours using SVAR-identified technology shocks and postwar U.S. quarterly data.

Our main findings are briefly summarized as follows. First, we find that the model is able to replicate the dynamic responses of several variables to a technology shock obtained from an estimated SVAR model. Second, unlike Dotsey (1999), the model predicts a short-run decline in hours following a positive technology shock under alternative specifications of the Taylor rule. We show that the ambiguous result obtained by Dotsey (1999) concerning the response of hours under alternative Taylor rules is attributable to his omission of habit formation. Third, the model delivers a short-run decline and a medium-run rise in hours following a positive technology shock. The medium-run increase in hours is due to the presence of capital accumulation which reduces the impact of the wealth effect on labor supply. Would the model abstract from capital accummulation as in Galí (1999) or Galí and Rabanal (2004), it would predict a decline of hours both in the short and medium run.

The model also produces a strong endogenous propagation, generating a persistent, hump-shaped response of output following a monetary policy shock under plausible parameter values. The key factor leading to this finding is the interaction between the input-output structure and sticky prices. Either a higher Calvo-probability of price reoptimization or a larger share of intermediate inputs into production will increase the persistence of output and contributes to generate a hump-shaped pattern in the response of output.

Finally, we also look at how the effects of technology shocks on employment can change over time. Empirical evidence in Basu et al. (2006) and Galí, López-Salido and Vallés (2003) suggests that a technology improvement had a more contractionary impact on employment prior to 1980. Galí et al. (2003) present anecdotal evidence that this empirical finding might be explained by a shift in the U.S. monetary policy regime that may have taken place after 1980. Representing the shift in monetary policy by a significant change in parameter values in the Taylor rules after 1980, we show that monetary policy is unlikely to be the source of a change in the employment response following a technology shock. Instead, we present evidence suggesting that smaller total factor productivity (TFP) shocks after 1980 are a more plausible source of the rise in the employment response following a technology improvement in the post-1980 period.

The second chapter seeks to explain the following postwar U.S. business-cycle salient features: i) real consumption is only half as volatile as output, ii) real investment is twice as volatile as output, iii) hours worked and labor productivity are 30 percent less volatile than output, iv) the volatility of real wages is about half the volatility of output, v) inflation is 40 percent less volatile than output, vi) consumption, investment, hours and productivity are all quite procyclical, vii) labor productivity is almost uncorrelated with hours worked, viii) inflation is mildly countercyclical, ix) output, consumption, investment, and hours worked are all positively, serially correlated at relatively short horizons and x) real wage growth exhibits almost no persistence.

It certainly is a challenge for any single model to account for all these stylized facts at once, since adding a new theoretical ingredient to a model in order to improve its fit on a particular dimension, often deteriorates its explanatory power on some other dimension. This sort of tension exists, for example, in the model of Kydland and Prescott (1982) which features a time-to-build technology and preferences for leisure that are not time-separable. While the first ingredient helps dampen investment fluctuations in response to technology shocks, the second generates larger fluctuations in hours worked by constraining hours supplied in different periods to be intertemporal substitutes. But combining both ingredients also comes with a cost: the volatility of consumption is much too low, the volatility of hours is not high enough, hours and productivity are strongly, positively correlated, and the autocorrelations of employment growth predicted by the model at short horizons are counterfactually negative (e.g., King, Plosser and Rebelo.

1988; Wen, 1998).[1]

This chapter develops and estimates DSGE models that shed new light on the comprehensive set of business-cycle statistics described above. While pursuing our goal, we have to take a stand on the number of frictions that our model must include. Here, our strategy is to focus only on a mix of nominal and real frictions that we think are essential to meet our objective, while deliberately omitting several other features that have recently received attention in the broader literature.

The structural parameters of our models are estimated using a maximum likelihood procedure. Our sample of data runs from 1959:I to 2006:II. Our main findings can be summarized as follows. Wage contracts last between 3 and 4 quarters on average. Consumption habit in the baseline model is mild compared to other estimates in the literature. Taking into account the two habits, the evidence demonstrates that habit formation on leisure choice is mild, and the degree of the consumption habit is mostly unaffected by the presence of leisure habit. The estimates of investment adjustment costs compare well with those of others (e.g., Christiano et al., 2005). The labor externality parameter is much smaller according to our baseline model than to other studies that have also used aggregate time series (e.g., Wen, 1998). It implies a degree of increasing returns to scale which is relatively small and similar to the value preferred by Baxter and King (1991). It is also in the range of the parameter values obtained by Cooper and Johri (1997) with plant-level data.

Turning to the baseline model's ability to account for the salient features of postwar business cycles, the evidence shows that it provides quite a good explanation of the main stylized facts. First, the model broadly reproduces the size of relative fluctuations for several aggregate variables. The model not only predicts that investment is much more volatile than output, while consumption and hours are somewhat less volatile than output, but it also implies that the volatility of real wages, productivity and inflation relative to the volatility of output are in broad agreement with the data.

[1] Such tensions also exist in other well known models. For example, in the indivisible labor model of Hansen (1985) and Rogerson (1988), fluctuations in hours become larger by assuming important nonconvexities that may make varying the number of employees more efficient than varying hours per worker, but at the cost that the ratio of the volatility of hours to the volatility of return to working becomes much too large. See also Hansen and Wright (1992).

Second, the model is able to reproduce some critical comovements between variables. For example, Christiano and Eichenbaum (1992) reinterpret the Dunlop-Tarshis observation as a near-zero correlation between hours and productivity. Standard real business cycle (RBC) models predict that this correlation should be high and positive. The correlation between hours and productivity has attracted a considerable attention in recent years (e.g., Baxter and King, 1991; Christiano and Eichenbaum, 1992; Hansen and Wright, 1992; Braun, 1994; McGrattan, 1994). Our baseline model correctly predicts that the correlation between the growth rates of hours and productivity is weak and positive.

Third, and perhaps more importantly, the baseline model generates plausible business-cycle dynamics, revealing the strength of its endogenous propagation mechanisms. King et al. (1988) have shown that the standard neoclassical growth model driven by a permanent technology shock fails to generate persistence in the growth rates of output, investment and hours. This finding leads them to conclude "that there are missing dynamic elements" (King et al., 1988 p.317) to the neoclassical growth model. More recently, Cogley and Nason (1995) have shown that this failure is shared by a large class of real business cycle models. Our evidence suggests that the growth rates of output, consumption, investment and hours all exhibit a positive serial correlation that broadly resembles the persistence observed in the data. At the same time, the model correctly predicts that there is little persistence in real wage growth.

To understand the baseline model's driving mechanisms, we isolate the specific contribution of each type of friction on our main results. We show that each friction contributes to the success of the baseline model in a significant way. Wage contracts allow policy shocks to affect the real side of the economy and help generate the typical hump-shaped impulse responses in several real variables. They also magnify the effects of technology shocks on output, consumption, investment and hours. Without the wage contracts, output volatility would be too low and the model would not generate plausible business-cycle dynamics.

Habit formation for consumption considerably dampens the initial response of output, consumption and hours following technology and policy shocks, making several variables respond in a hump-shaped fashion. Investment adjustment costs help avoid excessively large fluctuations in investment, output and hours. The employment externality magnifies the effects of policy and technology shocks on consumption, investment, hours and output. Without the externality, output fluctuations are too small. Furthermore, the externality has a significant impact on the response of real wages following a policy shock: a postive policy shock induces a slight decrease in real wages initially, which is then followed by a rise in real wages during several periods as the evidence suggests. Without the externality, the response of real wages is quite countercyclical following a policy shock. Also, the correlation between hours and productivity is significantly negative.

Using the estimated model featuring both types of habit, we gauge the relative importance of habit formation in consumption and habit formation in leisure. Our results suggest that consumption habit is more important than leisure habit for our main findings. Without the leisure habit, the results are almost unaffected. However, dropping consumption habit from the model has a significant impact on the results, especially on the short-run responses of output, consumption and hours to technology and policy shocks.

The third chapter explores the reasons behind the spectacular increase in macroeconomic stability from the Great Inflation to the Great Moderation. However, unlike previous studies that seek to understand the causes of the large declines in the volatilities of output growth and inflation (e.g., McConnell and Perez-Quiros, 2000; Blanchard and Simons, 2001; Stock and Watson, 2003; Sims and Zha, 2006; Smets and Wouters, 2007), this chapter proposes a fully-articulated DSGE model of the postwar U.S. economy that not only investigates the sources of the Great Moderation, but also tries to harmonize for the first time in this strand of literature the empirical evidence from microeconomic data suggesting that firms reoptimize prices relatively frequently (e.g., Bils and Klenow, 2004; Golosov and Lucas, 2007; Nakamura and Steinsson, 2007; Klenow and Kryvtsov, 2008) with that from aggregate time series about the inertial nature of the inflationary process (e.g., Fuhrer and Moore, 1995; Galí and Gertler, 1999).

To this end, we estimate a DSGE model of the U.S. economy that rests on two main pillars. First, following Kimball (1995), price-setting monopolistic competitors face a variable elasticity of demand. Second, following Woodford (2003, chapter 3), labor is specific to the firm or industry. While implying a plausible behavior of prices, our benchmark model goes a long way in the explanation of the Great Moderation, capturing close to 80 percent of the sharp decline in the volatility of output growth and 86 percent of the large fall in the variability of inflation.

Based on counterfactual experiments, we find as others do (e.g., Stock and Watson, 2003; Sims and Zha, 2006; Smets and Wouters, 2007; Arias, Hansen and Ohanian, 2007; Leduc and Sill, 2007), that the main drivers behind the reduced volatility in real output growth are the shocks. However, unlike others before us, we identify labor supply shocks as the key source of the increased stability in output fluctuations. Reminiscent of the evidence in Shapiro and Watson (1988) and Hall (1997) suggesting that shifts in labor supply have been the main determinant of postwar U.S. business cycles, our benchmark model assigns close to 50 percent of the decline in the volatility of output growth to smaller labor supply shocks. We also find that smaller investment-specific shocks (e.g., Greenwood, Hercowitz and Huffman, 1988; Fisher, 2006) account for nearly 22 percent of the fall in the volatility of output growth during the Great Moderation. In contrast, the decline in the volatility of inflation is attributable almost evenly to changes in the behavior of the private sector, a less accommodative monetary policy and smaller shocks.

Both the volatility of output growth and the variability of inflation have decreased dramatically during the Great Moderation, with the former falling by 55 percent and the latter by 65 percent.[2] Three broad categories of explanations have been proposed so far to explain these large reductions. A first category suggests that significant changes in economic institutions, technology, business practices, or other structural features have increased the capacity of the economy to absorb shocks. For example, McConnell and Perez-Quiros (2000) and Kahn, McConnell and Perez-Quiros (2002) argue that improved management of business inventories, resulting from advances in computation and communication, reduces fluctuations in inventory stocks, dampening the cyclical

[2] For further evidence on the Great Moderation, see Kim and Nelson (1999), McConnell and Perez-Quiros (2000), Blanchard and Simon (2001) and Stock and Watson (2003).

movements of output.[3] A second category, exemplified by the work of Clarida, Galí and Gertler (2000) and Boivin and Giannoni (2006), among others, says that the Federal Reserve has fought inflation more aggressively after 1980, increasing the stabilizing powers of monetary policy.[4] A third category, known as the "good luck hypothesis", claims that the economy has been prone to much smaller disturbances after 1984.

A recent literature has tried to reconcile the microeconomic and macroeconomic evidence about the behavior of prices. Using summary statistics from the Consumer Price Index micro data compiled by the U.S. Bureau of Labor Statistics, Bils and Klenow (2004) argue that firms change prices quite frequently, once every 4.3-5.5 months, depending if they look at posted prices or regular prices. Focusing on regular prices, Nakamura and Steinsson (2007) find that new prices are posted much less frequently, once every 8-11 months. Still, the evidence in Klenow and Kryvtsov (2008) says that the frequency of price changes is somewhere in between, once every 4-7 months, depending on the treatment of sale prices. On the other hand, looking at the behavior of prices from the perspective of aggregate time series, Fuhrer and Moore (1995) provide evidence from estimated vector-autoregression models indicating that inflation is quite persistent, with positive autocorrelations out to lags of about three years.

Following Kimball (1995) and Woodford (2003, chapter 3, 2005), Altig et al. (2005) and Eichenbaum and Fisher (2007) estimate a DSGE model where monopolistically competitive firms face a variable elasticity of demand and firm-specific physical capital is costly to adjust. Our model focuses instead on a variable elasticity of demand and firm-specific labor. Woodford (2003 chapter 3) shows that factor firm-specificity may increase the degree of strategic complementarity between price-setters, rendering current inflation less responsive to the marginal cost.[5] With a variable elasticity of demand and

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[3] Using DSGE models, Iacoviello, Schiantarelli and Schuh (2007) and Phaneuf and Rebei (2008) provide evidence that changes in the volatility of inventory shocks, or in structural parameters associated with inventories have played a minor role in dampening the volatility of output growth and inflation during the Great Moderation.

[4] Stock and Watson (2003), Sims and Zha (2006) and Smets and Wouters (2007) argue that monetary policy had a small impact on the decline in the volatility of output growth during the Great Moderation.

[5] See also Edge (2006) who looks at the impact of staggered nominal contracts and firm-specific labor on the transmission of monetary shocks from the perspective of a DSGE model calibrated to the U.S. postwar economy, and Matheron (2006) who uses Euro data to estimate a New Keynesian Phillips Curve with firm-specific labor.

firm-specific labor, a firm's marginal cost depends positively on its own level of output. Thus, when contemplating raising its price, a firm knows that a higher price lowers demand and output. In turn, a lower output reduces marginal cost, other things equal, generating the incentives for the firm to post a lower price. Therefore, with a variable elasticity of demand and firm-specific labor, aggregate inflation is less responsive to a given aggregate marginal cost shock.

The economy is subjected to five types of shocks. Our choice of shocks can be justified as follows. A first shock is a random-walk multifactor productivity shock. A second shock is an investment-specific shock in the spirit of Greenwood, Hercowitz and Huffman (1988). Fisher (2006) provides evidence based on structural vector autoregressions (SVAR) that investment-specific shocks have played a key role during the postwar business cycle. A third shock is one to the marginal utility of consumption. Using a DSGE model with nominal rigidities and real frictions, Galí and Rabanal (2004) offer evidence that this shock accounted for a large fraction of the cyclical variance of output during the postwar period. The fourth shock is one to the marginal disutility of hours. Using SVAR models, Shapiro and Watson (1988) show that labor supply shocks contributed to at least 40 percent of postwar output fluctuations at business cycle frequencies. Recently, Hall (1997) has argued that this type of shock had a strong impact on short-run output fluctuations. The fifth shock is one to the Taylor rule.

We adopt the following empirical strategy. First, we estimate the benchmark model for a sample of data covering the years 1948:I to 2006:II. We use the econometric procedure proposed by Ireland (2001, 2003). This allows us to compare our findings about the frequency of price reoptimization with those of others and to assess the ability of the benchmark model to match the volatility of output growth, the variability of inflation and the comovement between output growth and inflation during the postwar period. We find that the model reproduces these moments with accuracy. Assuming, as in standard Calvo-style models, a constant demand elasticity and integrated labor markets (i.e. without firm-specific labor), our estimates suggest that firms reoptimize prices once every 5.4 quarters on average during the postwar period (see also Galí and Gertler, 1999), which seems like an implausibly long period of time. With a constant elasticity of demand and firm-specific labor, the frequency of price reoptimization decreases to once every three quarters on average. With a variable elasticity of demand and firm-specific labor, it declines further, getting close to once every two quarters.

Meanwhile, the estimated model does quite well in matching the vector autocorrelation function and the lagged cross correlations from a vector autoregression. The model is able to predict a persistent inflation, despite our omission of any indexing scheme linking current to past inflation.[6] It also generates positive short-run serial correlation in the growth rates of per capita output and hours, implying plausible business-cycle dynamics (e.g., Cogley and Nason, 1995). We find that shocks to the marginal disutility of hours account for the bulk of the cyclical variance of output during the postwar period, followed by investment-specific shocks.

The model is next reestimated using a sample of data covering the Great Inflation (1948:I to 1979:II) and the Great Moderation (1984:I to 2006:II). Again, we find that the benchmark model closely matches the volatility of real output growth, the volatility of inflation and the correlation between output growth and inflation during the two subperiods. The model accounts for most of the sharp declines in the volatilities of output growth and inflation, predicting a 43 percent fall in the volatility of output growth and a 56 percent decline in the variability of inflation after 1984, close to the percentages observed in the data.

We are able to detect statistically significant changes in some structural parameter values from the Great Inflation to the Great Moderation. Habit persistence decreases. The degree of investment adjustment costs increases. The Federal Reserve's tendency to smooth changes in interest rates decreases, whereas monetary policy becomes less accommodative in response to inflation (see also Clarida, Galí and Gertler, 2000). The composite parameter governing the responsiveness of inflation to the marginal cost falls, implying that the frequency of price reoptimization increases somewhat during the Great Moderation. However, it always remains under three quarters in each subperiod. We also find important differences in the estimated variances of the shocks, but no strong evidence of statistically significant changes in the persistence of the stochastic processes

[6] Eichenbaum and Fisher (2007) also consider the possibility of a lag between the time at which firms reoptimize their price plans, and the time at which they implement the new plan.

generating the shocks.

Chapter 1

The Transmission of Shocks to Monetary Policy and Technology: The Role of Intermediate Inputs and Sticky Prices Under Taylor Rules

1.1 Introduction

This chapter develops a general equilibrium model that helps understand the macroeconomic consequences of the interactions between a roundabout input-output structure, sticky prices, a few plausible real frictions and Taylor-type monetary policy rules. The model is used to address the following issues. First, the predictions of the model concerning the adjustment of several variables to a technology improvement are confronted with the empirical findings from a structural vector autoregression (SVAR) where the technology shock is identified along the lines suggested by Galí (1999). Second, following Dotsey (1999), the model is used to analyse the conditions under which a technology improvement leads to a short-run decline in hours worked in the presence of Taylor rules. Third, based on the empirical evidence that a monetary policy shock generates a persistent, hump-shaped response of output (e.g., Galí, 1992; Bernanke and Mihov, 1998; Christiano, Eichenbaum and Evans, 2005), we assess whether the interaction between the input-output structure and sticky prices gives rise to this typical pattern in the response of output.

A recent SVAR literature identifies a technology shock as the only one that has a permanent effect on output and labor productivity (e.g, Galí, 1999; Francis and Ramey, 2005a, b). Under this identification strategy, Galí (1999) shows that hours worked decline in the short run following a technology improvement shock.[1] Using annual

[1] It should be stressed, however that the response of hours worked to a positive technology shock is sensitive to the treatment of hours in the SVAR. With first-differenced hours as in Galí (1999), hours fall after a positive technology shock. With hours in level as in Christiano, Eichenbaum and Vigfusson (2004), hours rise. Still, the evidence in Fernald (2007) shows that hours fall even with hours entering in level if a structural break in labor productivity is allowed. Using an improved measure of hours worked, Francis and Ramey (2005b) also find that both the level and the first-difference specification lead to a fall in hours following a positive technology shock.

data, Basu, Fernald and Kimball (2006) construct a direct and "purified" measure of technology and find that when thechnology improves, the response of hours is negative in the short run and positive in the medium run. We corroborate this pattern in the response of hours using SVAR-identified technology shocks and postwar U.S. quarterly data.

The model includes the following structural components. First, as in Basu (1995) and Huang, Liu and Phaneuf (2004), the model features an horizontal, roundabout input-output structure. Second, nominal prices are reoptimized on the basis of Calvo-type contracts (e.g., Yun, 1996). Third, the model accounts for a variable utilization rate of capital (e.g., Burnside and Eichenbaum, 1996; Christiano et al., 2005). Fourth, the model includes habit formation in consumption (e.g., Beaudry and Guay, 1996; Fuhrer, 2000; Christiano et al., 2005). Fifth, investment is costly to adjust (e.g., Christiano et al., 2005). Sixth, we use different Taylor-type specifications for the monetary policy rule.

Our main results are as follows. First, we find that the model is able to replicate the dynamic responses of several variables to a technology shock obtained from an estimated SVAR model. Second, unlike Dotsey (1999), the model predicts a short-run decline in hours following a positive technology shock under all different specifications of the Taylor rule that we examine. We show that the ambiguous result obtained by Dotsey (1999) concerning the response of hours under alternative Taylor rules is attributable to his omission of habit formation. Third, we show that the model delivers a short-run decline and a medium-run rise in hours following a positive technology shock. The medium-run increase in hours is due to the presence of capital accumulation which reduces the impact of the wealth effect on labor supply. Would the model abstract from capital accummulation as in Galí (1999) or Galí and Rabanal (2004), it would predict a decline of hours both in the short and medium run.

The model is also able to produce a strong endogenous propagation, generating a persistent, hump-shaped response of output following a monetary policy shock under plausible parameter values. The key factor leading to this finding is the interaction between the input-output structure and sticky prices. Either a higher Calvo-probability of price reoptimization or a larger share of intermediate inputs into production will increase the persistence of output and contribute to generate a hump-shaped pattern in the response of output.

Finally, we also look at how the effects of technology shocks on employment can change over time. Empirical evidence in Basu et al. (2006) and Galí, López-Salido and Vallés (2003) suggests that a technology improvement had a more contractionary impact on employment prior to 1980. Galí et al. (2003) present anecdotal evidence that this empirical finding might be explained by a shift in U.S. monetary policy regime that could have taken place after 1980. Representing the shift in monetary policy by a significant change in parameter values in the Taylor rules after 1980, we show that monetary policy is unlikely te be the source of a change in the employment response following a technology shock. Instead, we present evidence suggesting that smaller TFP shocks after 1980 are a more plausible source of the rise in the employment response following a technology improvement in the post-1980 period.[2]

The remainder of the chapter is organized as follows. Section 1.2 presents the SVAR evidence on the effects of technology shocks. Section 1.3 describes the DSGE model that serves for the purpose of our investigation. Section 1.4 justifies the choice of our calibration. The main results are presented and discussed in Section 1.5. A sensitivity analysis is conducted in section 1.6. Section 1.7 provides conclusions.

1.2 The Effects of Technology Shocks in a SVAR Model with Long-Run Restrictions

Following Galí (1999), we identify the technology shock as the only one that has a permanent effect on labor productivity. We consider the following six-variable moving average representation:

$$Y_t = C(L)\varepsilon_t,$$

[2]See chapter 3 for more details on this evidence.

where

$$Y_t = \begin{bmatrix} \Delta x_t \\ \Delta h_t \\ \Delta w_t \\ \Delta p_t \\ z_t \\ i_t \end{bmatrix}, \qquad \varepsilon_t = \begin{bmatrix} \varepsilon_t^x \\ \varepsilon_t^h \\ \varepsilon_t^w \\ \varepsilon_t^p \\ \varepsilon_t^z \\ \varepsilon_t^i \end{bmatrix}.$$

$C(L)$ is an infinite 6th order polynomial in the lag operator L, and Δ is the first-difference operator. The vector Y_t includes average labor productivity growth (Δx_t), the rate of change of hours (Δh_t), the rate of change of nominal wage (Δw_t), the rate of inflation (Δp_t), a capacity utilization rate (z_t), and the short-term nominal interest rate (i_t); ε_t^x is the technology shock and ε_t^h, ε_t^w, ε_t^p, ε_t^z, ε_t^i are non-technological shocks. The long-run restriction stipulates that the unit root in average labor productivity results exclusively from the technology shock. This assumption implies that $C_{1i}(1) = 0$ for $i = 2, 3 \ldots, 6$. The system is estimated using the econometric procedure proposed by Shapiro and Watson (1988). The data, which are quarterly, cover the sample 1950:I-2001:IV.[3]

Figure 1.1 displays the impulse responses of some selected variables to a positive, one percent technology shock.[4] Hours decline in the short run when technology improves, overshooting their pre-shock level two years after the shock. Note also that after a slight short-run decrease, output gradually rises towards its higher steady-state level. As it is the case for hours, the capital utilization rate falls in the short run and then increases in the medium run. Real wages gradually rises towards their higher steady-state level. Inflation falls weakly but persistently. The nominal interest rate also weakly declines. These findings are broadly consistent with those reported by Basu et al. (2006).

[3]The data are taken from the Haver Analytics Economics Database. Output is the output in the nonfarm business sector (LXNFO). Hours are measured by total hours in the nonfarm business sector (LXNFH). Nominal wage is the compensation per hour in the nonfarm business sector (LXNFC). Capacity utilization series is the manufacturing industry's capacity index (CUMFG). Nominal interest rate is the Three-Month Treasury Bills (FTB3). The price index is the implicit price deflator in the nonfarm business sector (LXNFI). Output and hours are converted to per capita terms after being divided by the civilian noninstitutional population 16 years and over (LNN).

[4]As a robustness check, we allow hours to enter the system in deviations from a quadratic trend. The results are similar to those obtained in Figure 1.1.

1.3 The Model

This section describes the main building blocks of the model. The economy consists of a representative household, a finished-good producing firm, a large number of intermediate-good producing firms indexed by i on the continuum 0 to 1, and a central bank.

1.3.1 The Representative Household

The infinitely lived representative household derives utility from consumption and leisure. His preferences are represented by the expected utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\ln(C_t - bC_{t-1}) + \frac{\eta}{1-\chi}(1 - H_t)^{1-\chi} \right), \tag{1.1}$$

where $\beta \in (0, 1)$ is the subjective discount factor, C_t is a composite of differentiated consumption goods at period t, and $b \in [0, 1]$ measures the degree of habit formation.

The household enters period t with bond holdings B_{t-1} and a predetermined stock of physical capital K_t. He supplies H_t units of hours at the nominal wage rate W_t and rents K_t units of capital at the nominal rental rate R_t^k to the intermediate-good producing firms. As in Christiano et al. (2005), we assume that z_t, the utilization rate of capital, is set by the household at the cost of $u(z_t)K_t$, which is expressed in units of the finished good. It is assumed that $u(.)$ is an increasing and convex function satisfying $u(1) = 0$.

At the end of period t, the household receives total dividends D_t from the firms. He purchases B_t units of bonds, C_t units of the consumption good, and I_t units of an investment good at the nominal price P_t from the finished-good producing firm. Let R_t be the gross nominal interest rate between periods t and $t + 1$.

The household faces the flow budget constraint:

$$C_t + I_t + \frac{(B_t/R_t)}{P_t} + u(z_t)K_t \leq \frac{B_{t-1} + W_t H_t + R_t^k z_t K_t + D_t}{P_t}. \tag{1.2}$$

In order to prevent the household from running Ponzi schemes, we impose an explicit borrowing constraint: $B_t \geq -B, B \geq 0$.

The capital stock evolves according to:

$$K_{t+1} = (1-\delta)K_t + (1 - S(I_t/I_{t-1}))I_t, \tag{1.3}$$

where δ is the depreciation rate. Following Christiano et al. (2005), the second term on the right-hand side of (1.3) embodies investment adjustment costs. The function $S(.)$ is positive, convex and it satisfies $S(a) = S'(a) = 0$, where the parameter a is the steady-state gross growth rate of output (see below). Investment adjustment costs allow Tobin's Q to vary in response to the shocks. The household seeks to maximize his utility function (1.1) subject to the budget constraint (1.2) and capital accumulation equation (1.3).

The first-order conditions of the household maximization's problem are:

$$\Lambda_t = \left(\frac{1}{C_t - bC_{t-1}}\right) - \beta b E_t \left(\frac{1}{C_{t+1} - bC_t}\right), \tag{1.4a}$$

$$\eta(1-H_t)^{-\chi} = \Lambda_t W_t / P_t, \tag{1.4b}$$

$$Q_t = E_t \left[\beta \gamma_{\Lambda,t+1} \left[\frac{R^k_{t+1}}{P_{t+1}} z_{t+1} - u(z_{t+1}) + (1-\delta)Q_{t+1}\right]\right], \tag{1.4c}$$

$$Q_t = \frac{1 - E_t\left[\beta \gamma_{\Lambda,t+1} Q_{t+1} S'(\gamma_{I,t+1}) \gamma^2_{I,t}\right]}{[1 - S(\gamma_{I,t}) - S'(\gamma_{I,t})\gamma_{I,t}]}, \tag{1.4d}$$

$$u'(z_t) = R^k_t / P_t. \tag{1.4e}$$

where Λ_t denotes the multiplier on the budget constraint (1.2) and $\gamma_{X,t} = \frac{X_t}{X_{t-1}}$. Equations (1.4a) and (1.4b) define the consumption/leisure trade-off and state that the marginal rate of substitution between consumption and leisure is equal to the real wage. The Euler condition for capital (1.4c) illustrates that the shadow price of installed capital as measured by marginal Tobin's Q depends on the expected future Q value net of depreciation plus the expected future return on capital minus the cost of changing the future rate of capital utilization. Equation (1.4d) gives the optimal level of investment. It implies that investment is increasing in Q. Equation (1.4e) indicates that the optimal rate of capital utilization involves weighting the benefit and cost of a marginal increment in utilization.

1.3.2 The Finished-Good Producing Firm

The representative finished-good producing firm acts competitively in the finished good market. It produces a quantity Y_t of the finished good using the Dixit-Stiglitz aggregator:

$$Y_t \leq \left[\int_0^1 Y_{i,t}^{(\theta-1)/\theta} di\right]^{\theta/(\theta-1)}, \tag{1.5}$$

where Y_{it} denotes the quantity of the intermediate good i used in the production of the finished good. and the parameter $\theta > 1$ is the elasticity of substitution between differentiated intermediate goods.

The finished-good producing firm purchases $Y_{i,t}$ at price $P_{i,t}$. The first-order condition corresponding to the profit maximization problem is:

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t}\right)^{-\theta} Y_t \tag{1.6}$$

The absence of profits for the firm implies:

$$P_t = \left[\int_0^1 P_{i,t}^{1-\theta} di\right]^{1/(1-\theta)}. \tag{1.7}$$

1.3.3 The Intermediate-Good Producing Firms

The intermediate-good firm i uses capital services $z_t K_{i,t}$, labor $H_{i,t}$ and an intermediate input $X_{i,t}$ to produce, according to the following technology:

$$Y_{i,t} = \begin{cases} \left[(z_t K_{i,t})^{\alpha}(A_t H_{i,t})^{1-\alpha}\right]^{1-\phi} X_{i,t}^{\phi} - A_t\Phi & \text{if } \left[(z_t K_{i,t})^{\alpha}(A_t H_{i,t})^{1-\alpha}\right]^{1-\phi} X_{i,t}^{\phi} \geq A_t\Phi \\ 0 & \text{otherwise,} \end{cases} \tag{1.8}$$

where the term in square brackets corresponds to value-added, $\alpha \in (0, 1)$ is the share of capital services in value added, and the $\phi \in (0, 1)$ denotes the share of intermediate inputs into production. The parameter $\Phi > 0$ represents an endogenous common fixed cost.[5]

A_t denotes the aggregate labor-augmenting level of technology. It is generated by the following logarithmic random-walk process with drift:

$$\ln(A_t) = \ln(a) + \ln(A_{t-1}) + \varepsilon_{a,t}. \tag{1.9}$$

[5] Rotemberg and Woodford (1995) argue that average pure profits in the U.S. economy have been close to zero. In our context, this possibility is allowed through the introduction of the fixed cost.

where $a > 1$, $\varepsilon_{a,t}$ is a zero-mean, serially uncorrelated, normally distributed variable with standard deviation σ_a.

All inputs are produced in competitive markets. Each period, the representative firm's cost-minimization problem implies the following first-order conditions:

$$(1-\alpha)(1-\phi)\left(\frac{Y_{i,t}+A_t\Phi}{H_{i,t}}\right)mc_t = \frac{W_t}{P_t}, \tag{1.10a}$$

$$\alpha(1-\phi)\left(\frac{Y_{i,t}+A_t\Phi}{K_{i,t}z_t}\right)mc_t = \frac{R_t^k}{P_t}, \tag{1.10b}$$

$$\phi\left(\frac{Y_{i,t}+A_t\Phi}{X_{i,t}}\right)mc_t = 1, \tag{1.10c}$$

where mc_t denotes the aggregate real marginal cost. The cost minimization conditions state that the firm equates the marginal product of each of input to its real price.

In each period, a firm i faces a fixed probability $1-\xi$ of reoptimizing its price $P_{i,t}$. Accordingly, the average amount of time between price reoptimization is given by $1/(1-\xi)$. Following Christiano et al. (2005), we also assume that firms which are not permitted to reoptimize their prices in a period use the following simple rule of thumb:

$$P_{i,t} = \pi_{t-1}^{\kappa} P_{i,t-1},$$

where $\pi_t = P_t/P_{t-1}$. Hence, these firms partially index their prices to past inflation, with κ measuring the degree of indexation. As in Christiano et al. (2005), the case $\kappa = 1$ corresponds to full indexation of prices. Such an indexation scheme increases inflation persistence.[6]

Let d_{t+j} be the real profit of the representative firm in period $t+j$; d_{t+j} is given by:

$$d_{t+j} = \left[(P_{i,t}/P_{t+j})^{1-\theta}(P_{t+j-1}/P_{t-1})^{\kappa} - (P_{i,t}/P_{t+j})^{-\theta}mc_{t+j}\right]Y_{t+j} - A_{t+j}\Phi mc_{t+j}. \tag{1.11}$$

In a symmetric equilibrium, all firms allowed to reoptimize prices choose the same optimal price P_t^*.[7] Profit maximization leads to the following first-order condition for

[6] The evidence in Galí and Gertler (1999) lends support for the presence of lagged inflation in the New Keynesian Phillips Curve (NKPC) equation.

[7] Note that this is not always the case. Golosov and Lucas (2007) develop a general equilibrium model with state-dependent pricing in which heterogeneity in individual pricing decisions arises due to idiosyncratic productivity shocks.

the relative price P_t^*/P_t.

$$\frac{P_t^*}{P_t} = \mu \frac{E_t \sum_{j=0}^{\infty}(\beta\xi)^j \left[(\Lambda_{t+j}/\Lambda_t)(P_t/P_{t+j})^{-\theta} Y_{t+j} mc_{t+j}\right]}{E_t \sum_{j=0}^{\infty}(\beta\xi)^j \left[(\Lambda_{t+j}/\Lambda_t)(P_t/P_{t+j})^{1-\theta}(P_{t-1+j}/P_{t-1})^{\kappa} Y_{t+j}\right]}, \tag{1.12}$$

where $\mu = \frac{\theta}{\theta-1} > 1$ is the steady-state markup of price over marginal cost, which is also the desired markup with perfectly flexible prices. Note that, as κ rises, the elasticity of the firm's optimal relative price to past inflation increases.

The aggregate price level in expression (1.7) can be reformulated as:

$$P_t^{1-\theta} = (1-\xi)P_t^{*1-\theta} + \xi(\pi_{t-1}^{\kappa} P_{t-1})^{1-\theta} \tag{1.13}$$

The aggregate resource constraint of the economy is given by

$$Y_t = C_t + I_t + u(z_t)K_t + X_t. \tag{1.14}$$

It is useful to define the value-added $\bar{Y}_t$ as

$$\bar{Y}_t = Y_t - X_t. \tag{1.15}$$

In what follows, we refer to value-added as output.

1.3.4 The Monetary Policy

We assume in the benchmark model that the Federal Reserve sets the nominal interest rate in accordance with the following Taylor-type of rule:

$$\hat{R}_t = \rho_r \hat{R}_{t-1} + (1-\rho_r)(\rho_\pi \hat{\pi}_t + \rho_y \hat{\gamma}_{\bar{y},t}) + \varepsilon_{r,t}, \tag{1.16}$$

where $\hat{R}_t$, $\hat{\pi}_t$, and $\hat{\gamma}_{y,t}$ denote the deviations of the nominal interest rate, the rate of inflation and the growth rate of output from their respective steady-state values, and $\varepsilon_{r,t}$ is a zero-mean, serially uncorrelated, normally distributed variable with standard deviation σ_r.

This specification differs from the standard Taylor (1993) rule. First, it allows for the gradual adjustment of the nominal interest rate. Second, it features the growth rate of the output gap rather than the level of the output gap. Other examples of models where the Taylor rule features output growth include Erceg and Levin (2003), Galí and Rabanal (2004) and Liu and Phaneuf (2007).

1.3.5 Equilibrium

Under clearing of factor markets, we have $\int_0^1 H_{it} = H_t$, $\int_0^1 K_{it} = K_t$, and $\int_0^1 X_{it} = X_t$, while under clearing of the bonds market, $B_t = B_{t-1} = 0$.

The household's preferences and the production technology are consistent with balanced growth. Because of the random-walk specification for technology, the following transformations are required to ensure stationnarity: $c_t = C_t/A_t$, $y_t = Y_t/A_t$, $\tilde{y}_t = \tilde{Y}_t/A_t$, $i_t = I_t/A_t$, $k_{t+1} = K_{t+1}/A_t$, $x_t = X_t/A_t$, $w_t = (W_t/P_t)/A_t$, $\lambda_t = \Lambda_t A_t$, $a_t = A_t/A_{t-1}$. Furthermore, we let $r_t^k = R_t^k/P_t$.

The rational expectations equilibrium for this economy is a set of endogenous processes for $\{c_t, H_t, k_{t+1}, i_t, z_t, r_t^k, w_t, \lambda_t, mc_t, R_t, y_t, \tilde{y}_t, x_t, P_t, P_t^*, A_t\}$, that satisfies the following conditions: (i) taking all prices and real wages as given, the household solves his utility optimization problem (1.1) subject to his budget constraint (1.2) and the capital accumulation equation (1.3); (ii) taking the factor prices and all prices but its own as given, each firm solves its profit maximization problem; (iii) the monetary authority follows (1.16); (iv) markets for factors, bonds and goods clear. These are given the initial condition of the economy and the exogenous processes for the technology shock (1.9) and the monetary policy shock.

1.4 Calibration

The calibration of the model's parameters is typical in the business cycle literature. First, the required zero-profits condition for the firms at the steady state implies that the share of the fixed cost in gross output is equal to $\mu - 1$. The quarterly depreciation rate δ is set equal to 0.025, which implies an annualized depreciation rate of 10%. The share of capital in value-added α is set equal to 0.36. We calibrate the steady-state values of the gross nominal interest rate R, and the gross growth rate of technological progress a, such as to match U.S. data over the period 1950:I-2001:IV.

With respect to the cost share of the intermediate input ϕ, available evidence suggests a range of 0.5-0.7.[8] So we set ϕ equal to 0.6. The parameter χ is chosen such that

[8]Based on the 1998 Annual Input-Output Table of the Bureau of Economic Analysis for the U.S. manufacturing sector. Huang, Liu, and Phaneuf (2004) estimate that ϕ lies between 0.55 and 0.74. Nevo (2001) found that the share of materials in the U.S. food sector (SIC20) over the period 1988-1992 is

the Frish elasticity of labor supply is 1.1, which complies with the estimates of Mulligan (1998). The parameter η is set such that the steady-state fraction of time endowment devoted to market work equals 0.30. The elasticity of the real rental rate of capital with respect to capital utilization rate $\sigma_u = \frac{u''(1)}{u'(1)}$ is calibrated along the lines of Altig, Christiano, Eichenbaum and Lindé (2005), precisely $\sigma_u = 2$. The curvature parameter $S''(a)$ controlling for investment adjustment costs is set equal to 3, also consistent with the estimates of Altig et al. (2005). The values of σ_u and $S''(a)$ do not matter for the calculation of the steady state of the economy, but they do for the model's dynamics. The habit parameter b is set equal to 0.8, which agrees with the estimates of Fuhrer (2000). Basu and Fernald (2000) suggest that, controlling for variable inputs utilization, the estimate of the value-added markup is 1.05; while the latter rises to 1.12 without any correction for variable utilization. Since we allow for variable capital utilization, it is reasonable to set $\theta = 11$ so that $\mu = 1.1$. We set $\xi = 0.75$, implying that the average frequency between price adjustment is one year, consistent with Taylor's (1999) survey. The indexation parameter κ is set equal to 0.75, which lies between the point estimate of 0.66 reported in Smets and Wooters (2005) and the value of 1 imposed by Christiano et al. (2005).

With respect to the interest-rate rule, we set ρ_π to 1.5, ρ_y to 0.25, and ρ_r to 0.75. Finally, we fix the standard deviations of the shocks σ_a, and σ_r to 0.01 and 0.003 respectively.

To examine the properties of the model, we take a log-linear approximation of the model's equilibrium conditions around the steady state. The resulting system of linear difference equations is solved using the methods outlined by Klein (2000).

1.5 Results

1.5.1 Impulse Responses

Figure 1.2 compares the model-based impulse responses to a technology shock with their empirical counterparts. Notice first that hours worked, capital utilization rate and intermediate input all fall on the impact of the shock. The responses of inflation and

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0.634.

the nominal interest rate are also negative. In the model as in data, the initial response of output is close to zero. The short run negative effect of a technology improvement on inputs is consistent with the findings of Basu et al. (2006).

The traditional explanation of Gali (1999) applies here to understand the contractionary effects of the technology shock. The rise in productivity created by the shock is not accompanied by a similar if not a larger rise in aggregate demand. The faint reaction of demand is expected to occur in a context of price rigidity and a weekly accommodative monetary policy. Dotsey (1999) argued that an *output-growth* rule is less accommodative of the technology shock than a standard Taylor rule that involves the output gap, which helps obtain a fall in hours worked and inflation. Hence, our results suggest that Dotsey's findings still hold within a richer theoretical framework including monetary policy inertia and an input-ouput structure under plausible parameter values.

Figure 1.3 shows the response of the economy to an expansionary monetary policy shock. We see that output, consumption, investment, and hours worked rise in a hump-shaped manner, which is consistent with the VAR literature (see e.g., Christiano et al., 2005). This is because the model includes several internal propagating mechanisms. In the next section we discuss the role played by some of these mechanisms in generating endogenous persistence.

On the whole, the model succeeds in accounting for the dynamic response of the selected variables to both technology and monetary policy disturbances.

1.6 Sensitivity Analysis

1.6.1 The Role of Capital Accumulation

In this section we examine the contribution of capital accumulation to the predictions of the model concerning the response of the economy, especially hours worked, to a technology shock. To do so, we consider a version of the benchmark model in which we abstract from capital. Figure 1.4 displays the results. Notice that without capital, hours worked still decline on the impact of the shock but adjust to their pre-shock level in a monotonic way. Once we allow for capital, hours fall initially and overshoot their steady-state level in the medium run. So with capital accumulation, the model is able to match better the empirical response of hours worked and also output.[9]

The reason for these findings is that in the no-capital case, consumption adjusts more quickly to its new steady-state level, which strengthens the wealth effect and consequently results in a larger decline in hours worked on impact of the shock and prevents them from increasing in the medium run. In other words, the presence of capital by making the adjustment of the economy, especially consumption, more gradual allows the substitution effect to be more important than the wealth effect and thereby the response of hours can be positive few periods after the shock.[10]

1.6.2 Price Rigidity, Intermediate Inputs and the Real Effects of Monetary Policy Shocks

We can attribute the success of the model in generating persistence to two elements: price stickiness and the presence of intermediate inputs in the production function.[11]

The first column of figure 1.5 shows the response of output and the price level to a negative interest rate shock for different values of ϕ . We fix all the remaining parameters at their benchmark values. Notice that when ϕ is very small, the response of output reaches its maximum in the first period of the shock. As ϕ rises, the response of output becomes hump-shaped, and the adjustment of the price level displays more sluggishness. Therefore, for an empirically plausible range for ϕ, say 0.5-0.7, the model succeeds in generating persistent responses of output and prices following a monetary policy shock, in a way that is consistent with the data.

The second column of figure 1.5 displays the response of the same variables for different settings of the probability ξ. When firms change their prices very frequently ($\xi = 0.5$), the response of output is monotonic. For higher degrees of price rigidity,

[9] With capital accumulation, the initial response of output is smaller than that obtained without capital. That's why it is closer to the one obtained from the VAR, which is close to zero.

[10] Using a specification including both price and wage rigidities but no capital accumulation, Galí and Rabanal (2004) also obtained a negative initial response of hours worked after a technology shock followed by a monotonic adjustment

[11] Since the hump-shaped pattern of the response of output, its components and employment to monetary policy shocks is incontestable in the literature, we need not to provide here any further evidence on these stylized facts.

output exhibits a hump-shaped pattern and the price index adjusts more gradually to its new steady-state level. Hence, there exists a positive interaction between these two mechanisms in producing endogenous persistence.[12]

1.6.3 Output-Growth *vs* Output-Level Rule

As showed by Dotsey (1999), the response of the economy to a technology shock is sensitive to the specification of the monetary policy rule. To assess this view, we compare the results obtained using our benchmark policy rule with those obtained using the more standard interest rate rule:

$$\hat{R}_t = \rho_r \hat{R}_{t-1} + (1-\rho_r)\left[\rho_\pi \hat{\pi}_t + \rho_y \hat{\bar{y}}_t\right] + \varepsilon_{r,t} \tag{1.17}$$

Otherwise, we keep the benchmark calibration unchanged.

Figure 1.6 displays the results. The main finding here is that under the more accommodative rule (1.17) the impact response of hours is still negative but its magnitude is smaller compared to that of the benchmark case. These results are in contrast with those of Dotsey (1999). In order to reconcile our findings with his, note that his model includes capital adjustment costs but no habit formation in consumption. Since we allow for both of these frictions, it is possible to obtain a fall in hours worked after a technology shock following the lines of Francis and Ramey (2005a) even with an accommodative policy rule.

Figure 1.7 confirms this intuition. It displays the same results as those in Figure 1.6 under a version of the benchmark model that abstracts from consumption habit, i.e., $b = 0$. As expected, the response of hours worked becomes positive under the standard rule but remains negative under the benchmark rule. We conclude that we need more than one friction that reduces the magnitude of the increase in the aggregate demand in response to the technology shock to obtain an initial fall in hours worked.

1.6.4 The Impact of Technology on Hours Worked Over Time

Galí et al. (2003) presented evidence concerning the significant change in the initial response of employment to a technological improvement from largely negative in the

[12] Bergin an Feenstra (2000) found a positive interaction between intermediate inputs and a translog demand structure in propagating monetary policy shocks.

pre-1979 period to mildly negative in the post-1979 period. This result is corroborated by Basu et al. (2006) who found that the initial response of hours worked to a technology shock goes from -0.62 % (significant) in the 1949-1979 period to -0.29 % (marginally significant) in the 1980-1996 period.

In this section we investigate the validity of Galí et al.'s suggestion that this could be linked to the change in the U.S. monetary policy regime over time.[13] To do so, we need an empirically plausible calibration for the monetary policy rules that might have been pursued by the Federal Reserve over the postwar era. Several empirical studies, including Clarida, Galí and Gertler (2000), found that the response of the Federal Reserve's nominal interest rate to changes in inflation has dramatically changed from the pre-1980 period to the post-1980 period. Based on Clarida et al., we assume that the Fed has conducted the monetary policy using the rule (1.17) with the following calibration: $\rho_\pi = 1$ for the pre-1980 period, and $\rho_\pi = 2$ for the post-1980 period. We keep the coeffcients ρ_y and ρ_r fixed at their benchmark values since there is little evidence for their instability over time.

We compute the response of the economy to a technology shock using (1.17) under the two calibrations for ρ_π. The results are displayed in figure 1.8. It can be seen that the drastic change in the value of ρ_π from 1 to 2 not only has a small effect on the response of hours worked but that it also leads to a more negative response of hours, which is in contrast with the evidence. Therefore, our simulation results cast doubt on Galí et al.'s suggestion. These findings seem to be robust to plausible changes in ρ_π, even if we replace the output gap by the output growth, i.e., using our benchmark rule (1.16).

A closer look at the reasons behind the hypothetical change in the relation between technology and hours over time is beyond the scope of this chapter. However, we can provide some possible explanation for this finding. Several studies found that the economy has been buffeted by smaller shocks during the 1980-2000 period compared to the previous era. For example, Ireland (2004), and Smets and Wouters (2007) found that the volatility of the technology shock has decreased from the earlier to the later

[13] It is widely admitted that the Federal Reserve policy regime has clearly changed since October 1979. See e.g., Clarida et al. (2000), Estrella and Fuhrer (2003), Ireland (2003), and Taylor (1998).

period. It is not difficult to understand that a lower value of the standard deviation of the technology shock should be accompanied by a smaller initial negative response of hours worked. Hence, a change in the properties of the technology shock can be one factor behind the possible shift in the link between technology and employment over time.

1.7 Conclusion

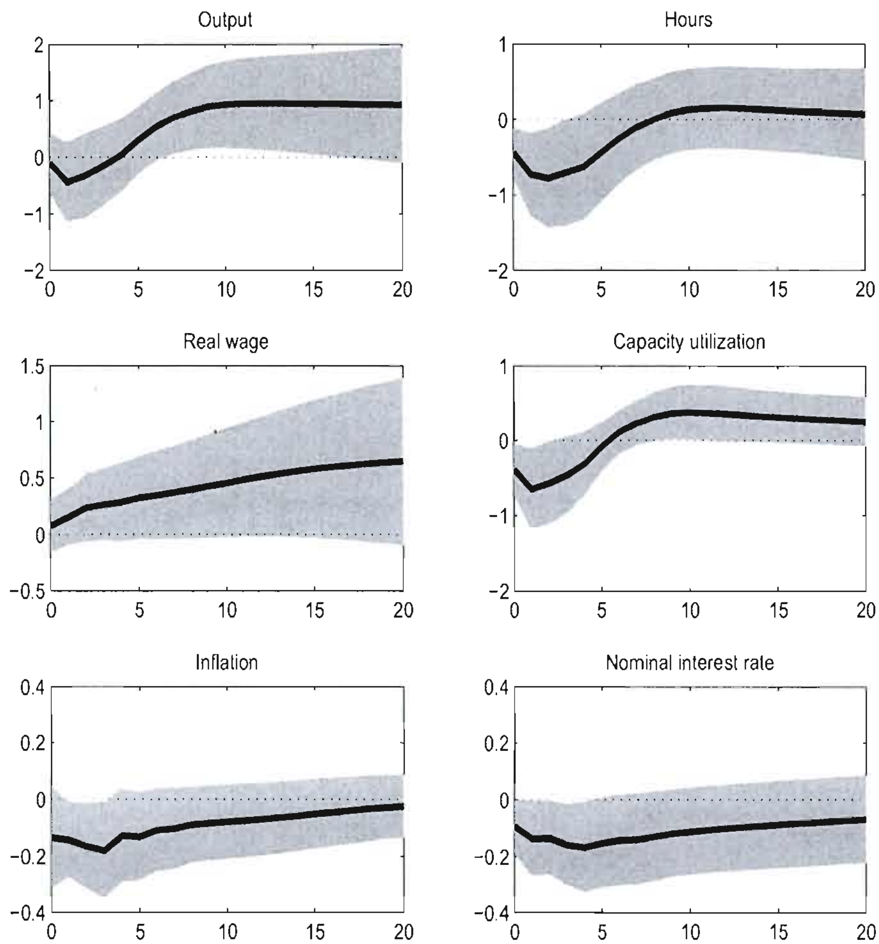
In this chapter, we constructed a sticky price model that features an input-output production structure and a number of real frictions. Once calibrated with empirically plausible values, the model performs quite well in accounting for the dynamics of selected macro variables induced by permanent technology shocks as well as monetary policy shocks.

Particularly, our model succeeds in matching the response of hours worked to a technology shock, which is characterised by a decline in the short-run followed by a rise in the medium-run. The initial decline in hours is mainly driven by the presence of both habit persistence in consumption and investment adjustment costs and it is robust to the use of an accommodative monetary policy rule. As to the increase in the subsequent periods, it is mainly attributable to the presence of capital accumulation.

One important implication of the model is the positive interaction between price rigidity and intermediate inputs in producing endogenous persistence. Consequently, we are able to obtain the stylized hump-shaped response of output to a monetary policy shock.

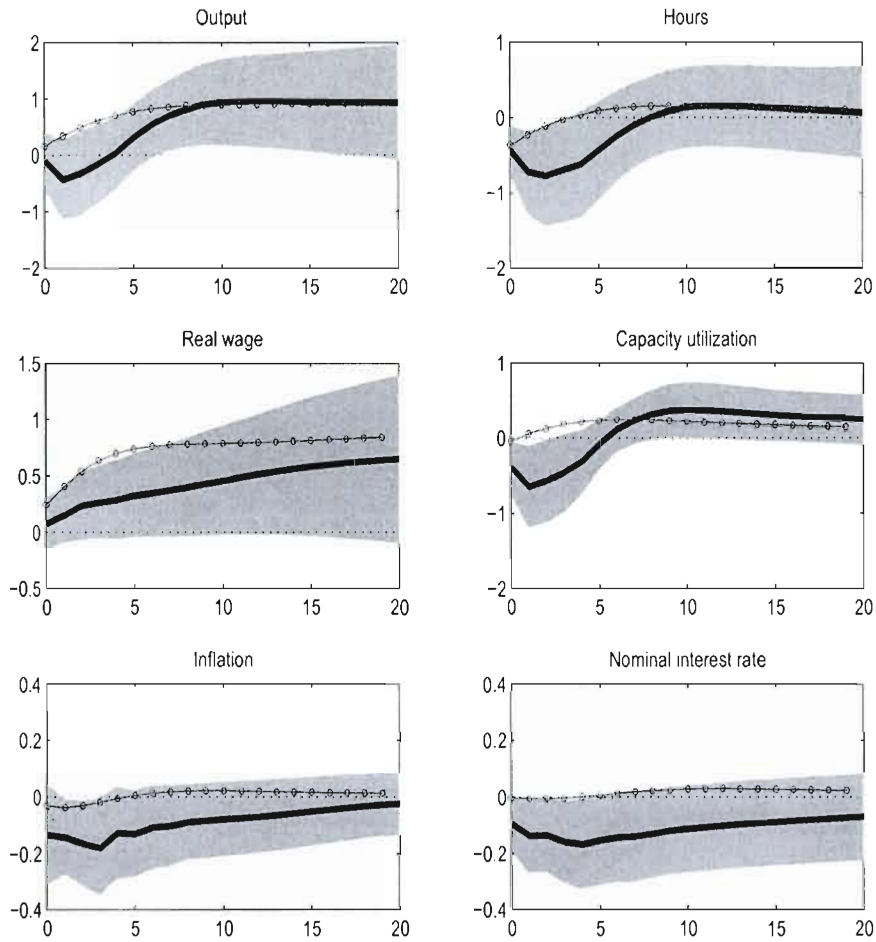
Finally, our simulations suggest that the effects of a technology shock on employment over time could not be explained by a change in the monetary regime but rather by a change in the size of the technology shock.

Figure 1.1: Var-Based Impulse Responses to a Technology Shock: 1950:I-2001:IV



Note: Dashed lines: 95% confidence interval.

Figure 1.2: Model-Based *vs* Empirical Impulse Responses to a Technology Shock



Note: Data: solid bold line. Model: line with circles. Dashed lines: 95% confidence interval.

Figure 1.3: Impulse Responses to an Expansionary Monetary Policy Shock

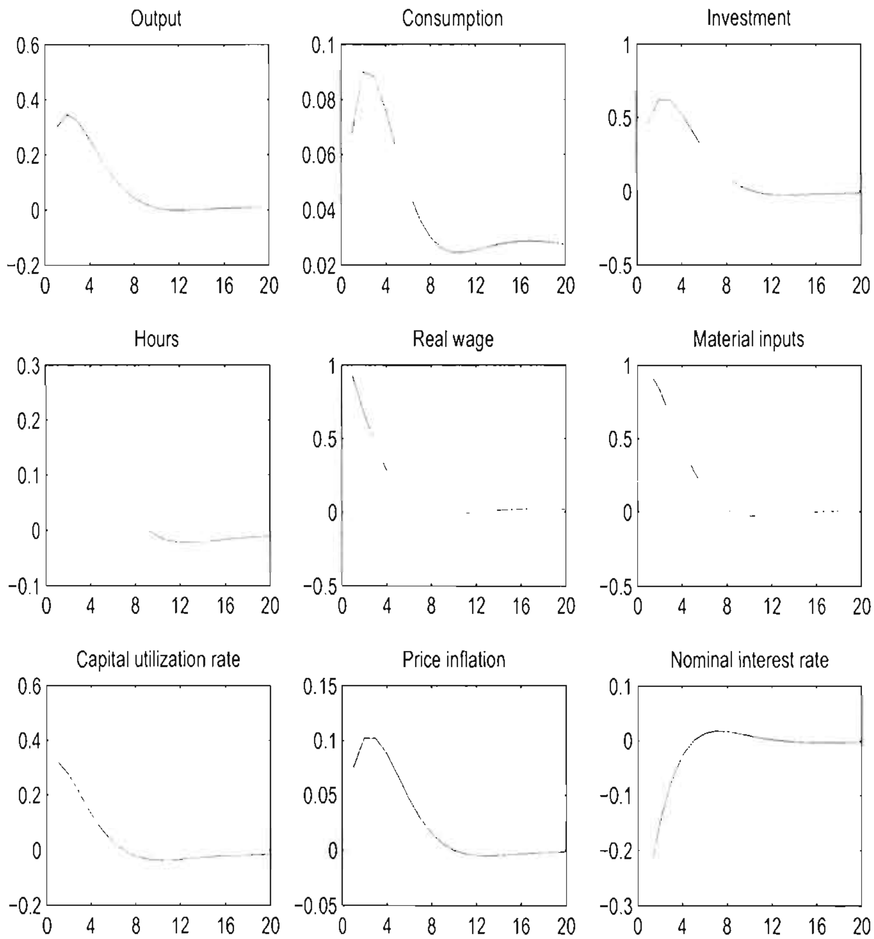
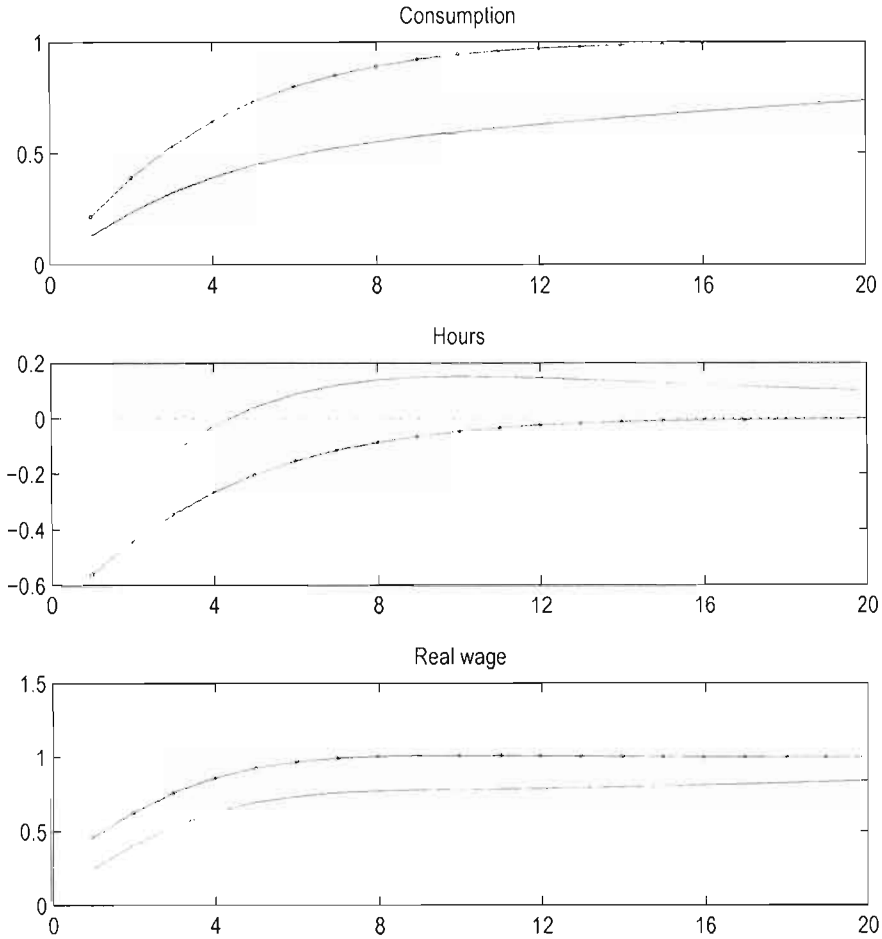
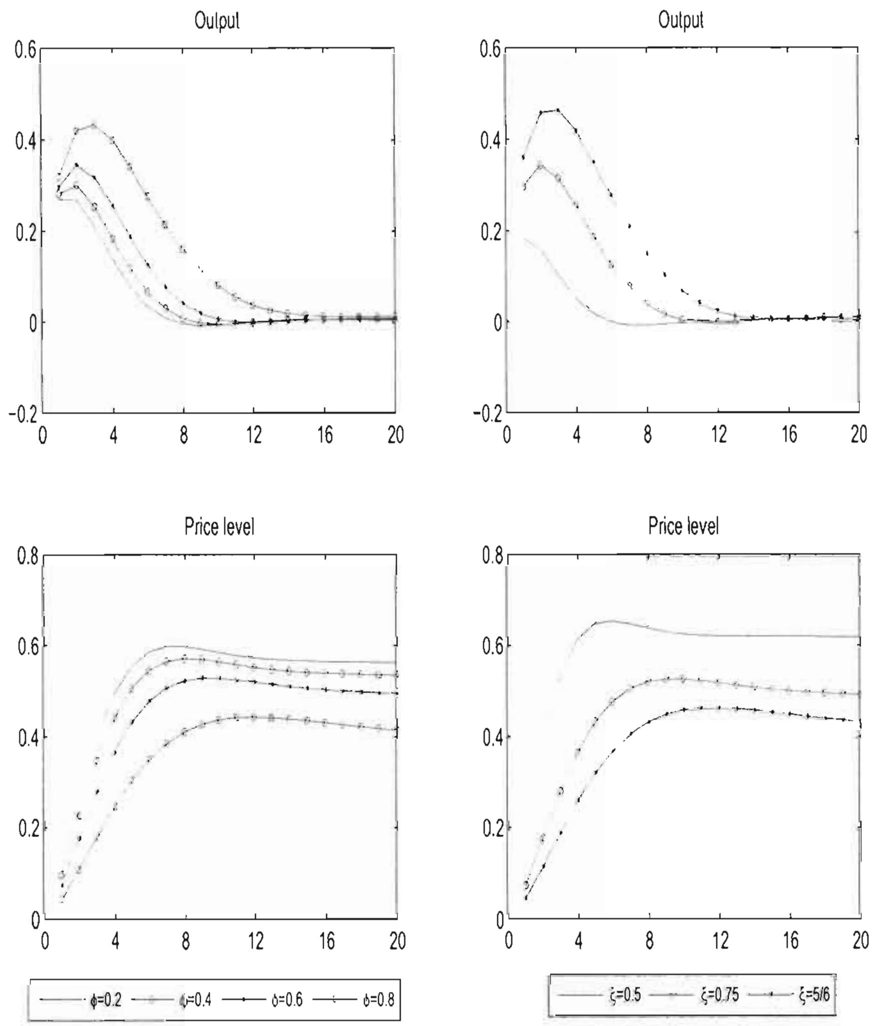


Figure 1.4: Role of Capital Accumulation



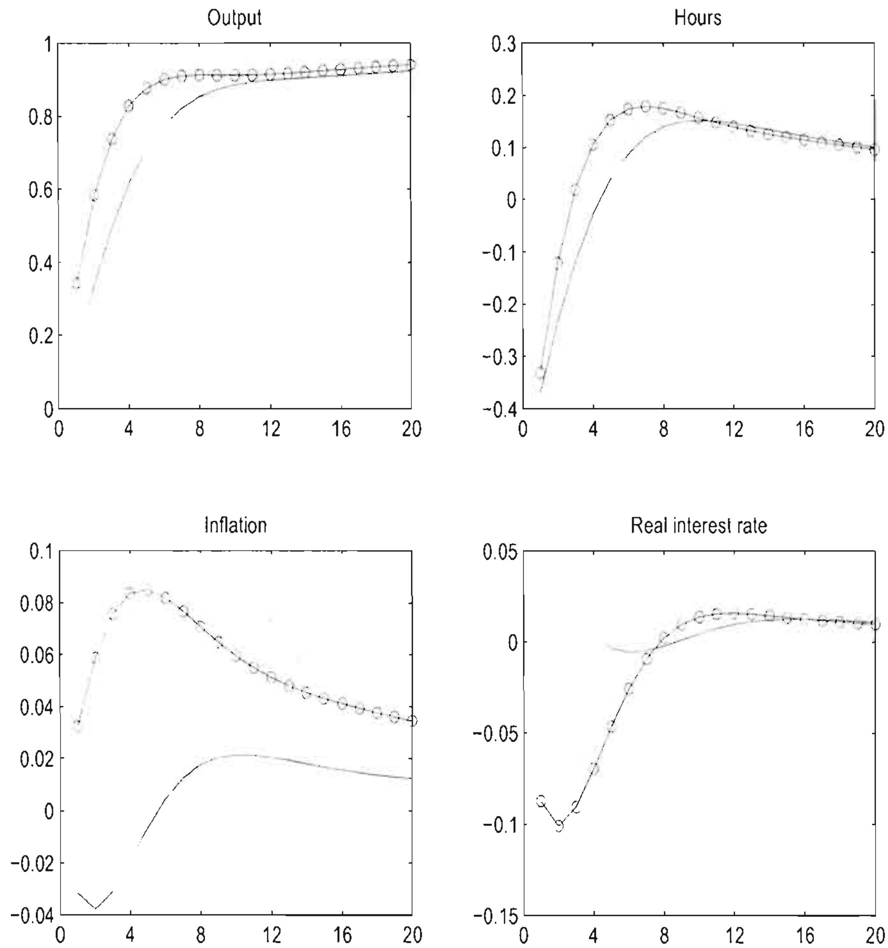
Note: Benchmark model: solid line. Model without capital: line with circles.

Figure 1.5: Interaction Between Price Rigidity and Intermediate Inputs



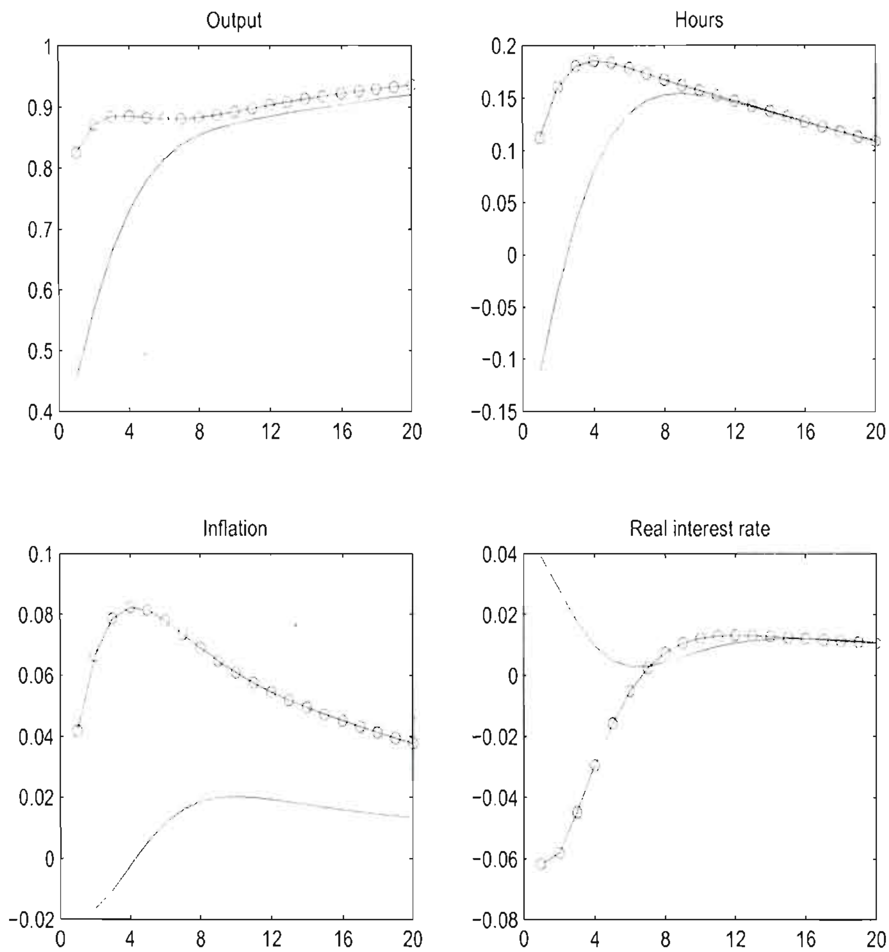
Note: The first column shows the sensitivity to a change in ϕ. The second column shows the sensitivity to a change in ξ.

Figure 1.6: Output-Growth *vs* Output-Level Rule



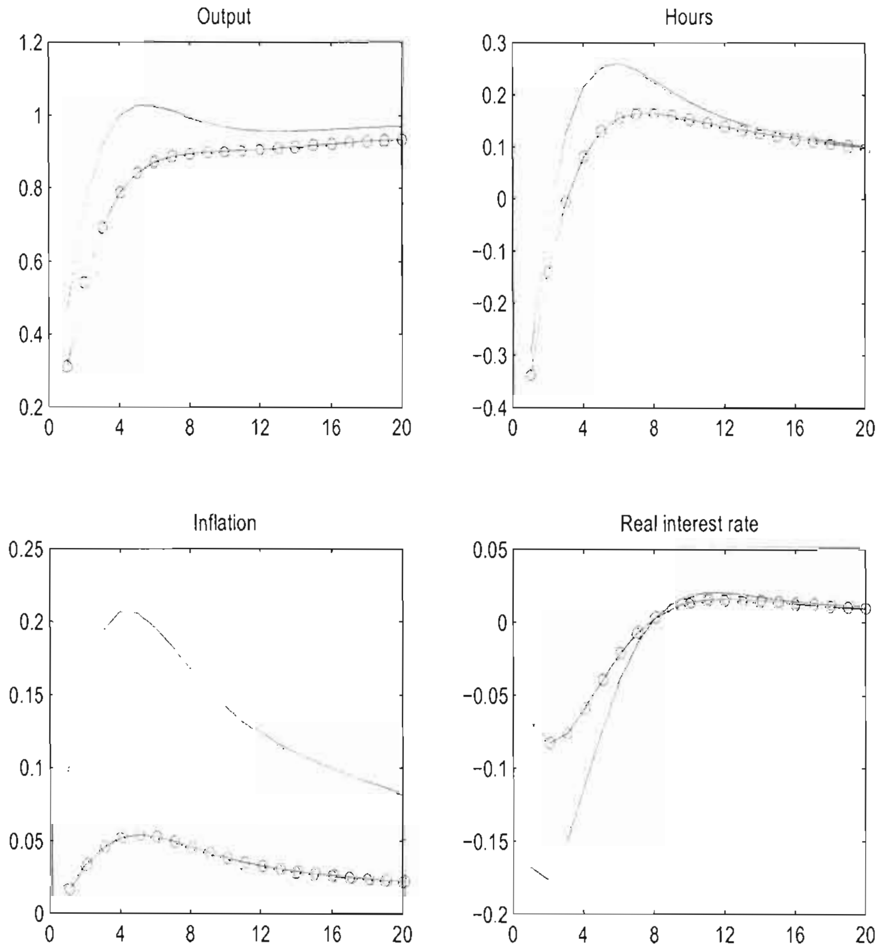
Note: Benchmark model: solid line. Model with the output-level rule: line with circles.

Figure 1.7: Output-Growth *vs* Output-Level Rule: with $b = 0$



Note: Benchmark model: solid line. Model with the output-level rule: line with circles.

Figure 1.8: Effects of a Change in the Monetary Policy Regime



Note: Impulse responses with $\rho_\pi = 1$: solid line. Impulse responses with $\rho_\pi = 2$: line with circles.

Chapter 2

An Estimated Model of U.S. Postwar Business Cycle Dynamics

2.1 Introduction

Postwar U.S. business cycles are characterized by the following salient features (see the evidence with log-differenced data presented in Table 2.2): i) real consumption is only half as volatile as output, ii) real investment is twice as volatile as output, iii) hours worked and labor productivity are 30 percent less volatile than output, iv) the volatility of real wages is about half the volatility of output, v) inflation is 40 percent less volatile than output, vi) consumption, investment, hours and productivity are all quite procyclical, vii) labor productivity is almost uncorrelated with hours worked, viii) inflation is mildly countercyclical, ix) output, consumption, investment, and hours worked all are positively, serially correlated at relatively short horizons and x) real wage growth exhibits almost no persistence.

In this chapter we develop and estimate DSGE models that shed new light on the comprehensive set of business-cycle statistics described above.

Our framework features monopolistic competition in both the goods market and the labor market (e.g., Blanchard and Kiyotaki, 1987). It embeds the following key ingredients. First, the economy is subject to two types of shocks: a permanent technology shock and a shock to the Taylor rule or monetary policy shock. Second, nominal wages across households that are imperfectly competitive in their labor skills are set by staggered contracts. Third, investment is costly to adjust. Fourth, the model features temporal nonseparabilities in preferences, i.e., habit formation both for consumption and leisure. Fifth, the production technology includes a labor externality in a way suggested by Baxter and King (1991).

The structural parameters of our models are estimated using a maximum likelihood procedure (e.g., Ireland, 2001, 2003). Our sample of data runs from 1959:I to 2006:II. Our main findings can be summarized as follows. Wage contracts last between 3 and 4 quarters on average. Consumption habit in the baseline model is mild compared to other estimates in the literature. Taking into account the two habits, the evidence shows that habit formation in leisure choice is mild, and the degree of the consumption habit is mostly unaffected by the presence of leisure habit. The estimates of investment adjustment costs compare well with those of others (e.g., Christiano et al., 2005). The externality parameter is much smaller according to our baseline model than that found in other studies (e.g., Wen, 1998). It implies a degree of increasing returns to scale which is relatively small and similar to the value preferred by Baxter and King (1991). It is also in the range of the parameter values obtained by Cooper and Johri (1997) with plant-level data.

Next, the baseline model broadly reproduces the size of relative fluctuations for several aggregate variables. The model not only predicts that investment is much more volatile than output, while consumption and hours are somewhat less volatile than output, but it also predicts that the volatility of real wages, productivity and inflation relative to the volatility of output are in broad agreement with the data.

The model is able to reproduce some critical comovements. It correctly predicts that the correlation between the growth rates of hours and productivity is weak and positive.

The model also generates plausible business-cycle dynamics, revealing the strength of its endogenous propagation mechanisms. Our evidence suggests that the growth rates of output, consumption, investment and hours all exhibit a positive serial correlation that broadly resembles the persistence observed in the data. At the same time, the model correctly predicts that there is little persistence in real wage growth.

Our sensitivity analysis shows first that wage contracts allow monetary policy shocks to affect the real side of the economy and help generate the typical hump-shaped impulse responses in several real variables. They also magnify the effects of technology shocks on output, consumption, investment and hours. Without the wage contracts, output volatility would be too low and the model would not generate plausible business-cycle dynamics.

Second, habit formation for consumption considerably dampens the initial response of output, consumption and hours following technology and policy shocks, making several variables respond in a hump-shaped fashion. Investment adjustment costs help avoid excessively large fluctuations in investment, output and hours. The employment externality magnifies the effects of policy and technology shocks on consumption, investment, hours and output. Without the externality, output fluctuations are too small. Furthermore, the externality has a significant impact on the response of real wages following a policy shock: a positive policy shock induces a slight decrease in real wages initially, which is then followed by a rise in real wages during several periods as the evidence suggests. Without the externality, the response of real wages is quite countercyclical following a policy shock. Also, the correlation between hours and productivity is significantly negative.

The remainder of the chapter is as follows. Section 2.2 provides a description of the model. Section 2.3 discusses the estimation procedure. Section 2.4 presents and analyses our main findings. Section 2.5 provides concluding remarks.

2.2 The Model

We assume an economy populated by a large number of members of a representative household, each endowed with a differentiated labor skill indexed by $i \in [0, 1]$; and a large number of firms, each producing a differentiated good indexed by $j \in [0, 1]$. There is also a monetary authority that sets the nominal interest rate according to a Taylor rule.

2.2.1 The Household

Denote by H_t a composite skill which is related to the differentiated labor skills $\{H_{i,t}\}_{[0,1]}$ by

$$H_t = \left[\int_0^1 H_{i,t}^{(\theta_w - 1)/\theta_w} di\right]^{\theta_w/(\theta_w - 1)}, \tag{2.1}$$

where $\theta_w \in (1, \infty)$ is the elasticity of substitution between skills. The composite skill is produced in an aggregation sector that is perfectly competitive. The demand function for labor skill i resulting from the optimizing behavior in the aggregation sector is given by

$$H_{i,t} = \left(\frac{W_{i,t}}{W_t}\right)^{-\theta_w} H_t, \tag{2.2}$$

where the wage rate W_t of the composite skill is related to the wage rates $\{W_{i,t}\}_{i\in[0,1]}$ of the differentiated skills by

$$W_t = \left[\int_0^1 W_{i,t}^{1-\theta_w} di\right]^{1/(1-\theta_w)}. \tag{2.3}$$

The household has a utility function,

$$E\sum_{t=0}^{\infty}\beta^t \left[\ln(C_t - bC_{t-1}) - \left(\int_0^1 \frac{\chi}{1+\eta}(H_{i,t} - hH_{i,t-1})^{1+\eta} di\right)\right]. \tag{2.4}$$

where E is the expectations operator, $\beta \in (0,1)$ is a subjective discount factor, C_t denotes real consumption, $H_{i,t}$ represents hours worked, $b > 0$ measures the relative importance of habit formation for consumption, and $h > 0$ measures the relative importance of habit formation in leisure choice.

A recent strand of the literature has stressed habit formation for consumption.[1] Hence, we call *baseline model* one that features only the consumption habit. In the baseline model, η denotes the inverse of the intertemporal elasticity of labor hours.

We also estimate the version of the model with both types of habit, and refer to it as the *double-habit (DH) model.*

The household faces the following budget constraint:

$$P_tC_t + P_tI_t + \frac{B_t}{R_t} \leq B_{t-1} + \int_0^1 W_{i,t}H_{i,t}di + R_t^k P_t K_t + D_t. \tag{2.5}$$

The household enters period t with bond holdings B_{t-1} and rents K_t units of capital at the real rental rate R_t^k to the intermediate-good firms. Each member of the household supplies $H_{i,t}$ at the nominal wage rate $W_{i,t}$. At the end of period t, the household receives nominal dividends D_t from the firms. The household purchases B_t units of

[1]See, for example, Beaudry and Guay (1996), Jermann (1998), Fuhrer (2000), Boldrin, Christiano and Fisher (2001), Christiano et al. (2005), Francis and Ramey (2005a), Bouakez et al. (2005), and Liu and Phaneuf (2007).

bonds. C_t units of the aggregate of consumption good. and I_t units of the aggregate investment good. at the nominal price P_t from the finished-good firm. R_t denotes the gross nominal interest rate between periods t and $t+1$. The household is prevented from running Ponzi schemes by imposing the borrowing constraint: $B_t \geq -B$. where B is a large positive number. The stock of physical capital, K_t, evolves according to:

$$K_{t+1} = (1-\delta)K_t + (1 - S(I_t/I_{t-1}))I_t, \tag{2.6}$$

where δ is the depreciation rate. The second term on the right-hand side of (2.6) summarizes the technology that transforms current and past investment into installed capital for use in the following period. It also embodies investment adjustment costs. The function $S(.)$ is positive and convex. and satisfies $S(a) = S'(a) = 0$. a being a parameter to be defined later. Investment adjustment costs allow Tobin's Q to vary in response to technology and policy shocks.

The household seeks to maximize the utility function (2.4) subject to the budget constraint (2.5), capital accumulation (2.6) and the demand schedule for skill i (2.2).[2] The first order conditions for consumption. marginal Tobin's Q, and investment are respectively given by:

$$\Lambda_t = \left(\frac{1}{C_t - bC_{t-1}}\right) - \beta b E_t \left(\frac{1}{C_{t+1} - bC_t}\right). \tag{2.7a}$$

$$Q_t = \beta E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t}\left(R^k_{t+1} + (1-\delta)Q_{t+1}\right)\right], \tag{2.7b}$$

$$Q_t = \frac{1 - \beta E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t} Q_{t+1} S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2\right]}{\left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\left(\frac{I_t}{I_{t-1}}\right)\right]}, \tag{2.7c}$$

where $\Lambda_t = P_t \nu_t$. ν_t denotes the Lagrange multiplier attached to the budget constraint. Equation (2.7a) states that Λ_t equals the marginal utility of consumption in period t. The Euler equation for capital (2.7b) says that the shadow price of installed capital. measured by marginal Tobin's Q. equals the sum of the expected future value of Q net of depreciation and of the expected future return on capital. Equation (2.7c),

[2] I assume complete financial markets. which implies that members are identical with respect to consumption, bond holdings and capital stock. Heterogeneity among members is only produced by the staggered wage contracts. This allows us to drop the subscript i for consumption. bonds and capital.

which determines the optimal level of investment, implies that investment increases with Q. Because of consumption habit and investment adjustment costs, the household's optimality conditions are dynamic.

We assume that the household's members set nominal wages through staggered contracts in the spirit of Calvo (1983). In each period, the probability of nominal wage readjustment is $1 - d_w$. In a symmetric equilibrium, all reoptimizing household's members choose the same relative wage in period t. It is given by:

$$w_t^* = \mu_w \frac{E_t \sum_{\tau=0}^{\infty} (\beta d_w)^{\tau} \left[(W_{t+\tau}/W_t)^{\theta_w} MRS_{i,t+\tau} H_{t+\tau} \right]}{E_t \sum_{\tau=0}^{\infty} (\beta d_w)^{\tau} \left[(W_{t+\tau}/W_t)^{\theta_w - 1} (W_{t+\tau}/P_{t+\tau}) H_{t+\tau} \right]}. \tag{2.8}$$

where $w_t^* = W_t^*/W_t$, $\mu_w = \frac{\theta_w}{\theta_w - 1}$ denotes the steady-state wage markup. $MRS_{i,t}$ is the marginal rate of substitution between consumption and leisure of the member i. The optimal wage is thus a constant markup over a weigthed average of the individual MRS in the current and future periods during which the wage set today is expected to remain in effect. The aggregate wage in equation (2.3) can be expressed by the following recursive equation:

$$W_t^{1-\theta_w} = (1 - d_w) W_t^{*1-\theta_w} + d_w W_{t-1}^{1-\theta_w}. \tag{2.9}$$

2.2.2 The Firms

The representative finished good-producing firm acts competitively in the finished good market, producing a composite finished good Y_t which is related to the differentiated intermediate goods $\{Y_{j,t}\}_{j\in[0,1]}$ through the Dixit-Stiglitz CES aggregator:

$$Y_t \leq \left[\int_0^1 Y_{j,t}^{(\theta_p - 1)/\theta_p} dj \right]^{\theta_p/(\theta_p - 1)}, \tag{2.10}$$

where $\theta_p \in (1, \infty)$ is the elasticity of substitution between differentiated goods. The finished good-producing firm purchases $Y_{j,t}$ at the nominal price $P_{j,t}$. The first order condition corresponding to the finished good-producing firm's optimization problem is:

$$Y_{j,t} = \left(\frac{P_{j,t}}{P_t} \right)^{-\theta_p} Y_t. \tag{2.11}$$

With zero profits, the price of the composite good P_t is related to the prices $\{P_{j,t}\}_{j\in[0,1]}$ of the differentiated goods by :

$$P_t = \left[\int_0^1 P_{j,t}^{1-\theta_p} dj \right]^{1/(1-\theta_p)}. \tag{2.12}$$

Each intermediate good-producing firm j produces an output $Y_{j,t}$ using the following technology:

$$Y_{j,t} = \begin{cases} K_{j,t}^{\alpha}(A_t H_{j,t})^{1-\alpha} H_t^{\epsilon} - A_t \Phi & \text{if} \quad K_{j,t}^{\alpha}(A_t H_{j,t})^{1-\alpha} H_t^{\epsilon} \geq A_t \Phi \\ 0 & \text{otherwise,} \end{cases} \tag{2.13}$$

where $K_{j,t}$ is the stock of physical capital of the j^{th} firm, $H_{j,t}$ denotes the hours worked employed by firm j, the composite skill H_t represents an employment externality, and $\Phi > 0$ is a fixed cost common to all intermediate-good producing firms.[3] The exponent ϵ controls the size of the external effect. The labor augmenting technological progress A_t evolves according to the following nonstationary process:

$$ln(A_t) = ln(a) + ln(A_{t-1}) + \varepsilon_{a,t}, \tag{2.14}$$

where $\varepsilon_{a,t}$ is a zero-mean, serially uncorrelated, and normally distributed random shock with standard deviation σ_a. Capital and labor inputs are both produced in competitive markets. In each period, the representative firm's cost-minimization implies the following first order conditions:

$$(1-\alpha)\left(\frac{Y_{j,t} + A_t\Phi}{H_{j,t}}\right) MC_t = \frac{W_t}{P_t}, \tag{2.15a}$$

$$\alpha\left(\frac{Y_{j,t} + A_t\Phi}{K_{j,t}}\right) MC_t = R_t^k, \tag{2.15b}$$

where MC_t denotes the economy-wide real marginal cost.

In a symmetric equilibrium, all firms in period t choose the same optimal nominal price P_t^*, which is equal to the product of the markup $\mu_p = \frac{\theta_p}{\theta_p - 1}$ and the aggregate nominal marginal cost

2.2.3 The Monetary Policy

The monetary authority sets the short-run nominal interest rate according to the following Taylor-type rule:

$$\ln(R_t/R) = \rho_r \ln(R_{t-1}/R) + (1-\rho_r)\left[\rho_\pi \ln(\pi_t/\pi) + \rho_y \ln(g_{yt}/g_y)\right] + \varepsilon_{m,t}, \tag{2.16}$$

[3] Introducing a fixed cost allows firms to earn zero profits in the steady state. Rotemberg and Woodford (1995) argued that the average pure profits in the U.S. economy are close to zero.

where $g_{yt} \equiv Y_t/Y_{t-1}$ is the growth rate of output, $\pi_t \equiv P_t/P_{t-1}$ is the inflation rate; R, π, and g_y are the steady-state values of the nominal interest rate, the inflation rate and the growth rate of output, respectively, and $\varepsilon_{m,t}$ is a zero-mean, serially uncorrelated, and normally distributed random shock with standard deviation σ_m. The monetary rule (2.16) recognizes the Federal Reserve's practice of smoothing changes in interest rates. The parameters ρ_π and ρ_y determine the extent of monetary policy accommodation.

2.2.4 Market-Clearing

We define the alternative price index and the alternative wage index as (see also Yun, 1996):

$$\bar{P}_t = \left[\int_0^1 P_{j,t}^{-\theta_p} dj\right]^{-1/\theta_p}, \qquad \bar{W}_t = \left[\int_0^1 W_{i,t}^{-\theta_w} di\right]^{-1/\theta_w}.$$

The aggregate resource constraint of the economy can therefore be written as:

$$\left(\frac{\bar{P}_t}{P_t}\right)^{\theta_p} \left(\frac{\bar{W}_t}{W_t}\right)^{(1-\alpha+\epsilon)\theta_w} [K_t^\alpha A_t^{1-\alpha} \bar{H}_t{}^{1-\alpha+\epsilon}] - A_t\Phi = C_t + I_t. \tag{2.17}$$

where $\bar{H}_t = \int_0^1 H_{i,t} di$ corresponds to total labor as measured in the data (see the appendix in Christiano et al., 2001) and $K_t = \int_0^1 K_{j,t} dj$ Since technology is nonstationary, all real variables, except hours worked, must be scaled by the level of technology to obtain stationarity.

2.3 Model Estimation

2.3.1 Econometric Procedure

We take a log-linear approximation of the model's equilibrium conditions around the deterministic steady state. The resulting system of linear difference equations is solved using the method described in Klein (2000). The system can be written in its state-space representation as:

$$x_{t+1} = \Psi_1 x_t + \Psi_2 \varepsilon_{t+1} \tag{2.18}$$

$$z_t = \Psi_3 x_t$$

where x_t is a vector of unobservable state variables, ε_{t+1} is a vector that includes the two disturbances $\varepsilon_{a,t}$, and $\varepsilon_{m,t}$, and z_t is a vector of observable variables. The elements of matrices Ψ_1, Ψ_2, and Ψ_3 depend on the deep parameters of the model. We estimate the system using a maximum likelihood procedure and time series on five variables that compose z_t: per capita consumption growth, per capita investment growth, per capita hours, the rate of change of nominal wages and the nominal interest rate.

As the number of variables included in the estimation exceeds the number of structural disturbances, additional shocks are introduced in the form of measurement errors to avoid the stochastic singularity problem discussed in Ingram, Kocherlakota and Savin (1994). Hence, (2.18) is replaced by the following innovations representation:

$$
\begin{aligned}
x_{t+1} &= \Psi_1 x_t + \Psi_2 \varepsilon_{t+1} \\
z_t &= \Psi_3 x_t + \xi_t \\
E(\xi_{t+1}\xi'_{s+1}) &= \begin{cases} R & \text{for} \quad t = s \\ 0 & \text{otherwise} \end{cases}
\end{aligned}
\tag{2.19}
$$

where $\xi_t = [\xi_{c,t}, \xi_{i,t}, \xi_{h,t}, \xi_{w,t}, \xi_{r,t}]'$ is vector of zero-mean and normally distributed measurement errors. The matrix R is diagonal and its diagonal elements are denoted by r_{ii}, for $i = 1, 2, 3, 4, 5$; hence, r_{11} is associated with the measurement error in the growth rate of consumption, etc. Since the vector z_t is composed of five variables and that our model comprises two structural shocks, we add measurement errors in the investment growth rate, hours worked, and the nominal wages growth rate. The Gaussian log likelihood function $L(\Upsilon)$, for the sample $\{z_t\}_{t=1}^T$, is constructed recursively using the Kalman filter (e.g., Hamilton, 1994, ch.13): Υ is the vector of parameters that we seek to estimate, and T is the number of observations. The likelihood function can be written (ignoring the constant term) as:

$$
L(\Upsilon) = -\frac{1}{2}\sum_{t=1}^{T} \ln|\Omega_t| - \frac{1}{2}\sum_{t=1}^{T} u'_t \Omega_t^{-1} u_t \tag{2.20}
$$

where $u_t = z_t - \hat{E}(z_t | z_{t-1}, z_{t-2}, \ldots z_1)$, $E(u_t u'_t) = \Omega_t$ and $\hat{E}(.)$ denotes the linear projection operator.

2.3.2 Calibration

It is not possible to estimate all the structural parameters of our models, so that some parameters must be calibrated prior to the estimation. The value assigned to δ, the quarterly rate of depreciation of physical capital, is 0.025, implying an annualized rate of 10%. The share of physical capital α in the production function is 0.36. The steady-state gross growth rate of technological progress a and the steady-state nominal interest rate R are chosen so as to match the data in our sample. These values imply $\beta = 0.9909$. The parameter χ associated with the disutility of work ensures that the steady-state fraction of time devoted to market work is 0.30. The elasticity of substitution between differentiated goods θ_p is 10, so that the price markup is 11 percent. The elasticity of substitution between differentiated skills θ_w is 5, which is consistent with the micro evidence in Griffin (1996) and the macro evidence produced by Ambler, Guay and Phaneuf (2007).

2.3.3 Data

Our sample of data runs from 1959:I to 2006:II. The variables used to estimate the structural parameters of our models are defined as follows. Consumption is measured by per capita real personal consumption expenditures on nondurable goods and services. Investment is the sum of per capita personal consumption expenditures on durable goods and per capita private fixed investment. Total hours are measured by per capita hours in the nonfarm business sector. The nominal wage is the hourly compensation in the nonfarm business sector. The nominal interest rate is the three-month Treasury bills rate. The per capita variables are obtained after dividing the series by the civilian noninstitutional population, age 16 and over.[4]

[4] All data are taken from the Haver Database.

2.4 Estimation Results

2.4.1 Maximum Likelihood Estimates (Baseline Model)

In the baseline model, the set of structural parameters that we seek to estimate is

$$\left\{d_w,\ b,\ 1/\psi,\ S''(a),\ \epsilon,\ \rho_r,\ \rho_\pi,\ \rho_g,\ \sigma_a,\ \sigma_m\right\}.$$

while in the DH model it is,

$$\left\{d_w,\ b,\ h,\ 1/\psi,\ S''(a),\ \epsilon,\ \rho_r,\ \rho_\pi,\ \rho_g,\ \sigma_a,\ \sigma_m\right\}.$$

Table 2.1 reports the point estimates of the structural parameters of the models with their respective standard deviations.

We first consider the estimates of the baseline model. The point estimate of d_w, the probability of wage non-adjustment is 0.7468, implying that the wage contracts last 3.94 periods on average. This estimate is consistent with the empirical evidence covered by Taylor (1999) in his survey on the duration of nominal wage and price contracts. Our point estimate of the consumption-habit parameter b is 0.4774, which is much lower than the habit coefficients reported in Fuhrer (2000) (0.8), Boldrin et al. (2001) (0.7), Christiano et al. (2005) (0.65), and Bouakez et al. (2005) (0.98); however, it is significantly higher than the estimate in Ireland (2006) (0.25). The point estimate of the intertemporal Frisch elasticity of labor supply $1/\psi$ is 1.1287, which is close to the elasticity in Mulligan (1998). The curvature parameter $S''(a)$ determining the size of investment adjustment costs is 1.6091, and lies in the range of estimates found by Christiano et al. (2005) (0.91 to 3.24). The point estimate of ϵ is 0.2687, which is much smaller than the externality reported in Wen (1998) (0.45 and 0.5). Interestingly, our estimate is very close to Baxter and King's (1991) preferred value which is 0.23, based on the evidence presented in Caballero and Lyons (1989). It is also in line with the evidence produced by Cooper and Johri (1997) using plant-level data. Our point estimate of ρ_π the response of monetary policy to deviations of inflation from its steady-state value is 1.2485; this estimate is somewhat smaller than the value estimated by Taylor (1993) which is 1.5.[5] The point estimate of ρ_g the policy-response to deviations of actual

[5] However, Taylor's sample is shorter.

output growth from its steady-state value is 0.0725. The smoothness parameter ρ_r is 0.703, consistent with the evidence presented in Clarida, Gali and Gertler (2000).

2.4.2 Fluctuations and Comovements

Does the baseline model explain the main characteristics of postwar business cycles? To answer this question, we look at some volatility statistics and comovements. They are presented in Table 2.2 for moments of the log-differenced data.[6]

Panel A of Table 2.2 reports the volatility statistics for consumption, investment, hours worked, productivity, real wages and prices relative to the volatility of output, $\sigma_{\Delta x}/\sigma_{\Delta y}$ measuring the standard deviation of the first-differenced logarithm of variable x to the standard deviation of the first-differenced logarithm of output. Output is measured by real output in the nonfarm business sector and prices, by the implicit price deflator in the nonfarm business sector.

Overall, the baseline model does an adequate job in capturing the relative movements in the aggregate variables. For example, the model generates the right amount of fluctuations in hours worked relative to fluctuations in output. It also correctly predicts that real wages and productivity are significantly less volatile than output. Note that the model accounts well for the ratio of the volatility of inflation to the volatility of output growth.

Panel B of Table 2.2 reports the comovements. The baseline model broadly reproduces the main correlations, even though most comovements between the real variables are somewhat higher according to the model. Among others, the model generates the right correlations between the growth rates of hours and output, the growth rates of productivity and output, and the growth rates of productivity and hours. This result is interesting in itself considering that a large class of business cycle models has failed to explain these three comovements simultaneously (e.g., Hansen, 1985; Hansen and Wright, 1992).

Among the comovements studied in the business cycle literature, the correlation between hours and productivity has aroused a considerable interest following the work

[6] I have also generated results with the HP-filtered data. The conclusions are quite similar to those reached with the log-differenced data so that we do not report the results with HP-filtered data.

of Christiano and Eichenbaum (1992). These authors argue that standard, technology-driven RBC models assuredly predict a strong positive correlation between hours worked and return to working since the time series on productivity and hours are modeled as the intersection of a stochastic labor-demand curve with a fixed labor-supply curve. They suggest adding measurable economic impulses that shift the labor-supply curve in order to reduce this correlation. Working with a model featuring nonconvexities in labor supply of the type proposed by Hansen (1985) and Rogerson (1988), they allow government consumption shocks to affect labor-market dynamics. They obtain a correlation of 0.575 under the assumptions that an increase in government consumption is financed by lump sum taxes and that government consumption acts as a pure resource drain on the economy.[7]

Now, the main suspicion regarding sticky-wage models is that they predict a negative correlation between return to working (or real wages) and hours worked, as the time series for these variables lie on a stable, downward-sloped marginal productivity-of-labor curve (e.g. Sargent, 1987; McCallum, 1989). Yet, our baseline model with sticky nominal wages predicts a weak positive correlation between productivity and hours worked of about 0.21, while the actual correlation is 0.01. As we discuss below, the employment externality plays a significant role in shaping this correlation. The model also predicts a correlation between inflation and output growth which is close to the actual one.

2.4.3 Business-Cycle Persistence

The baseline model also has important dynamic properties. In recent years, a major area of research in the business cycle literature has been motivated by the lack of endogenous propagation that seems to plague a wide class of DSGE models. King et al. (1988) have shown that the basic neoclassical growth model driven by a permanent technology shock generates near-zero autocorrelations of output growth at various horizons and weak negative autocorrelations in the growth rates of investment and hours,

[7] They use HP-filtered data instead of log-differenced data as we do. A similar approach is followed by Braun (1994) and McGrattan (1994) who also incorporate stochastic tax rates in an otherwise standard RBC model.

far from the positive autocorrelations that are observed in reality. More recently, Cogley and Nason (1995) have shown that the failure to produce plausible output dynamics seems to extend to a large variety of business cycle models.

Figure 2.1 displays the autocorrelation functions for the growth rates of output, consumption, investment, hours and real wages. The estimated baseline model generates plausible patterns of positive serial correlation in the first four variables. Note in particular that the model produces substantial persistence in the growth rates of investment and hours worked. Also, the baseline model correctly predicts that real wage growth exhibits almost no persistence.[8]

2.4.4 Impulse-Response Functions

The impulse response functions of the baseline model to a one-standard-deviation technology shock and to a one-standard-deviation policy shock are presented in Figure 2.2a and Figure 2.2b, respectively. Figure 2.2a displays the impulse responses of output, consumption, investment, hours worked, labor productivity, the real wages, the nominal interest rate and the rate of inflation to a positive technology shock. Investment and, to a lesser extent, output respond in an hump-shaped fashion to a technology improvement, before reaching their new, higher steady-state levels. The response of hours to a positive technology shock is positive, persistent and hump-shaped. Note, however, that the initial rise in hours is quite small, with an increase of only 0.2 percent on impact. The response of hours in the baseline model is broadly consistent with the structural vector autoregression (SVAR) evidence reported by Christiano, Eichenbaum and Vigfusson (2004) and Vigfusson (2004).

There is an ongoing debate about the employment effects of a technology shock. One side of the empirical literature suggests that a positive technology shock leads to a short-run fall in per capita hours. This evidence emerges from structural vector autore-

[8]Admittedly, the model does not account for inflation persistence if it is measured by the autocorrelation function for the inflation rate. Nelson (1998) shows that models with nominal rigidities are unable to generate high positive serial correlation in inflation unless one assumes implausibly long nominal price contracts. In light of recent evidence showing that price contracts appear to be quite short (e.g. Bils and Klenow, 2004; Altig et al. 2005), we believe it is not strongly implausible, as a first approximation, to assume price flexibility.

gression (SVAR) models where a technology shock is identified as the only shock that affects labor productivity in the long run (e.g., Gali, 1999; Francis and Ramey, 2005a, b). A similar result is also obtained with technology shocks measured by a "purified Solow residual" that controls for non-technological factors that may affect measured total factor productivity (e.g., Basu, Fernald, and Kimball, 2006).[9] Yet another line of research argues that a positive technology shock triggers a rise in per capita hours, even when technology shocks are identified using the same long-run restrictions as in Gali (1999) (e.g., Christiano, Eichenbaum and Vigfusson , 2004; Vigfusson, 2004)). The difference in conclusions arises from the different treatments of hours in the SVAR: whether hours rise or fall following a positive technology shock depends on whether hours enter the SVAR in log-levels or log-differences.

Our framework is not necessarily inconsistent with the fact that a technology improvement could eventually induce a short-run decline in hours. For example, Liu and Phaneuf (2007) find that sticky wages and habit formation in consumption may trigger a short-run fall in hours if consumption habit considerably dampens the responses of consumption and output following a positive technology shock. However, the model in Liu and Phaneuf (2007) is calibrated, and they assign a value of 0.8 to the habit parameter based on the evidence reported in Fuhrer (2000) and others. The estimated baseline model delivers a smaller estimate of the habit parameter of about 0.48, which tends to refrain the downward pressure on hours. Also, as we see below, the employment externality further boosts output and hours. These two factors explain why the baseline model predicts an initial response of hours which is both small and positive after a technology improvement, instead of a short-run decline as in Liu and Phaneuf (2007).

Figure 2.2b displays the impulse responses to a negative shock to the nominal interest rate. Following a positive policy shock, the nominal interest rate initially falls by 0.4 percent. Output rises on impact by 0.85 percent, reaches a maximum increase of 1.2 percent after three quarters and slowly returns to its pre-shock after twenty quarters or so. Investment also increases sharply following a positive policy shock, with an initial

[9] Basu et al. (2006) stress the fact that hours initially fall following a positive technology shock, but then rise during several quarters.

increase of 1.8 percent. The policy shock generates a typical hump-shaped pattern in the response of investment. The response of consumption, which is smaller, also exhibits a hump-shaped pattern. The response of hours is both significant and hump-shaped. Interestingly, productivity weakly rises. Note also that the response of real wages is nearly acyclical following the policy shock. This finding is consistent with the SVAR evidence reported by other researchers (e.g., Christiano et al., 1997, 2005). Thus, despite the presence of nominal wage contracts, the baseline model does not have the implication that productivity and real wages are strongly countercyclical in response to a policy shock.

2.4.5 The Role of Nominal and Real Frictions

We inspect our model's driving mechanisms by examining the role of the nominal and real frictions embedded in the baseline model. Figures 2.3a and 2.3b summarize the effects of technology and policy shocks if nominal wages are optimal in each period. The remaining parameters are fixed at their baseline values. With optimal wages adjusting in each period, the policy shock does not affect the real side of the economy as expected. But, our findings also suggest that the wage contracts greatly magnify the effects of technology shocks on output, consumption, investment and hours. Note that, without the wage contracts a technology improvement produces a short-run *decline* in hours worked since the consumption habit significantly dampens the responses of consumption and output, as Francis and Ramey (2005a) have suggested in a RBC context.

Figures 2.4a and 2.4b assess the role of the employment externality. Without the externality, the increases in output, consumption, investment and hours that result from a positive technology shock are much smaller, especially the rise in investment. The employment externality also has a strong impact on the real effects of a policy shock. In response to a positive policy shock, output reaches a maximum increase of 1.2 percent with the externality, while it is only 0.7 percent when the externality is excluded from the model. Productivity is also significantly affected. With the externality, productivity weakly rises. Without the externality, productivity persistently declines in response to the policy shock, and as a result, the correlation between hours and productivity is

-0.21 Thus, although the mixture of shocks certainly contributes to get the comovement between hours and productivity right, the employment externality remains helpful in producing a weak positive correlation by rendering productivity less countercyclical in response to policy shocks. The externality has a similar impact on real wages which are more or less acyclical following a policy shock, while they are strongly countercyclical without the externality.

Figures 2.5a and 2.5b examine the role of habit formation in consumption. Without consumption habit, output initially increases by almost 2 percent following a positive technology shock, compared to 1.2 percent when habit is present. Furthermore, there is no gradual rise in output towards its new, higher steady-state level when consumption habit is omitted. The maximum increase in consumption takes place immediately after the shock and is almost twice as large as in the baseline model. Without consumption habit, hours do not exhibit the typical hump-shaped pattern. Moreover, the initial rise in hours is close to 1 percent, rather than 0.2 percent with habit. Consumption habit has also a crucial role to play for the transmission of policy shocks. Without it, the policy shock does note generate a hump-shaped response in output, consumption and hours. Note that the increase in consumption resulting from a positive policy shock is quite strong without habit.

Finally, Figures 2.6a and 2.6b assess the contribution of investment adjustment costs in the baseline model. By imposing that the curvature parameter $S''(a)$ takes a value which is arbitrarily small, most variables become excessively volatile.

2.4.6 Consumption Habit vs Leisure Habit

There is in the literature some evidence of habit formation in leisure choice. Eichenbaum et al. (1987) offer evidence based on aggregate time series which reveals temporal complementarities in periods of leisure. Their approach exploits the Euler equations of a model where the representative agent has nontime-separable preferences for consumption and leisure. Bover (1991) also finds that periods of leisure are temporal complements using micro data. Wen (1998) estimates a technology-driven RBC model that features an employment externality and nontime-separable preferences for leisure, and also finds evidence of significant habit formation in leisure.

The DH model features habit formation for consumption and leisure. The estimates of the structural parameters of the DH model are presented in Table 2.1. Interestingly, the estimates are not too different from those reported for the baseline model. The point estimate of the leisure-habit parameter h is 0.5177. Consumption habit is almost unaffected by the presence of leisure habit, as the consumption-habit parameter is 0.4802. The estimated Calvo-probability of nominal wage non-adjustment is somewhat lower now at 0.7144. The employment-externality parameter is also lower, with a point estimate of 0.2265. In terms of business-cycle statistics, the predictions of the DH and baseline models are very similar (results not reported).

Figure 2.7a and 2.7b analyze the role of each type of habit in the estimated DH model. Clearly, habit formation in consumption is more important for our main findings than habit formation in leisure. Excluding leisure habit almost has no impact on the impulse-response functions of the DH model, while omitting consumption habit has a significant effect on several impulse responses.

2.5 Conclusion

This chapter has proposed and estimated a business cycle model that helps understand the salient features of postwar business cycles. These include the near-zero correlation between hours worked and return to working, and the positive serial correlation in the growth rates of output, consumption, investment and hours worked, and the near-zero serial correlation in real wage growth. The model thus meets the challenge of producing plausible business-cycle dynamics through its internal structure (endogenous business-cycle propagation).

Our findings lead us to conclude that a model featuring sticky nominal wages, a relatively small employment externality, mild consumption habit, and relatively modest investment adjustment costs does quite well in capturing the main characteristics of postwar business cycles. Each of these frictions plays a significant role in shaping the key aspects of the business cycle. Interestingly, wage contracts which are often seen as affecting mostly the transmission of monetary policy shocks, also have a significant impact on the effects of technology shocks.

Table 2.1: Maximum Likelihood Estimates

	Baseline model		DH model	
Parameter	Estimate	Standard Error	Estimate	Standard Error
b	0.4774	0.0373	0.4802	0.0223
h	-	-	0.5177	0.0252
$1/\psi$	1.1287	0.2987	1.0510	0.0054
$S''(a)$	1.6091	0.2073	1.6311	0.0570
ρ_r	0.7030	0.0227	0.6679	0.0245
ρ_π	1.2485	0.0387	1.0026	0.0048
ρ_g	0.0725	0.0411	0.1344	0.0456
d_w	0.7468	0.0104	0.7144	0.0535
ϵ	0.2687	0.0548	0.2265	0.0888
σ_a	0.0159	0.0011	0.0145	0.0013
σ_m	0.0051	0.0003	0.0043	0.0003

Table 2.2: Cyclical Properties of the Baseline Model (Log-differenced Data)

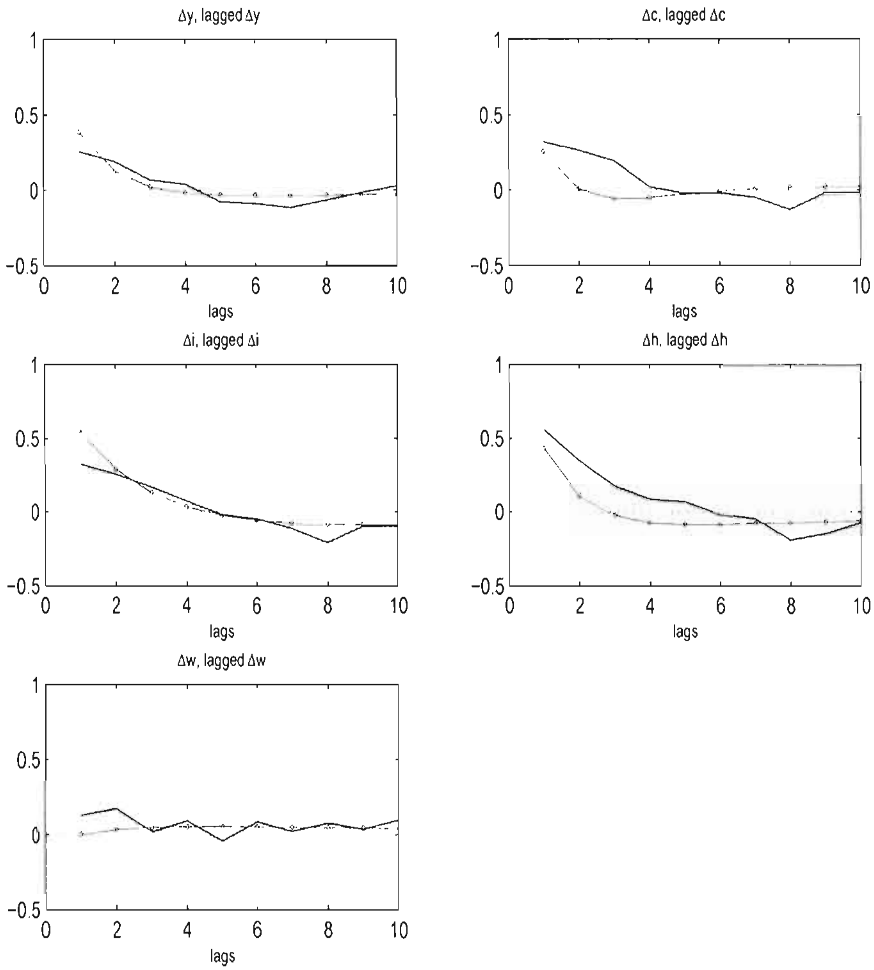
Panel A

Moments	data	Baseline model
$\sigma_{\Delta c}/\sigma_{\Delta y}$	0.5007	0.7403
$\sigma_{\Delta i}/\sigma_{\Delta y}$	1.9786	1.8013
$\sigma_{\Delta h}/\sigma_{\Delta y}$	0.6927	0.6779
$\sigma_{\Delta y/h}/\sigma_{\Delta y}$	0.7150	0.6041
$\sigma_{\Delta w/p}/\sigma_{\Delta y}$	0.5371	0.6308
$\sigma_{\Delta p}/\sigma_{\Delta y}$	0.5935	0.5729

Panel B

Moments	data	Baseline model
$corr(\Delta c, \Delta y)$	0.5303	0.9718
$corr(\Delta i, \Delta y)$	0.7384	0.9666
$corr(\Delta h, \Delta y)$	0.6991	0.8073
$corr(\Delta y/h, \Delta y)$	0.7212	0.7493
$corr(\Delta p, \Delta y)$	-0.3514	-0.3697
$corr(\Delta y/h, \Delta h)$	0.0089	0.2141

Figure 2.1: Autocorrelation Functions



Note: Data: solid line. Baseline model: line with circles.

Figure 2.2a: Impulse Responses to a Technology Shock: Baseline Model

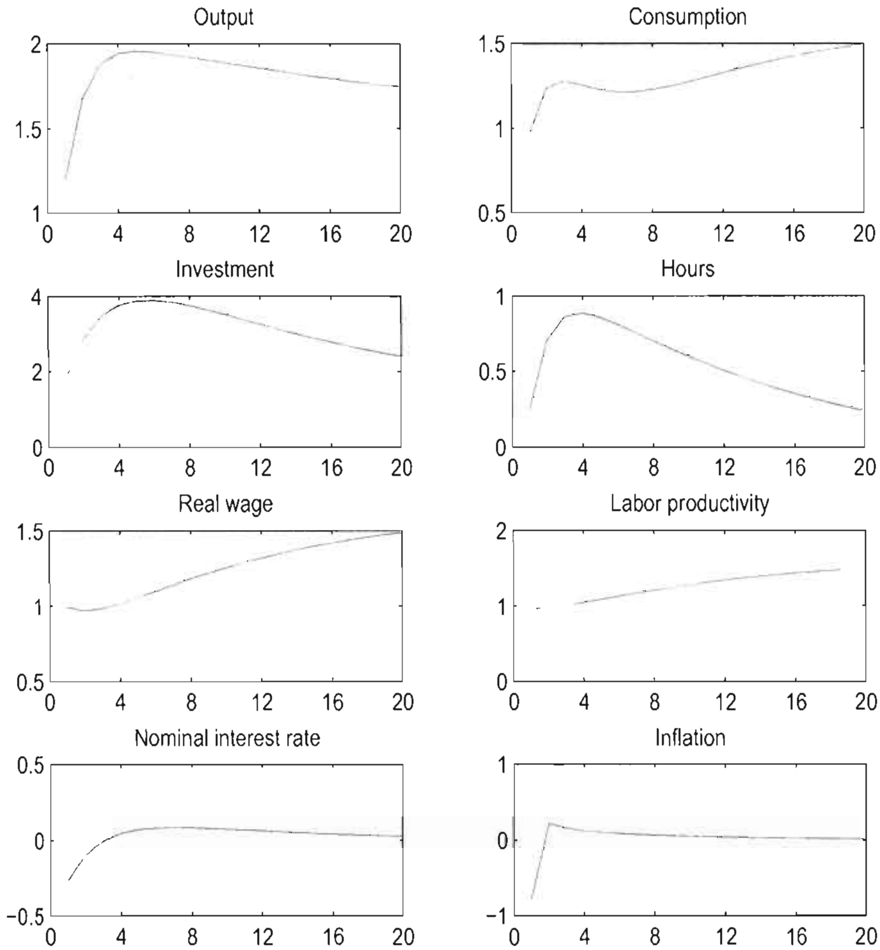


Figure 2.2b: Impulse Responses to a Monetary Policy Shock: Baseline Model

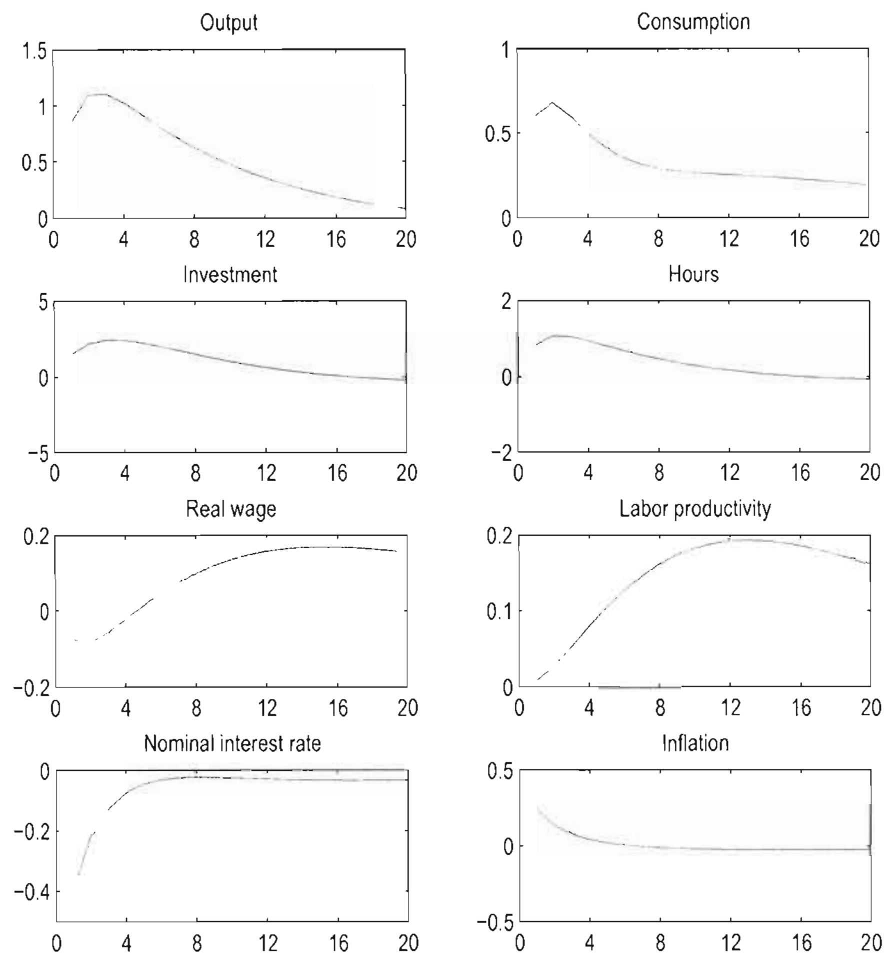
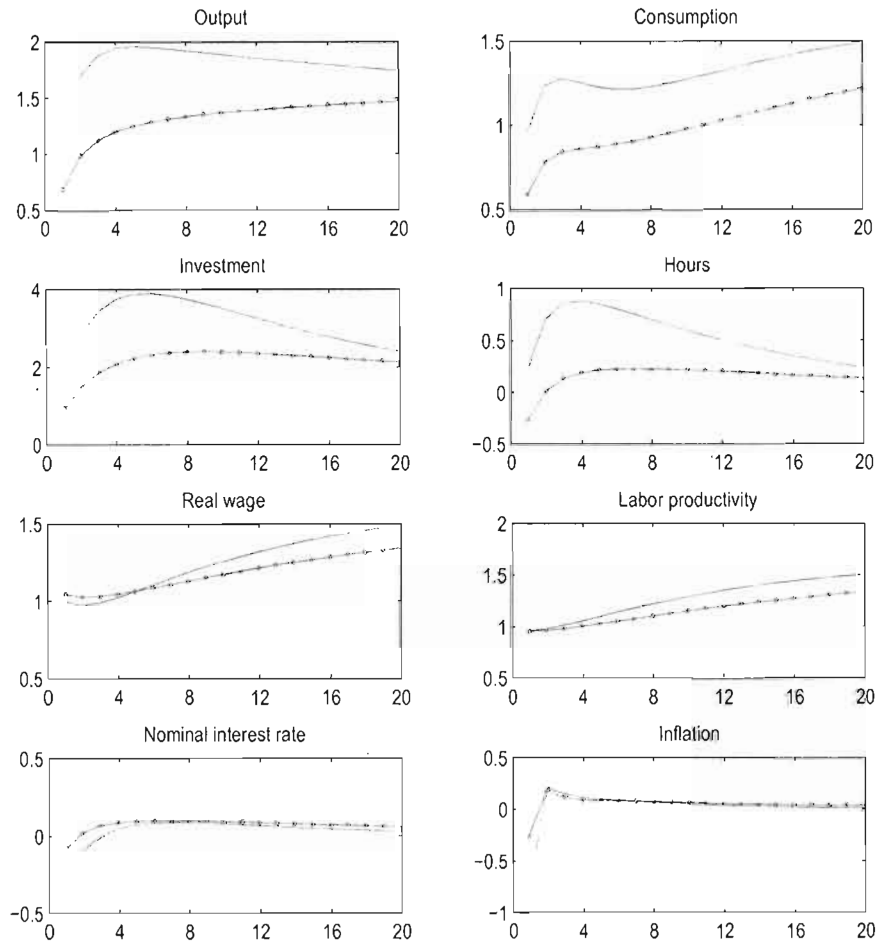
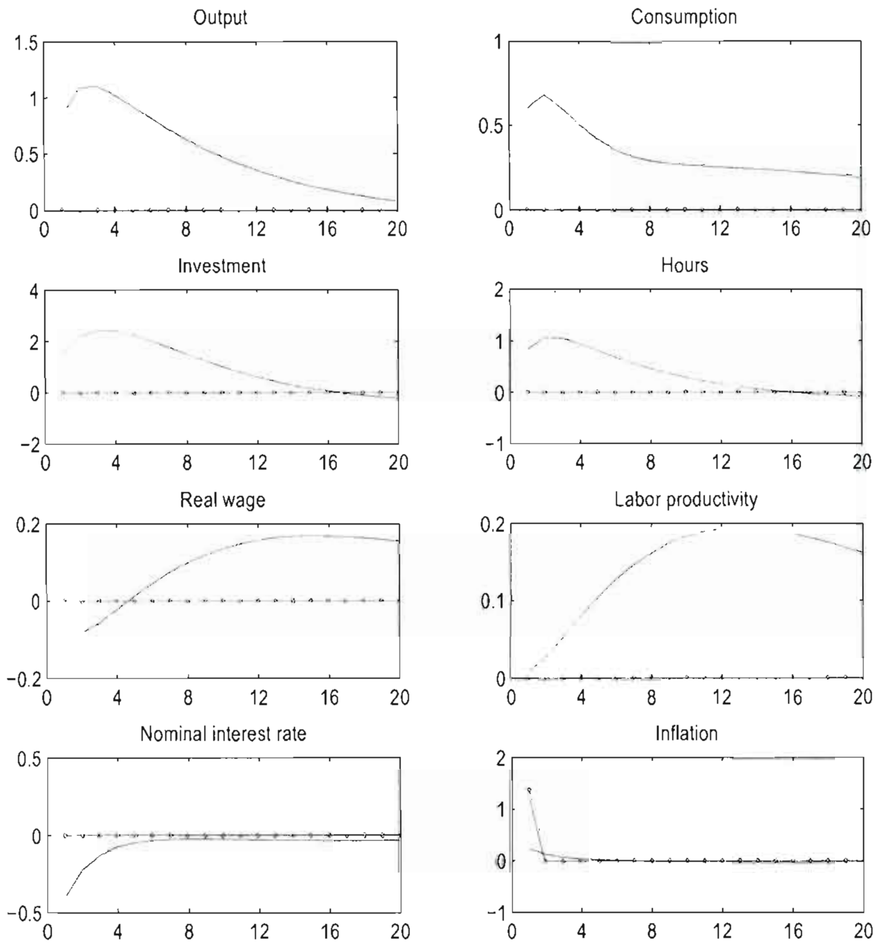


Figure 2.3a: Impulse Responses to a Technology Shock: Role of Nominal Wage Contracts



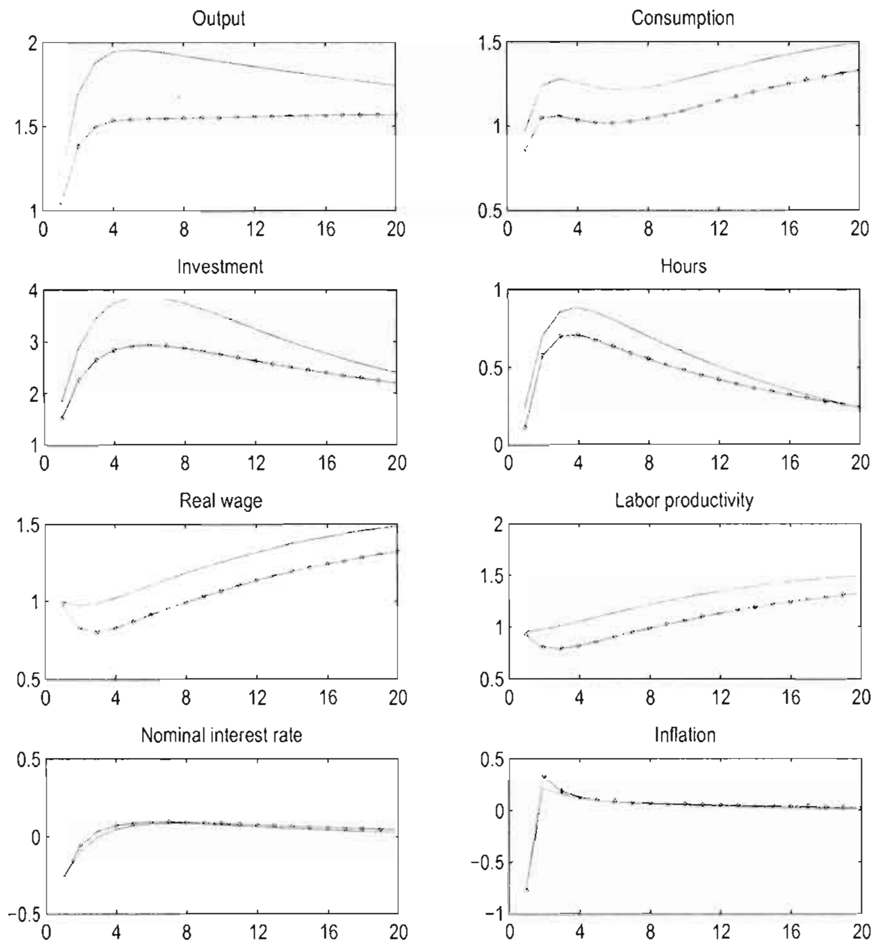
Note: Baseline model: solid line. No wage contracts: line with circles.

Figure 2.3b: Impulse Responses to a Monetary Policy Shock: Role of Nominal Wage Contracts



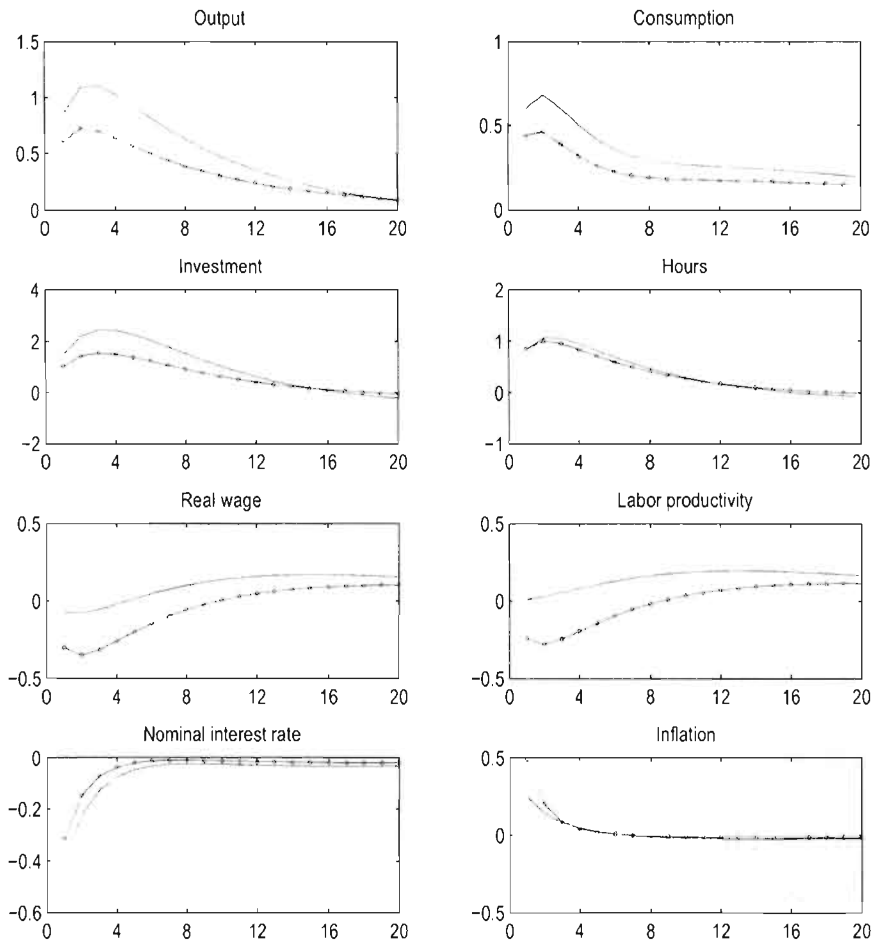
Note: Baseline model: solid line. No wage contracts: line with circles.

Figure 2.4a: Impulse Responses to a Technology Shock: Role of Employment Externality



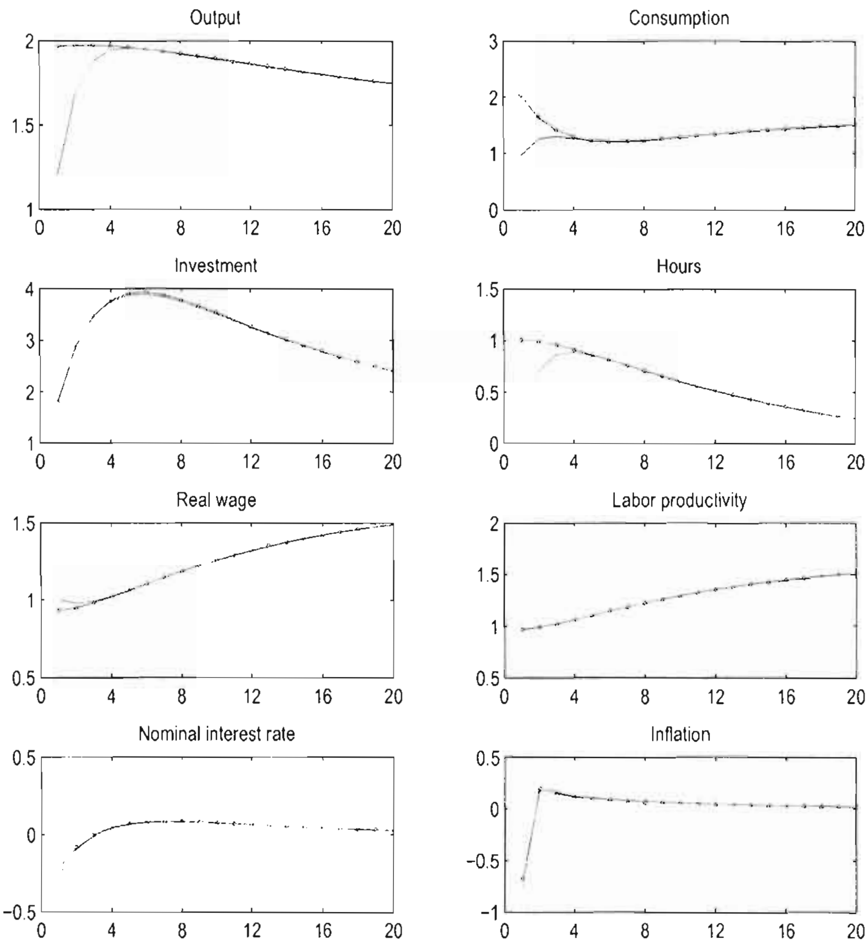
Note: Baseline model: solid line. No externality: line with circles.

Figure 2.4b: Impulse Responses to a Monetary Policy Shock: Role of Employment Externality



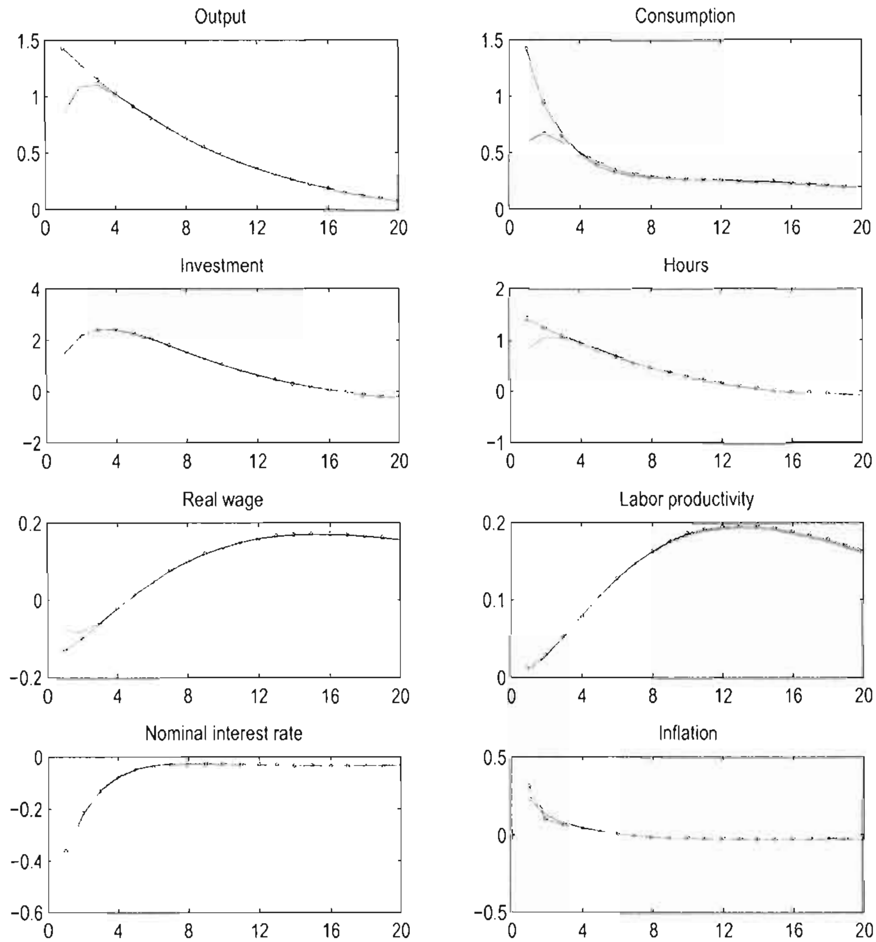
Note: Baseline model solid line. No externality: line with circles.

Figure 2.5a: Impulse Responses to a Technology Shock: Role of Consumption Habit



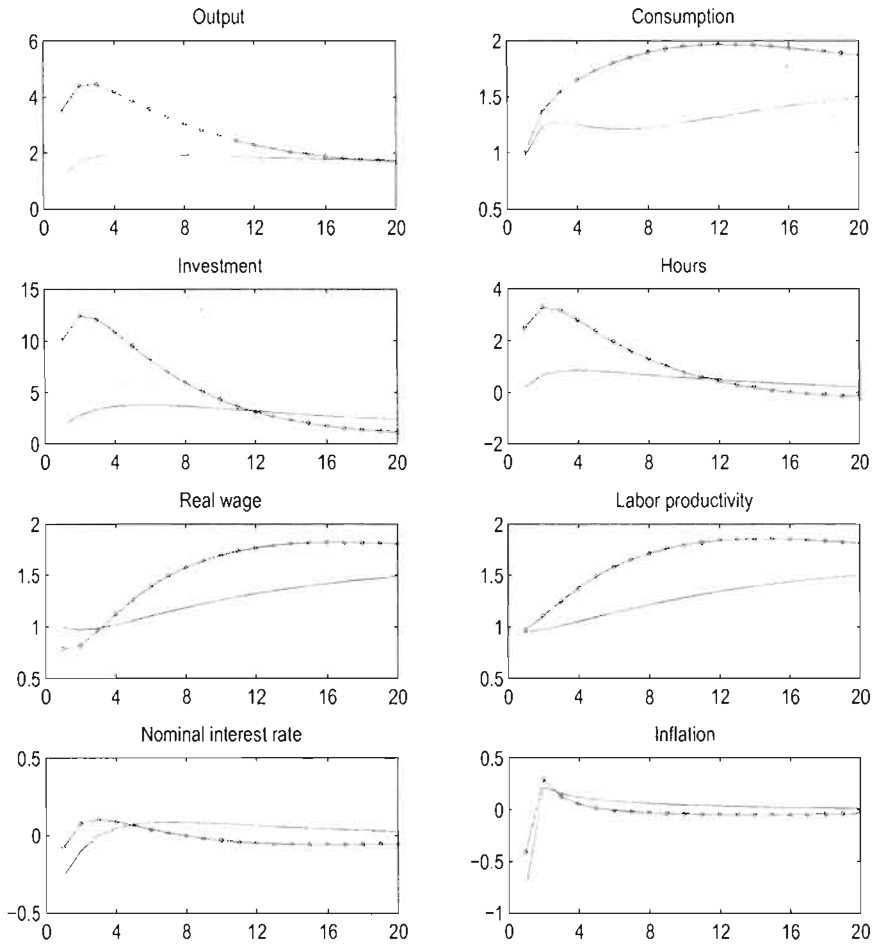
Note: Baseline model, solid line. No habit: line with circles.

Figure 2.5b: Impulse Responses to a Monetary Policy Shock: Role of Consumption Habit



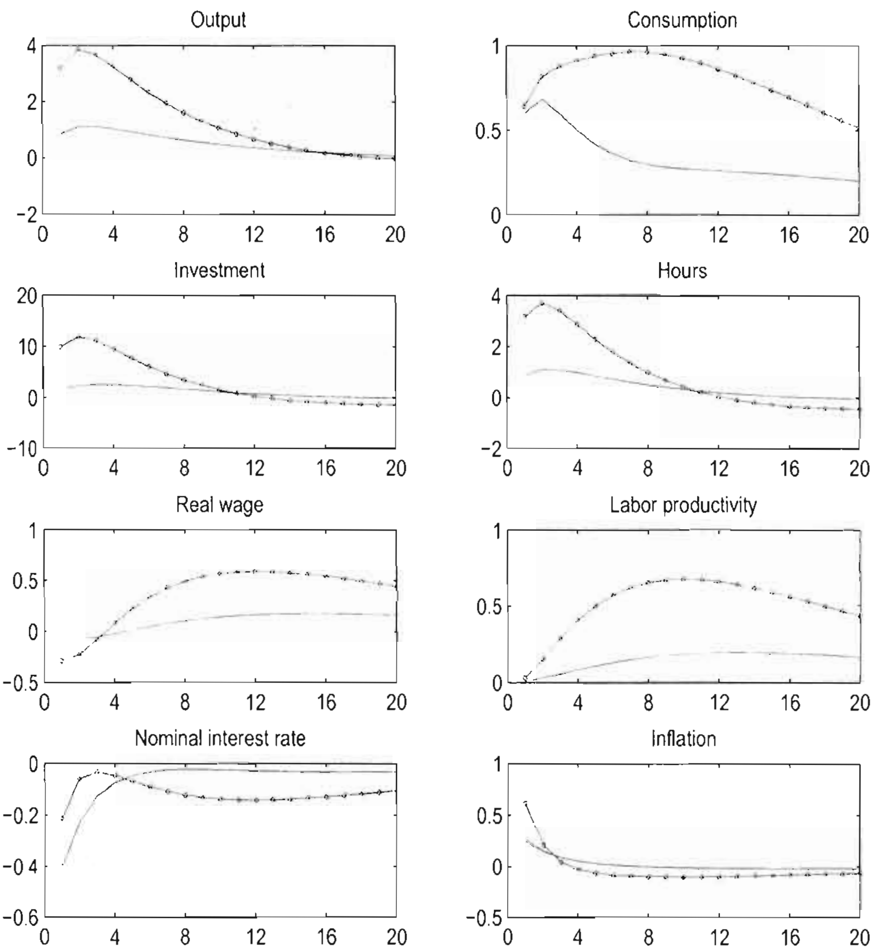
Note: Baseline model: solid line. No habit: line with circles.

Figure 2.6a: Impulse Responses to a Technology Shock: Role of Investment Adjustment Costs



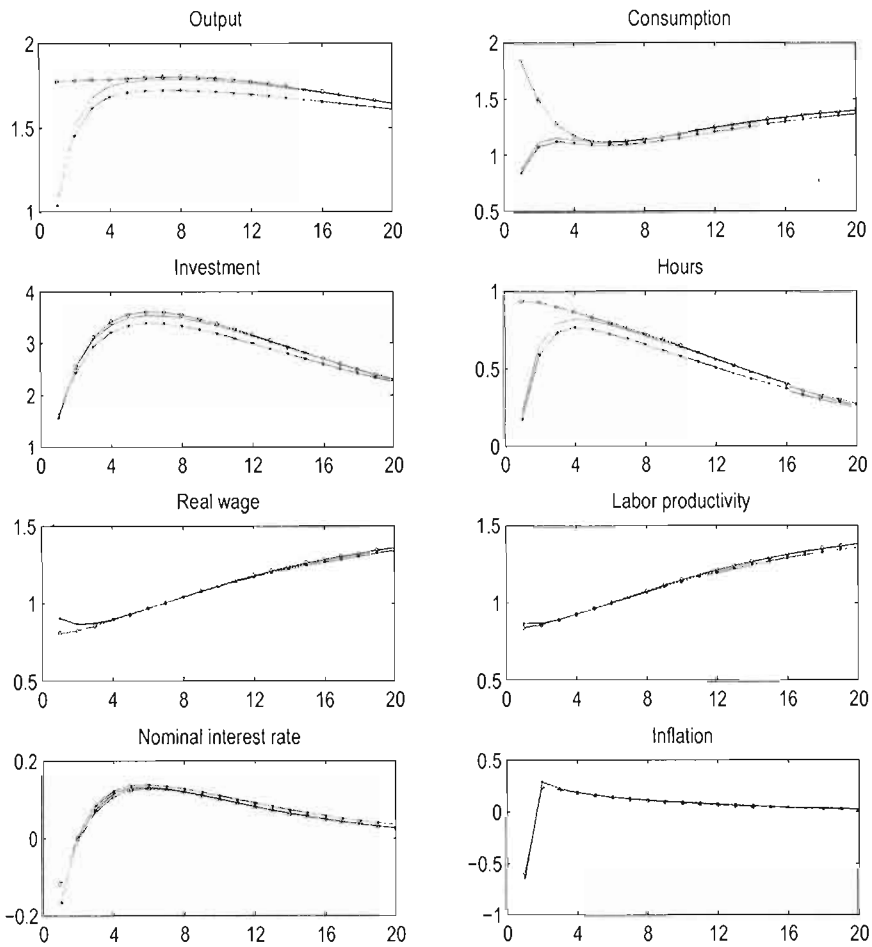
Note: Baseline model: solid line. No adjustment costs: line with circles

Figure 2.6b: Impulse Responses to a Monetary Policy Shock: Role of Investment Adjustment Costs



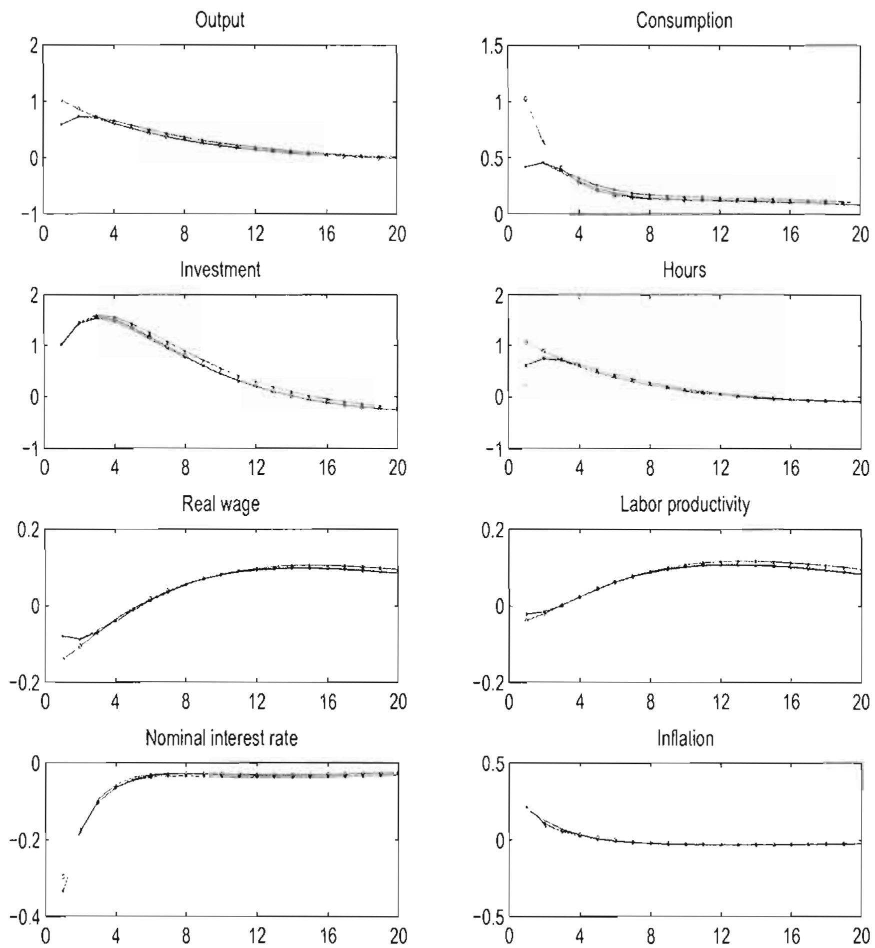
Note: Baseline model: solid line. No adjustment costs: line with circles

Figure 2.7a: Impulse Responses to a Technology Shock: DH Model



Note: DH model: solid line. No consumption habit: line with circles. No leisure habit: line with asterisks.

Figure 2.7b: Impulse Responses to a Monetary Policy Shock: DH Model



Note: DH model: solid line. No consumption habit: line with circles. No leisure habit: line with asterisks.

Chapter 3

From the Great Inflation to the Great Moderation: An Estimated Structural Model With Firm-Specific Labor and Nominal Price Rigidities

3.1 Introduction

This chapter explores the reasons behind the spectacular increase in macroeconomic stability from the Great Inflation to the Great Moderation and tries to harmonize the empirical evidence from microeconomic data suggesting that firms reoptimize prices relatively frequently (e.g., Bils and Klenow, 2004; Golosov and Lucas, 2007; Nakamura and Steinsson, 2007; Klenow and Kryvtsov, 2008) with that from aggregate time series about the inertial nature of the inflationary process (e.g., Fuhrer and Moore, 1995; Galí and Gertler, 1999).

We estimate a DSGE model of the U.S. economy that rests on two main pillars. First, following Kimball (1995), price-setting monopolistic competitors face a variable elasticity of demand. Second, following Woodford (2003, chapter 3), labor is specific to the firm or industry. While implying a plausible behavior of prices, our benchmark model goes a long way in the explanation of the Great Moderation, capturing close to 80 percent of the sharp decline in the volatility of output growth and 86 percent of the large fall in the variability of inflation.

Based on counterfactual experiments, we find that the main drivers behind the reduced volatility in real output growth are the shocks. However, unlike others before us, we identify labor supply shocks as the key source of the increased stability in output fluctuations. In contrast, the decline in the volatility of inflation is attributable almost equally to changes in the behavior of the private sector, a less accommodative monetary policy and smaller shocks.

We adopt the following empirical strategy. First, we estimate the benchmark model, using Ireland's (2001, 2003) econometric procedure for a sample of data covering the years 1948:I to 2006:II. This allows us to compare our findings about the frequency of price reoptimization with those of others and to assess the ability of the benchmark model to match the volatility of output growth, the variability of inflation and the comovement between output growth and inflation during the postwar period. We find that the model reproduces these moments with accuracy. Assuming, as in standard Calvo-style models, a constant demand elasticity and integrated labor markets (i.e. without firm-specific labor), our estimates suggest that firms reoptimize prices once every 5.4 quarters on average during the postwar period (see also Galí and Gertler, 1999), which seems like an implausibly long period of time. With a constant elasticity of demand and firm-specific labor, the frequency of price reoptimization decreases to once every three quarters on average. With a variable elasticity of demand and firm-specific labor, it declines further, getting close to once every two quarters.

The model is next reestimated using a sample of data covering the Great Inflation (1948:I to 1979:II) and the Great Moderation (1984:I to 2006:II). We find that the benchmark model closely matches the volatility of real output growth, the volatility of inflation and the correlation between output growth and inflation during the two subperiods.

Finally, we are able to detect statistically significant changes in some structural parameter values from the Great Inflation to the Great Moderation. Habit persistence decreases. The degree of investment adjustment costs increases. The Federal Reserve's tendency to smooth changes in interest rates decreases, whereas monetary policy becomes less accommodative in response to inflation (see also Clarida, Galí and Gertler, 2000). The composite parameter governing the responsiveness of inflation to marginal cost falls, implying that the frequency of price reoptimization increases somewhat during the Great Moderation. However, it always remains under three quarters in each subperiod. We also find important differences in the estimated variances of the shocks, but no strong evidence of statistically significant changes in the persistence of the stochastic processes generating the shocks.

The chapter is organized as follows. Section 3.2 briefly describes the changes in the volatility of output growth and inflation from the Great Inflation to the Great Moderation. Section 3.3 develops our DSGE model with a variable elasticity of demand and firm-specific labor. Section 3.4 discusses some econometric issues. Section 3.5 reports our empirical findings for the entire postwar period and analyzes the results. Section 3.6 presents our findings for the two subperiods and identifies the sources of the Great Moderation. Section 3.7 offers concluding remarks.

3.2 Output Growth Volatility and Inflation Variability from the Great Inflation to the Great Moderation

Figure 3.1 displays the evolution of the growth rate of output and the rate of inflation from 1948:I to 2006:II.[1] It also presents 20-quarter rolling standard deviations for these variables. The volatility of output growth and the variability of inflation have both considerably declined from the Great Inflation (1948:I to 1979:II) to the Great Moderation (1984:I to 2006:II).[2] The volatility of output growth has recorded two major declines, the first occurring between 1961 and 1965, and the second between 1984 and 1990. However, the recent decline is more dramatic, with the volatility of output growth falling from a high 1.8 percent in 1984 to a low 0.45 percent in 1990. It has remained below 1 percent ever since.

The U.S. economy has also experienced a lengthy period of high inflation from the mid-1960s to the early 1980s. However, there have been large declines both in the level and in the volatility of inflation after 1984. The variability of inflation has decreased from a high 0.81 percent in 1984 to a low 0.25 percent in 2006.[3]

Table 3.1 reports the standard deviations of output growth and inflation, and the correlations between output growth and inflation during the postwar period, the Great Inflation and the Great Moderation. In all periods, output growth is considerably more volatile than inflation. Furthermore, the correlation between output growth and

[1] Output is converted into per capita terms after being divided by the civilian noninstitutional population 16 years and above.

[2] Following McConnell and Perez-Quiros (2000) and others, we adopt 1984:I as the starting date of the Great Moderation.

[3] I have also looked at HP-filtered data and found similar results.

inflation was mildly negative. The volatility of output growth declined by 55 percent and the variability of inflation by 65 percent from the Great Inflation to the Great Moderation. Meanwhile, the correlation between the growth rate of output and the inflation rate became increasingly negative, falling from -0.1672 in the first subperiod to -0.3104 in the second subperiod.

3.3 A DSGE Model with a Variable Elasticity of Demand, Firm-Specific Labor and Nominal Price Rigidity

The economy is populated by a large number of members of a household, each endowed with a differentiated labor skill indexed by $i \in [0, 1]$. There is also a large number of firms, each producing a differentiated intermediate good indexed by $j \in [0, 1]$. Following Woodford (2003, chapter 3), a key feature of the model lies in the specificity of the labor relationship between a particular firm or industry, and a particular type of skill. That is, the i^{th} member of the household supplies labor only to firm j, while firm j hires only the i^{th} type of skill. For the sake of simplicity, we assume $i = j$.

While labor is firm-specific, no single household's member has monopoly power and no single firm has monopsony power. Hence, a way to understand the specificity of the labor relationship between the i^{th} member of the household and the j^{th} firm is to think of each point i on the unit interval continuum as representing a large number of individuals supplying a specific type of labor and of each point j on the unit interval continuum as representing a large number of firms employing that particular type of skill. For example, one can think of factor specificity at the level of a region or an industry.

3.3.1 The Household

The household's preferences are described by the following expected utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\varsigma_{c,t} U(C_t, C_{t-1}) - \varsigma_{h,t} \int_0^1 V(H_{i,t}) di - \int_0^1 \varkappa(e_{i,t}) di \right], \tag{3.1}$$

where

$$U(C_t, C_{t-1}) = \ln(C_t - bC_{t-1}),$$

$$V(H_{i,t}) = \frac{\lambda_h}{1+\eta_h} H_{i,t}^{1+\eta_h},$$

$$\varkappa(e_i) = \frac{\chi_e}{1+\eta_e} e_{i,t}^{1+\eta_e}.$$

$\beta \in (0,1)$ is the subjective discount factor, C_t is the aggregate consumption good in period t, and C_{t-1} is the habit reference level for consumption. The variables $H_{i,t}$ and $e_{i,t}$ denote the hours worked and the level of effort of the i^{th} member of the household, respectively. The parameter $b \in [0,1]$ measures the degree of habit formation for consumption, while η_h and η_e are two positive parameters. The household's preferences are affected by shocks to the marginal utility of consumption $\epsilon_{c,t}$ and to the marginal disutility of hours worked $\epsilon_{h,t}$. Both are described by first-order autoregressive processes:

$$\ln(\epsilon_{c,t}) = \rho_c \ln(\epsilon_{c,t-1}) + \varepsilon_{c,t}, \tag{3.2}$$

$$\ln(\epsilon_{h,t}) = \rho_h \ln(\epsilon_{h,t-1}) + \varepsilon_{h,t}, \tag{3.3}$$

where $0 \leq \rho_c < 1$, $0 \leq \rho_h < 1$; $\varepsilon_{c,t}$ and $\varepsilon_{h,t}$ are zero-mean, serially uncorrelated, and normally distributed innovations with standard deviations σ_c and σ_h, respectively.

The household enters period t with bond holdings B_{t-1}, and a predetermined stock of physical capital K_t which is rent to the intermediate-good firms at the real rental rate R_t^k. Household i supplies effective hours worked $e_{i,t}H_{i,t}$ to firm j at the nominal wage rate $W_{i,t}$. At the end of period t, the household receives total nominal dividends D_t from the firms. The household purchases B_t units of bonds, C_t units of an aggregate consumption good at the nominal price P_t, and I_t units of an aggregate investment good from the finished-good firm.[4] The household's flow budget constraint is:

$$C_t + I_t + \frac{B_t}{R_t P_t} \leq \frac{B_{t-1}}{P_t} + \int_0^1 W_{i,t}^r e_{i,t} H_{i,t} di + R_t^k K_t + \frac{D_t}{P_t}, \tag{3.4}$$

where $W_{i,t}^r = \frac{W_{i,t}}{P_t}$ is the real wage of the i^{th} member of the household, and R_t is the gross nominal interest rate between periods t and $t+1$. We impose the explicit borrowing constraint $B_t \geq -B, B \geq 0$ to prevent the household from running Ponzi schemes.

The stock of physical capital obeys:

$$K_{t+1} = (1-\delta)K_t + \epsilon_{i,t}(1 - S(I_t/I_{t-1}))I_t, \tag{3.5}$$

[4] I follow the standard practice of assuming complete financial markets. This implies that the household's members are identical with respect to consumption and bond holdings. The source of heterogeneity between the household's members is produced only by the existence of segmented labor markets.

where δ is the depreciation rate of physical capital. The second term on the right-hand side of (3.5) embodies the investment adjustment costs. The function $S(.)$ is positive, convex and it satisfies $S(\epsilon_a) = S'(\epsilon_a) = 0$. where ϵ_a determines the steady-state growth rate of output (see below). Following Greenwood et. al. (1988) and Fisher (2006), $\epsilon_{i,t}$ is an investment-specific shock which follows the first-order autoregressive process:

$$\ln(\epsilon_{i,t}) = \rho_i \ln(\epsilon_{i,t-1}) + \varepsilon_{i,t}, \tag{3.6}$$

where $0 \leq \rho_i < 1$. and $\varepsilon_{i,t}$ is a zero-mean. serially uncorrelated. and normally distributed innovation with standard deviation σ_i. The household maximizes the utility function (3.1) subject to the budget constraint (3.4), and the capital accumulation equation (3.5). The first-order conditions corresponding to this problem are:

$$\left(\frac{\epsilon_{c,t}}{C_t - bC_{t-1}}\right) - \beta b E_t \left(\frac{\epsilon_{c,t+1}}{C_{t+1} - bC_t}\right) = \Lambda_t, \tag{3.7a}$$

$$\epsilon_{h,t} \chi_h H_{i,t}^{\eta_h} = W_{i,t}^{r} e_{i,t} \Lambda_t, \tag{3.7b}$$

$$\chi_e e_{i,t}^{\eta_e} = W_{i,t}^{r} H_{i,t} \Lambda_t, \tag{3.7c}$$

$$Q_t = \beta E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t} \left(R_{t+1}^k + (1 - \delta) Q_{t+1}\right)\right], \tag{3.7d}$$

$$Q_t = \frac{1 - \beta E_t \left[\frac{\Lambda_{t+1}}{\Lambda_t} Q_{t+1} S'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2 \epsilon_{i,t+1}\right]}{\left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right)\left(\frac{I_t}{I_{t-1}}\right)\right] \epsilon_{i,t}}. \tag{3.7e}$$

where Λ_t is the Lagrange multiplier associated with the budget constraint (3.4). Equation (3.7a) equals the marginal utility of date-t consumption to its opportunity cost. Equations (3.7b) and (3.7c) equal the marginal disutility of hours and effort to their respective earnings. The Euler condition for capital (3.7d) says that the shadow price of installed capital, measured by marginal Tobin's Q, equals the sum of the expected future value of Q net of depreciation and the expected future return on capital. Equation (3.7e) determines the optimal level of investment, increasing in Q.

3.3.2 The Firms

The representative finished-good firm is perfectly competitive and produces Y_t units of the finished good, with the following general variety aggregator proposed by Kimball

(1995):

$$\int_0^1 G\left(\frac{Y_{i,t}}{Y_t}\right) di = 1, \tag{3.8}$$

where $Y_{i,t}$ denotes the quantity of the intermediate good i used in the production of the composite finished-good Y_t. The function G(.) is increasing, strictly concave, and it satisfies $G(1) = 1$. The finished-good firm purchases $Y_{i,t}$ at the nominal price $P_{i,t}$. The first-order condition corresponding to the finished-good firm's profit maximization problem is

$$\zeta_{i,t} = G'^{-1}\left(\frac{P_{i,t}}{P_t}\int_0^1 G'(\zeta_{i,t}).\zeta_{i,t} di\right), \tag{3.9}$$

where $\zeta_{i,t} = Y_{i,t}/Y_t$, and $G'(.)$ denotes the partial derivative of G(.). In the absence of profits, the nominal price P_t is given by,

$$P_t = \int_0^1 P_{i,t} G'^{-1}\left(\frac{P_{i,t}}{P_t}\int_0^1 G'(\zeta_{i,t}).\zeta_{i,t} dj\right) di. \tag{3.10}$$

The intermediate-good firm i produces $Y_{i,t}$ units of a differentiated intermediate good i using firm-specific effective labor hours $e_{i,t}H_{i,t}$, and $K_{i,t}$ units of the homogeneous stock of physical capital. Hence, output $Y_{i,t}$ is produced through the following production function:

$$Y_{i,t} = \begin{cases} K_{i,t}^{\alpha}(\epsilon_{a,t}e_{i,t}H_{i,t})^{1-\alpha} - \epsilon_{a,t}\Phi & \text{if} \quad K_{i,t}^{\alpha}(\epsilon_{a,t}e_{i,t}H_{i,t})^{1-\alpha} \geq \epsilon_{a,t}\Phi \\ 0 & \text{otherwise,} \end{cases} \tag{3.11}$$

where $\alpha \in (0, 1)$ is the share of physical capital into the production of the intermediate good i, $\Phi > 0$ is a common fixed-cost term,[5] and $\epsilon_{a,t}$ is the labor-augmenting level of technology. The technology shock is generated by the logarithmic random-walk process with drift:

$$\ln(\epsilon_{a,t}) = \ln(\epsilon_a) + \ln(\epsilon_{a,t-1}) + \varepsilon_{a,t}, \tag{3.12}$$

where $\varepsilon_{a,t}$ is a zero-mean, serially uncorrelated, and normally distributed innovation with standard deviation σ_a.

[5]The inclusion of increasing returns to scale through the fixed term cost allows the firms to earn zero profits in the steady state. Rotemberg and Woodford (1995) argue that during the postwar period, average pure profits have been close to zero in the U.S. economy. The price markup can thus be calibrated at conventional values.

Each period, cost minimization implies the following first-order conditions for the representative firm :

$$(1-\alpha)\left(\frac{Y_{i,t}+\epsilon_{a,t}\Phi}{\epsilon_{i,t}H_{i,t}}\right)MC_{i,t} = W^r_{i,t}, \tag{3.13a}$$

$$\alpha\left(\frac{Y_{i,t}+\epsilon_{a,t}\Phi}{K_{i,t}}\right)MC_{i,t} = R^k_t, \tag{3.13b}$$

where $MC_{i,t}$ denotes the real marginal cost of firm i. Hence, the firm equates the marginal product of each input to its shadow price. Firms set nominal prices in a staggered fashion in the spirit of Calvo (1983). In each period, firm i faces probability $1-\xi$ of reoptimizing its price $P_{i,t}$. In a symmetric equilibrium, the firms that are allowed to reoptimize prices in period t choose the same optimal price P^*_t . Profit maximization yields the following first-order condition:

$$\frac{P^*_t}{P_t} = \frac{E_t\sum_{\tau=0}^{\infty}(\beta\xi)^{\tau}\frac{\Lambda_{t+\tau}}{\Lambda_t}\left(-\varepsilon(\zeta_{i,t+\tau})MC_{i,t+\tau}\right)}{E_t\sum_{\tau=0}^{\infty}(\beta\xi)^{\tau}\frac{\Lambda_{t+\tau}}{\Lambda_t}\left(\frac{P_t}{P_{t+\tau}}(1-\varepsilon(\zeta_{i,t+\tau}))\right)}, \tag{3.14}$$

where $\varepsilon(\zeta_{i,t})$ denotes the demand elasticity of a differentiated good i, which is given by $\varepsilon(\zeta_{i,t}) = -\left(\frac{G'(\zeta_{i,t})}{G''(\zeta_{i,t})\zeta_{i,t}}\right)$. If firms are allowed to reoptimize their prices in each period, (3.14) simplifies to:

$$\frac{P^*_t}{P_t} = \frac{\varepsilon(\zeta_{i,t})}{\varepsilon(\zeta_{i,t})-1}MC_{i,t}$$

This equation says that a firm's optimal relative price is equal to the product of the markup and the real marginal cost. The markup implied by Kimball's (1995) specification is time-varying.[6] The aggregate price level in (3.10) is determined by,

$$P_t = (1-\xi)P^*_tG'^{-1}\left(\frac{P^*_t}{P_t}\int_0^1 G'(\zeta_{i,t}).\zeta_{i,t}di\right) + \xi P_{t-1}G'^{-1}\left(\frac{P_{t-1}}{P_t}\int_0^1 G'(\zeta_{i,t}).\zeta_{i,t}di\right). \tag{3.15}$$

Inflation dynamics can be described by the Phillips Curve equation (see the appendix for a complete derivation):

$$\pi_t = \beta E_t\pi_{t+1} + \Gamma mc_t, \tag{3.16}$$

where

$$\Gamma = \frac{(1-\beta\xi)(1-\xi)}{\xi}\varphi^{-1}.$$

[6] It is constant under the familiar Dixit-Stiglitz aggregator.

From now on, a lower case variable denotes the log-deviation of the corresponding upper case variable from its steady-state value; π_t is the rate of inflation, and mc_t is the aggregate real marginal cost.

The composite term Γ determines the responsiveness of inflation to the real marginal cost. This term is negatively related to φ, which is a function of structural parameters of the model (see the appendix). In the benchmark model, this composite parameter is $\varphi = 1 + \varphi_1 + \varphi_2$, with $\varphi_1, \varphi_2 > 0$. Hence, the responsiveness of inflation to the real marginal cost is dampened via two distinct channels. The parameter φ_1 follows from the assumption that firms face a variable elasticity of demand. The parameter φ_2 reflects the assumption of firm-specific labor.

Consider the φ_1-channel. The parameter φ_1 is given by $\varphi_1 = \mu\epsilon$, where μ stands for the net price markup defined as $\mu = \frac{1}{\varepsilon(1)-1}$, $\varepsilon(1)$ for the demand elasticity of intermediate good i evaluated at the steady state, and ϵ for the percent change in the elasticity of demand following a one percent change in the relative price of the good evaluated at the steady state. A Dixit-Stiglitz form of demand ($\epsilon = 0$) implies $\varphi_1 = 0$, so inflation becomes more responsive to the real marginal cost and less persistent.

The second channel is related to φ_2, which is given by.

$$\varphi_2 = (\varepsilon(1)-1)\left[\frac{A-B}{(1+\alpha(A-B))^{I^F}} - 1\right], \quad A = \left(\frac{1+\eta_h}{1-\alpha}\right), \quad B = \left(\frac{(1+\eta_h)^2}{(2+\eta_h+\eta_e)(1-\alpha)}\right),$$

where I^F is an indicator function which takes a value of 1 if capital is homogenous and mobile across firms as in the benchmark model, and a value of 0 if capital is fixed as in Sbordone (2002), for example. [7]

To better understand how firm-specific labor lowers the responsiveness of inflation to the real marginal cost and increases the persistence of inflation, we make the following simplifying assumptions: capital is fixed ($I^F = 0$), effort is constant ($\eta_e \to \infty$ and $B = 0$), and demand is of the Dixit-Stiglitz form ($\epsilon = 0$). With these simplifications, the Phillips Curve equation can be written as

$$\pi_t = \beta E_t \pi_{t+1} + \frac{(1-\beta\xi)(1-\xi)}{\xi}(1+\varphi_2')^{-1} mc_t, \tag{3.17}$$

[7] Notice that $\frac{Y}{Y+\Phi} = \frac{\varepsilon(1)-1}{\varepsilon(1)}$, where Y denotes the steady-state level of output.

where

$$\varphi_2' = \varepsilon(1)\left(\frac{Y}{Y+\Phi}\right)(1-\alpha)^{-1}(\alpha+\eta_h).$$

Consider, for example, the case of an expansionary policy shock. With sticky prices, the policy shock exerts an upward pressure on real wages, so a firm contemplates raising its price with or without firm's specific labor. With firm-specific labor, a firm's labor demand depends positively on its own level of output. In turn, a firm's output depends negatively on its relative price. The expansionary policy shock generates a rise in the firm's relative price, putting a downward pressure on the firm's output, labor demand and real wages. The downward pressure on real wages thus acts as a countervailing influence on the firm's incentive to raise its price.

The feedback effect from real wages to prices, captured by the composite parameter φ_2', is the product of four factors. First, following the increase in the firm's relative price, the firm's level of output falls by a factor of $\varepsilon(1)$. The firm's labor demand then decreases by $\left(\frac{Y}{Y+\Phi}\right)$. With labor demand falling, the real wages decline, lowering the firm's price by a factor of $(1-\alpha)^{-1}$. The lower the elasticity of labor supply (i.e. the higher is η_h), or the higher the elasticity of labor demand (i.e. the higher is α), the stronger is the response of real wages and the larger is the firm's price adjustment in response to the policy shock.[8]

3.3.3 The Monetary Policy Rule

The Federal Reserve sets the short-term nominal interest rate in accordance with the following Taylor-type of rule:

$$r_t = \rho_r r_{t-1} + (1-\rho_r)\left[\rho_\pi \pi_t + \rho_y g_{yt}\right] + \varepsilon_{m,t}. \tag{3.18}$$

where π_t and g_{yt} denote deviations of inflation and the growth rate of output from their steady-state values, and $\varepsilon_{m,t}$ is a zero-mean, serially uncorrelated, and normally distributed innovation with standard deviation σ_m.[9]

[8] This can be seen more clearly by combining the log-linearized labor demand equation, $\left(\frac{Y}{Y+\Phi}\right) y_{i,t} + mc_{i,t} = w_{i,t} + h_{i,t}$ and the log-linearized real marginal cost equation, $mc_{i,t} = (1-\alpha)w_{i,t} + \alpha r_t^k$

[9] Erceg and Levin (2003), and Galí and Rabanal (2004) also specify Taylor rules that feature the growth rate of output.

3.4 Econometric Procedures

We take a log-linear approximation of the model's equilibrium conditions around the deterministic steady state. The resulting system of linear difference equations is solved using the methods outlined in Klein (2000). The system can be written in its state-space form as

$$x_{t+1} = \Upsilon_1 x_t + \Upsilon_2 \varepsilon_{t+1},$$

$$z_t = \Upsilon_3 x_t,$$

where x_t is a vector of unobservable state variables, ε_{t+1} is a vector composed of the five structural shocks $\varepsilon_{a,t}$, $\varepsilon_{m,t}$, $\varepsilon_{c,t}$, $\varepsilon_{h,t}$, and $\varepsilon_{i,t}$, and z_t is a vector of observable variables. The elements of matrices Υ_1, Υ_2, and Υ_3 are functions of the parameters of the model. We estimate the system using maximum likelihood methods and quarterly U.S. data on four variables: the growth rate of per capita consumption, the growth rate of per capita investment, the rate of inflation, and the nominal interest rate. Let Θ be the vector of parameters that we seek to estimate, and T the number of observations on each variable. The Gaussian log likelihood function $L(\Theta)$ for the sample $\{z_t\}_{t=1}^{T}$ can be constructed recursively using the Kalman filter described by Hamilton (1994, chapter 13). The likelihood function (if we ignore the constant term) can be written as :

$$L(\Theta) = -\frac{1}{2}\sum_{t=1}^{T} \ln|\Omega_t| - \frac{1}{2}\sum_{t=1}^{T} u_t'\Omega_t^{-1}u_t,$$

where $u_t = z_t - \hat{E}(z_t|z_{t-1}, z_{t-2}, ... z_1)$, $E(u_t u_t') = \Omega_t$ and $\hat{E}(.)$ denotes the linear projection operator.

The benchmark model includes 26 parameters which are related to preferences, technology, the shock processes, and monetary policy. They are summarized by $\{\beta,\ \delta,\ \eta_h,\ \chi_h,\ \eta_e,\ \chi_e;\ b,\ S''(\epsilon_a),\ \alpha,\ \Phi,\ \epsilon_a,\ \rho_r,\ \rho_\pi,\ \rho_g,\ \rho_c,\ \rho_h,\ \rho_i,\ \Gamma,\ \varepsilon(1),\ \epsilon,\ \xi,\ \sigma_c,\ \sigma_h,\ \sigma_i,\ \sigma_a,\ \sigma_m\}$. Some parameters are calibrated prior to estimation. The parameter δ takes a value of 0.025, implying an annualized rate of capital depreciation of 10 percent. The share of physical capital into the production of intermediate goods α is 0.36. The steady-state values of the nominal interest rate and ϵ_a determining the steady-state growth rate of output are chosen to match the U.S. data for our sample. These values also imply

$\beta = 0.9935$. The value of χ_h in the utility function is such that the fraction of time devoted to work in the steady state is 0.30, while that assigned to χ_e implies a value of effort of one in the steady state. Since we cannot simultaneously estimate ξ, $\varepsilon(1)$, ϵ, and Γ, we assign to the steady-state demand elasticity of good i, $\varepsilon(1)$, a benchmark value of 10, implying that the gross price markup is 11 percent. The benchmark value for ϵ is also 10, which is consistent with the symmetric translog specification of Bergin and Feenstra (2000).

3.4.1 Data

Our sample of data runs from 1948:I to 2006:II.[10] Real consumption is measured by the sum of real personal consumption expenditures on nondurable goods and services. Investment is the sum of real personal consumption expenditures on durable goods and fixed private investment. The nominal interest rate is the Three-Month Treasury Bill rate. The price index is the price deflator of output in the nonfarm business sector. The consumption and investment series are divided by the civilian noninstitutional population 16 years and over.

3.5 Empirical Results

3.5.1 Maximum Likelihood Estimates

The estimates of the structural parameters of the benchmark model for the period 1948:I to 2006:II are reported in Table 3.2. The parameters of the benchmark model are estimated precisely. The point estimate of b the coefficient of habit formation for consumption is 0.57. The point estimate of $1/\eta_h$ in the utility function is 0.84, while that of $1/\eta_e$ is 0.14. These estimates imply an elasticity of labor supply of 0.9. The point estimate of $S''(\epsilon_a)$ determining the degree of investment adjustment costs is 2.75, lying within the range of parameter values obtained by Christiano, Eichenbaum and Evans (2005). The interest-rate smoothing parameter ρ_r is 0.75, consistent with the evidence in Clarida, Galí and Gertler (2000). The parameter ρ_π measuring the Fed's response to deviations of inflation from its steady-state value is 1.53, close to the value advocated

[10]The data have been obtained from the Haver Analytics Economics Database.

by Taylor (1993) which is 1.5. The coefficient ρ_y determining the Fed's response to deviations of output growth from its steady-state value is relatively small at 0.15.

Turning our attention to the shock-generating processes, we find that the shock with the highest AR(1) estimated coefficient is the shock to the marginal disutility of hours with 0.8832, followed by the investment-specific shock with 0.7978, and by the shock to the marginal utility of consumption with 0.5696. The shock to the marginal disutility of hours has the largest estimated standard error at 0.0726, followed by the investment-specific shock at 0.0343, the shock to the marginal utility of consumption at 0.0122, the technology shock at 0.0115, and the policy shock at 0.0025.

The point estimate of Γ measuring the sensitivity of inflation to the real marginal cost is 0.0432. Given this estimate, the Calvo-probability of price non-reoptimization ξ can be recovered by assigning values to $\varepsilon(1)$ and ϵ. Table 3.3 reports estimates of ξ and the average amount of time between price reoptimization for $\Gamma = 0.0432$, $\varepsilon(1) = 10$, and alternative values of ϵ. We consider the cases of homogeneous and firm-specific labor. These variants of the benchmark model are all observationally equivalent with respect to the data.

As in Eichenbaum and Fisher (2007), we consider three different values of ϵ: 0, 10 and 33. Assuming $\epsilon = 0$ corresponds to a constant elasticity of demand, while assuming $\epsilon = 10$ or 33 implies a variable elasticity of demand and encompasses the calibration in Dotsey and King (2005). With firm-specific labor, and $\varepsilon(1)$ and ϵ that both take a value of 10, firms reoptimize prices once every 2.65 quarters on average. With $\epsilon = 33$, prices are reoptimized once every 2.29 quarters. With a constant elasticity of demand, the frequency of price reoptimization increases to almost once every three quarters. Relaxing the assumption of firm-specific labor has a significant impact on the average amount of time between price reoptimization. With homogeneous labor and $\epsilon = 10$, firms reoptimize prices once every 3.88 quarters on average, whereas with $\epsilon = 33$, the frequency of price reoptimization decreases to once every 2.79 quarters. With $\epsilon = 0$, the average amount of time between price reoptimization increases to 5.4 quarters.

These findings are consistent with those of other researchers. With firm-specific capital, a labor' share of $\frac{2}{3}$, a 10 percent markup, a 10 percent annual depreciation rate and an investment adjustment-cost parameter of 3.0, Eichenbaum and Fisher (2007) report that the average length of time between price reoptimization is 3.6, 3.3 and 2.9 quarters for $\epsilon = 0$, 10 and 33, respectively. Altig et al. (2005) find that for plausible markup values, the average duration between price reoptimization is 2.25-3.5 quarters.

We conclude that for given values of $\varepsilon(1)$ and ϵ, accounting for firm-specific labor induces a relatively large increase in the frequency of price reoptimization. Furthermore, with or without firm-specific labor, an increase in ϵ also leads to a higher Calvo-probability of price reoptimization for a given value of the price markup.

Finally, as shown by the first two columns in Table 3.4, the volatilities of output growth and inflation, and the correlation between these variables predicted by the benchmark model closely match those found in the data.

3.5.2 Vector Autocorrelations

Following Fuhrer and Moore (1995) and Ireland (2001, 2003), we compare the vector autocorrelation function from an estimated vector autoregression with that obtained from the benchmark model. We estimate an unconstrained fourth-order vector autoregression which includes the following variables : the growth rate of per capita output, the rate of change of per capita hours worked and the rate of inflation. First, we perform a Phillips-Perron (1988) test for the presence of a unit root in per capita hours and inflation (not reported). The null hypothesis of a unit root in per capita hours is not rejected at the 5 percent level, whereas that of a unit root in the rate of inflation is rejected at the 5 percent level.

Figure 3.2 displays the autocorrelation functions from the vector autoregression and the benchmark model. The diagonal elements are the univariate autocorrelation functions for inflation, the rate of change of per capita hours and the growth rate of per capita output, while the off-diagonal elements are the lagged cross correlations between these variables. In the data, inflation is highly persistent, exhibiting positive serial correlation at short and medium horizons. The growth rates of output and per capita hours are positively serially correlated at a short horizon of one and two quarters. The benchmark model correctly predicts that inflation is more persistent than the growth rates of output and hours. Also, despite our deliberate omission of any indexing scheme relating current to past inflation, the benchmark model produces a significant amount of nominal price inertia. By predicting that the growth rates of output and hours are positively serially correlated, the benchmark model meets the challenge of producing plausible business-cycle dynamics. The evidence in Cogley and Nason (1995) shows that a large class of business cycle models fails to account for output dynamics, generating only weak endogenous business-cycle propagation.

Also, note from the off-diagonal elements in the vector autoregression that the only definite pattern in the lagged cross correlations is that between the growth rates of output and hours. The benchmark model does quite well matching the lagged cross correlations between the variables.

3.5.3 Impulse-Response Functions

Figures 3.3 to 3.7 display the impulse responses of several variables following each type of shock according to the benchmark model. Figure 3.3 summarizes the effects of a positive one percent technology shock. The benchmark model generates a gradual, permanent rise in output, investment and consumption, consistent with the evidence reported by Francis and Ramey (2005a). Hours and effort decline in the short run and then rise in the medium run. The short-run fall in hours is consistent with the evidence in Galí (1999), Francis and Ramey (2005a) and Fernald (2007).[11] The prediction of a short-run decline in hours which is followed by an increase in the medium run is consistent with the empirical evidence offered by Basu, Fernald and Kimball (2006). The factors which are mainly responsible for the short-run declines in hours and effort are the sticky prices (e.g., Galí, 1999), habit persistence and the investment adjustment costs (e.g., Francis and Ramey, 2005a). Prices do not decrease as much following a technology improvement with Calvo-contracts than without them, restraining the stimulative impact of the fall in prices on aggregate demand. Both habit persistence and the investment adjustment costs dampen the short-run increase in aggregate demand following a rise in wealth. Overall, the increase in aggregate demand is not sufficiently strong to keep up with the

[11] However, it is at odds with the evidence in Christiano, Eichenbaum and Vigfusson (2004) saying that hours rise following a technology improvement.

increase in productivity, so hours and effort have to fall, at least in the short run.

It is worth noticing that the benchmark model is able to produce a short-run decline in hours despite the realistic treatment of monetary policy. Dotsey (1999) argues that Galí's (1999) contention that hours fall following a technology improvement may reflect his assumption that the gross growth rate of money supply weakly responds to the technology shock. He shows that with a Taylor-type of rule, hours worked may actually rise when technology improves. Note that the benchmark model also predicts that the real wages gradually rise towards their new steady-state level, a finding which is consistent with the empirical evidence in Liu and Phaneuf (2007).

Figure 3.4 summarizes the effects of an expansionary policy shock measured as a negative one percent shock to the nominal interest rate. The responses of output, consumption, investment, hours and effort all exhibit typical hump-shaped patterns. Note, however, that the effects of a policy shock on output, hours, consumption and investment are relatively modest. The policy shock is also followed by a modest rise in inflation and a temporary increase in real wages.

Figure 3.5 shows that in response to a positive one percent shock to the marginal utility of consumption, output and consumption both rise temporarily, while investment falls. Baxter and King (1991) and Cooper and Johri (1997) report similar effects. Hours, effort and the real wages also rise. Inflation and the nominal interest rate weakly increase.

Figure 3.6 displays the impulse responses to a positive one percent shock to the marginal disutility of hours worked. Output, hours, consumption and investment all increase sharply, and display pronounced hump-shaped responses. With the surge in hours, effort falls. While labor supply increases, the real wages fall. As a result, both inflation and the nominal interest rate decline.

Lastly, Figure 3.7 shows that following a positive one percent investment-specific shock, output, investment, hours and effort all significantly rise in a hump-shaped fashion. After declining during a few periods, consumption rises for several periods. The real wages, inflation and the nominal interest rate all rise.

3.5.4 Variance Decompositions

What have been the main sources of the cyclical variance of output, hours and inflation during the postwar period? Table 3.5 reports the results of a variance decomposition of the forecast errors of output, hours worked, and inflation for different forecast horizons predicted by the benchmark model. First, the shock to the marginal disutility of hours is the key source of output fluctuations at an horizon of one to twelve quarters, explaining from 43 to 55 percent of its variance at these horizons. Using vector autoregression models, Shapiro and Watson (1988) find similar percentages. Investment-specific shocks explain between 22 and 32 percent of the variance of output at the same horizons, while technology shocks explain less than 20 percent. The relatively small contribution of neutral technology shocks is consistent with the evidence in Galí (1999), Christiano, Eichenbaum and Vigfusson (2004) and Fisher (2006). The shocks to the marginal utility of consumption and monetary policy feed only a small percentage of the variance of output.

The variance of hours worked is mostly driven by the shock to the marginal disutility of hours with 73 percent or more at all horizons. This leaves about 13 percent to investment-specific shocks at business-cycle frequencies, and relatively little to other shocks.

The shock to the marginal disutility of hours explains 62 percent of the one-quarter ahead forecast variance of inflation and 44 percent of its variability at an horizon of fourty quarters. Investment-specific shocks contribute between 24 and 40 percent of the variability of inflation at the same horizons. Monetary policy shocks explain about 11 percent of the variance of inflation at all horizons.

These findings thus suggest that the shock to the marginal disutility of hours is the key disturbance determining output fluctuations and inflation during the postwar period, followed by investment-specific shock.

3.6 From the Great Inflation to the Great Moderation

Does the benchmark model account for the large declines in the volatilities of output growth and inflation that have been observed during the Great Moderation? To answer this question, we reestimate the benchmark model for the subperiods 1948:I to 1979:II and 1984:I to 2006:II. The results are presented in Table 3.2.

3.6.1 Estimation Results

The last column of Table 3.2 reports the Andrews and Fair's (1988) Wald statistics allowing for a stability test of the structural parameters of the model over the two subperiods. The stability tests indicate that there have been some statistically significant changes in structural parameters from the first to the second subperiod. The coefficient of habit formation b has declined during the second subperiod, while the parameter $S''(\epsilon_a)$ determining the degree of investment adjustment costs has marginally increased.

The standard errors of all structural shocks have fallen considerably during the Great Moderation. Moreover, the declines in the standard errors of shocks to the marginal utility of consumption, the marginal disutility of hours, investment and monetary policy are statistically significant. The investment-specific shock has been 36 percent less volatile after 1984, followed by the technology shock and the shock to the marginal disutility of hours with 33 percent, the shock to the marginal utility of consumption with 30 percent, and the policy shock with 25 percent. Changes in the AR(1) coefficients of the stochastic processes generating the shocks to consumption, investment and the marginal disutility of hours are not statistically significant at a conventional confidence level.

Our estimates also say that the Federal Reserve has been more aggressive fighting inflation after 1984, with ρ_π increasing from 1.31 during the Great Inflation to 1.74 during the Great Moderation (see also Clarida, Galí and Gertler, 2000). However, we find no evidence of a statistically significant change in the Fed's reaction to the output gap. These results are different from those of Smets and Wouters (2007) who find that the Fed's reaction to inflation has not changed significantly during the Great Moderation, while its response to the output gap did. We also find that the interest-rate smoothing coefficient has marginally decreased during the second subperiod.

The point estimate of Γ determining the responsiveness of inflation to the real marginal cost is 0.0579 during the Great Inflation and 0.0341 during the Great Moderation. Table 3.3 reports the frequency of price reoptimization corresponding to these estimates. With $\Gamma = 0.0579$, the benchmark model implies an average amount of time between price reoptimization of 2.32 quarters with $\epsilon = 10$ and 2.04 quarters with $\epsilon = 33$. In comparison, the benchmark model predicts a frequency of price reoptimization during the Great Moderation of once every 2.93 quarters with $\epsilon = 10$ and 2.51 quarters with $\epsilon = 33$. Hence, the average length of time between price reoptimization has slightly increased from the Great Inflation to the Great Moderation. Working in the context of a DSGE model without factor firm-specificity, Smets and Wouters (2007) find that the Calvo-probability of price non-reoptimization has increased from 0.55 during the Great Inflation to 0.73 during the Great Moderation. Assuming firm-specific capital, Eichenbaum and Fisher (2007) report that the frequency of price reoptimization has slightly increased after 1982:III.

Table 3.4 compares the standard deviations of output growth and inflation and the correlation between these variables in the benchmark model and in the data during each subperiod. The benchmark model accounts very well for the severity of the declines in the volatilities of output growth and inflation from the Great Inflation to the Great Moderation. While the data tell that the volatility of output growth has decreased by 55 percent, the model predicts a drop of 43 percent. Also, the variability of inflation has fallen by 65 percent, compared to a decline of 56 percent predicted by the benchmark model. Finally, the benchmark model correctly predicts that the correlation between output growth and inflation has become increasingly negative from the first to the second subperiod.

3.6.2 What Are the Sources of the Great Moderation?

What are the sources of the large reductions in the volatilities of output growth and inflation? We try to answer this question by performing some counterfactual experiments. We partition the model's structural parameters into three subsets of parameters. G_1 regroups the parameters pertaining to the behavior of the private sector and is thus described by $G_1 = \{\beta, b, 1/\eta_h, 1/\eta_c, S''(\epsilon_a), \Gamma\}$. G_2 is composed of the parameters describing the systematic portion of the Fed's policy rule and is given by $G_2 = \{\rho_r, \rho_\pi, \rho_g\}$. G_3 includes the AR(1) parameters and the standard errors of the structural shocks, so $G_3 = \{\rho_c, \rho_h, \rho_i, \sigma_c, \sigma_h, \sigma_i, \sigma_a, \sigma_m\}$. Denote by $C_x(G_1)$, $C_x(G_2)$, and $C_x(G_3)$, respectively, the contributions of G_1, G_2, and G_3 to the change in the volatility of variable of interest x during the Great Moderation, where $x = \{\text{output growth, inflation}\}$. These contributions can be measured by (see also Leduc and Sill, 2007):

$$C_x(G_1) = \frac{\sigma_x(G_1^{79}, G_2^{79}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{79}, G_3^{79})}{\sigma_x(G_1^{79}, G_2^{79}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{84}, G_3^{84})}$$

$$C_x(G_2) = \frac{\sigma_x(G_1^{84}, G_2^{79}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{84}, G_3^{79})}{\sigma_x(G_1^{79}, G_2^{79}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{84}, G_3^{84})}$$

$$C_x(G_3) = \frac{\sigma_x(G_1^{84}, G_2^{84}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{84}, G_3^{84})}{\sigma_x(G_1^{79}, G_2^{79}, G_3^{79}) - \sigma_x(G_1^{84}, G_2^{84}, G_3^{84})}$$

Here, the term $\sigma_x(G_1^{84}, G_2^{79}, G_3^{79})$ measures the standard deviation of x predicted by the benchmark model during the second subperiod would the properties of the shock-generating processes and the policy rule have remained the same as they were during the first subperiod. Hence, $C_x(G_1)$ measures the percentage of the variation in the standard deviation of the variable x explained by the change in the behavior of the private sector G_1. The denominator, which is common to all three measures, denotes the overall change in the volatility of x. A similar reasoning applies to the other sources of the variation in the standard deviation of x.

The results of these counterfactual experiments are presented in Table 3.6. Looking at the real side of the Great Moderation, we find that smaller shocks contribute to almost 85 percent of the decline in the volatility of output growth, leaving only 15 percent to be explained by changes in the behavior of the private sector and monetary policy. Table 3.7 shows that smaller labor-supply shocks explain 50 percent of the decline in output fluctuations, followed by smaller investment-specific shocks with 22 percent.

Looking at the nominal side of the Great Moderation, we find that smaller shocks explain only one third of the decline in the volatility of inflation, leaving 32.5 and 34.3 percent, respectively, to changes in the behavior of the private sector and monetary policy.

3.6.3 Related Literature

How do our findings about the sources of the Great Moderation relate to the existing literature? Other researchers, including Stock and Watson (2003), Sims and Zha (2006), Smets and Wouters (2007), Arias et. al. (2007) and Leduc and Sill (2007), also find that the decline in the volatility of output growth after 1984 has resulted mostly from smaller shocks. Most papers, however, do not identify the shocks that contribute most to the increased stability in output fluctuations.

Smets and Wouters (2007) use a DSGE model featuring nominal rigidities, real frictions and a variable elasticity of demand, but without factor firm-specificity. The benchmark model underpredicts the volatility of output growth by 7.2 percent during the Great Inflation and overpredicts it by 17.3 percent during the Great Moderation. In comparison, the model in Smets and Wouters (2007) overpredicts the volatility of output growth by 11.9 percent during the former subperiod and by 23.7 percent during the later subperiod. Also, the benchmark model overpredicts the variability of inflation by only 2.5 percent during the Great Inflation and by 29.6 percent during the Great Moderation, while Smets and Wouters' (2007) model overpredicts it by 47.2 percent during the first subperiod and by 36 percent during the second subperiod.

The papers by Arias et. al. (2007) and Leduc and Sill (2007) identify smaller TFP shocks as the main source of the decline in real output volatility. Arias et. al. (2007) use a real business cycle model featuring variable capacity utilization, variable effort and indivisible labor along the lines of Burnside and Eichenbaum (1996) to study the sources of the decline in the volatility of output growth. Yet, they make no attempt to also explain the large drop in the volatility of inflation. But, it is well known that real business models grossly overstate the variability of inflation in response to TFP shocks because in these models prices are perfectly flexible (see Liu and Phaneuf, 2007).

Leduc and Sill (2007) develop a sticky-price model with an energy sector and firms facing a quadratic price-adjustment cost. The volatility of inflation in the data is 6.6 times larger than that predicted by their model.

3.7 Conclusion

Hall (1997) forcefully argues that the emphasis on technology shocks in business cycle theory may have been misplaced. He offers evidence consistent with Shapiro and Watson's (1988) finding that shifts in labor supply have been a key driving force at business-cycle frequencies during the postwar period. This chapter provides new evidence of the potential importance of labor supply shocks by showing that they have been the main source of the large decline in the volatility of real output growth during the Great Moderation. However, we also find that the large drop in the variability of inflation is almost evenly explained by changes in the behavior of the private sector, a less accommodative monetary policy and smaller shocks.

The DSGE framework used for the purpose of our empirical investigation is built on the premises that price-setting firms face a variable elasticity of demand and that labor is firm-specific. These assumptions help resolve the conflicting pictures between the microeconomic evidence indicating that firms reoptimize prices quite frequently with the evidence from aggregate time series that inflation is quite persistent.

Table 3.1: Summary Statistics about Output Growth and Inflation

	1948:I-2006:II	1948:I-1979:II	1984:I-2006:II
Output growth	0.0130	0.0153	0.0069
Inflation	0.0069	0.0078	0.0027
$corr(\Delta y_t, \pi_t)$	-0.2079	-0.1672	-0.3104

Table 3.2: Maximum Likelihood Estimates (Benchmark Model)

	1948:I-2006:II		1948:I-1979:II		1984:I-2006:II		
Parameter	Estimate	S.E	Estimate	S.E	Estimate	S.E	W' statistic
b	0.5713	0.0012	0.5938	0.0104	0.5598	0.0010	10.6521***
$1/\eta_h$	0.8496	0.0010	0.8204	0.2133	0.8618	0.0119	0.0377
$1/\eta_e$	0.1484	0.0081	0.1229	0.0887	0.1551	0.0018	0.1315
$S''(\epsilon_a)$	2.7520	0.0192	2.6416	0.0092	3.1621	0.2882	3.2585*
ρ_r	0.7542	0.0234	0.7861	0.0260	0.7433	0.0001	2.7278*
ρ_π	1.5295	0.1337	1.3143	0.0079	1.7401	0.1595	7.1105***
ρ_y	0.1511	0.0652	0.1739	0.0611	0.1428	0.0732	0.1060
ρ_c	0.5696	0.0461	0.5903	0.0068	0.5477	0.1530	0.0773
ρ_h	0.8832	0.0198	0.9090	0.0101	0.8621	0.0240	3.2368*
ρ_i	0.7918	0.0336	0.7536	0.0709	0.7738	0.0109	0.0789
Γ	0.0432	0.0125	0.0579	0.0004	0.0341	0.0055	18.3266***
σ_a	0.0115	0.0027	0.0128	0.0039	0.0086	0.0038	0.6016
σ_m	0.0025	0.0002	0.0020	0.0002	0.0015	0.0001	4.6748**
σ_c	0.0122	0.0010	0.0134	0.0012	0.0094	0.0014	4.7707**
σ_h	0.0726	0.0118	0.0733	0.0104	0.0488	0.0038	4.8841**
σ_i	0.0343	0.0030	0.0371	0.0040	0.0238	0.0012	9.9570***

Note: S.E denotes the standard deviation. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Table 3.3: Implied Probability of Price Reoptimization

	Homogeneous labor			Specific labor		
	$\epsilon = 0$	$\epsilon = 10$	$\epsilon = 33$	$\epsilon = 0$	$\epsilon = 10$	$\epsilon = 33$
1948:I-2006:II						
ξ	0.815	0.7422	0.6423	0.6563	0.6233	0.5637
$1/(1-\xi)$	5.4052	3.8794	2.7953	2.9099	2.6544	2.2919
1948:I-1979:II						
ξ	0.7879	0.7073	0.5989	0.6035	0.5698	0.5094
$1/(1-\xi)$	4.7149	3.4165	2.493	2.5218	2.3245	2.0383
1984:I-2006:II						
ξ	0.834	0.7674	0.6746	0.6905	0.6591	0.602
$1/(1-\xi)$	6.0257	4.2999	3.0727	3.2313	2.933	2.5125

Table 3.4: Output Growth and Inflation:

Standard Deviations and Correlations

	1948:I-2006:II		1948:I-1979:II		1984:I-2006:II	
	Data	Model	Data	Model	Data	Model
Output growth	0.0130	0.0129	0.0153	0.0142	0.0069	0.0081
Inflation	0.0069	0.0064	0.0078	0.0080	0.0027	0.0035
$corr(\Delta y_t, \pi_t)$	-0.2079	-0.0851	-0.1672	-0.0583	-0.3104	-0.1461

Table 3.5: Forecast Error Variance Decompositions (in %)

Output					
Horizons	Technology	Monetary	Consumption	Labor supply	Investment
1	9.5055	6.1120	10.1568	42.5481	31.6776
4	11.9442	2.6982	2.7433	53.8372	28.7771
8	15.6078	1.3945	1.1437	56.9637	24.8903
20	29.7602	0.7397	0.5854	50.1616	18.7531
40	49.4559	0.5009	0.3949	36.2612	13.3871
100	74.3662	0.2528	0.1992	18.3844	6.7975

Hours worked					
Horizons	Technology	Monetary	Consumption	Labor supply	Investment
1	6.3384	2.5617	4.2570	73.5662	13.2768
4	1.2622	1.8642	2.0406	78.8516	15.9814
8	0.8186	1.1641	1.1084	83.3553	13.5535
20	1.0844	0.9022	0.8531	86.0103	11.1501
40	1.2658	0.8945	0.8433	85.3536	11.6428
100	1.2903	0.8925	0.8410	85.2350	11.7412

Inflation					
Horizons	Technology	Monetary	Consumption	Labor supply	Investment
1	0.5180	11.8608	1.3689	61.9231	24.3292
4	0.4848	12.2765	1.3148	48.3301	37.5939
8	1.3026	11.8163	1.2281	45.0892	40.5638
20	2.8080	11.4288	1.1894	43.9853	40.5885
40	3.2304	10.9257	1.1383	43.7724	40.9331
100	3.2762	10.8197	1.1274	43.8799	40.8968

Table 3.6: Contributions to the Reduction of the Standard Deviation of Output Growth and Inflation (in %)

	Private sector	Monetary policy	Shocks
Δy_t	9.2	5.9	84.9
π_t	32.5	34.3	33.2

Table 3.7: Contributions of Shocks to the Reduction of the Standard Deviation of output growth and inflation (in %)

	Technology	Monetary policy	Consumption	Labor supply	Investment
Δy_t	8.2	1.4	5.9	58.8	25.7
π_t	3.8	5.1	1.6	47.3	42.2

Figure 3.1: Output Growth and Inflation

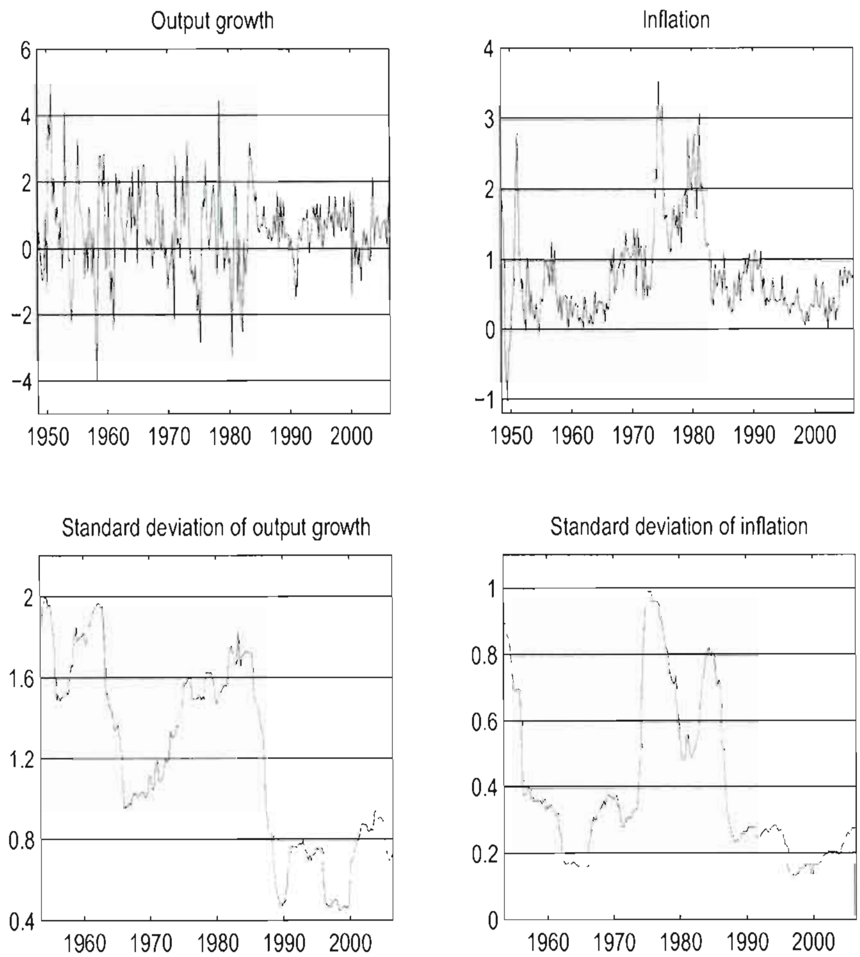
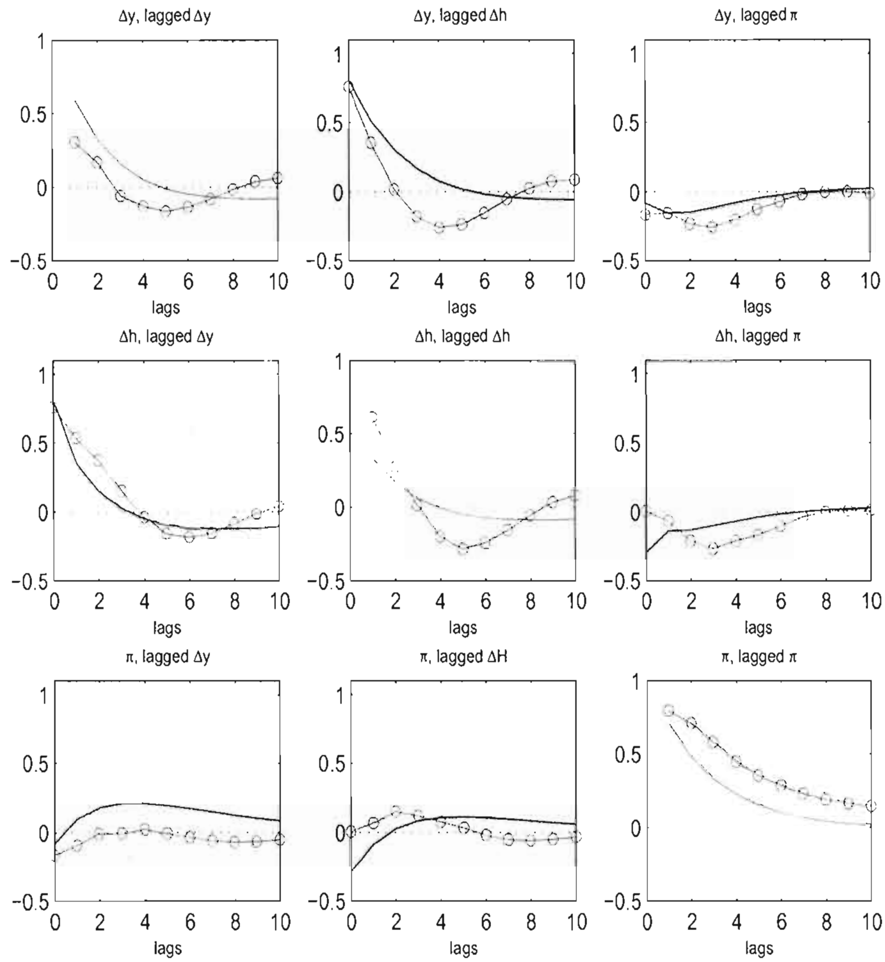


Figure 3.2: Vector Autocorrelation Functions: Benchmark Model vs Vector Autoregression



Note: Benchmark Model: solid line. Data: line with circles.

Figure 3.3: Impulse Responses to a Positive Technology Shock

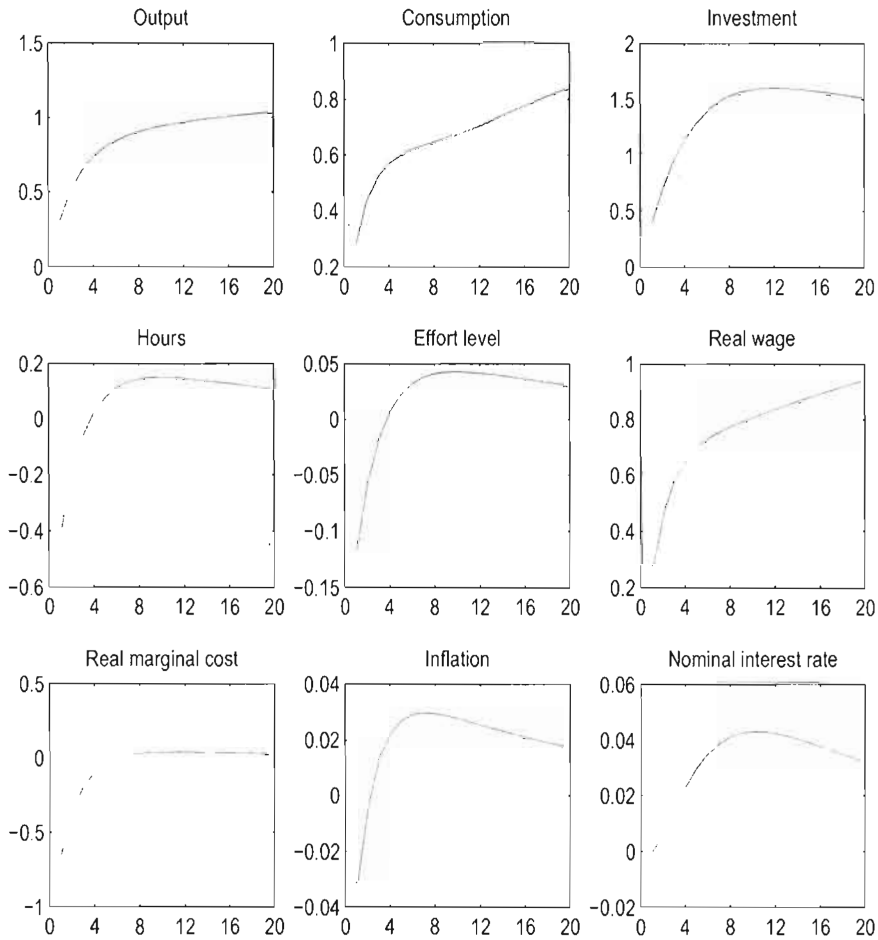


Figure 3.4: Impulse Responses to an Expansionary Policy Shock

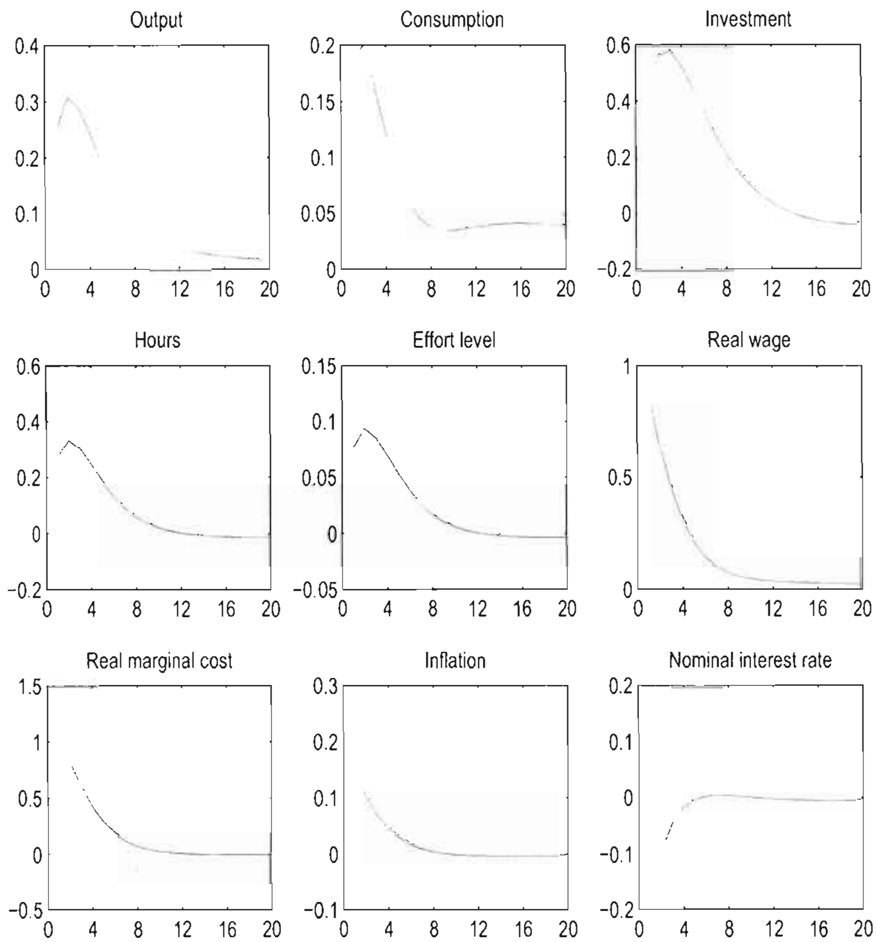


Figure 3.5: Impulse Responses to a Positive Shock to the Marginal Utility of Consumption

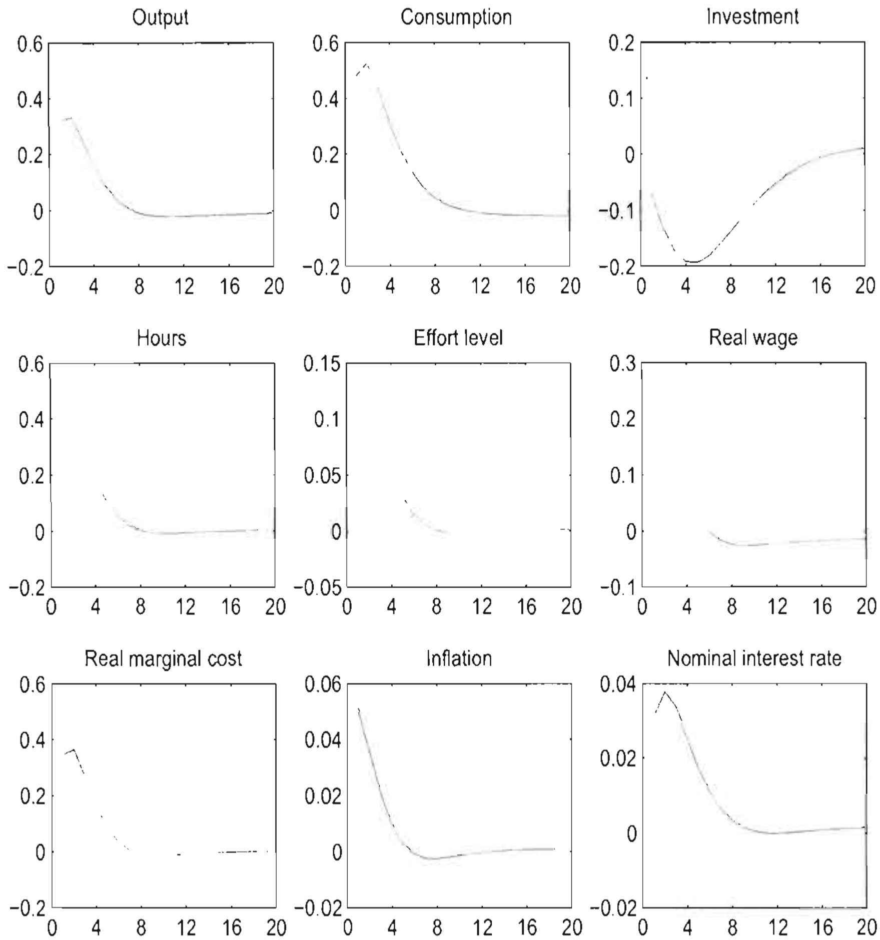


Figure 3.6: Impulse Responses to a Positive Labor Supply Shock

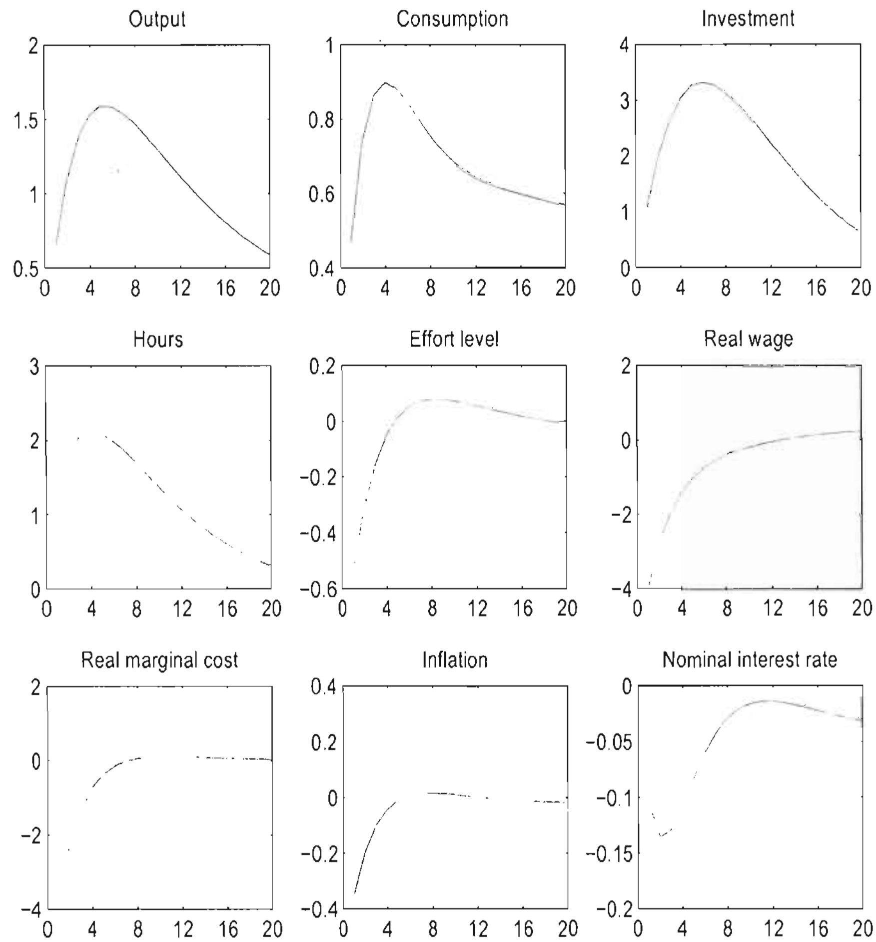
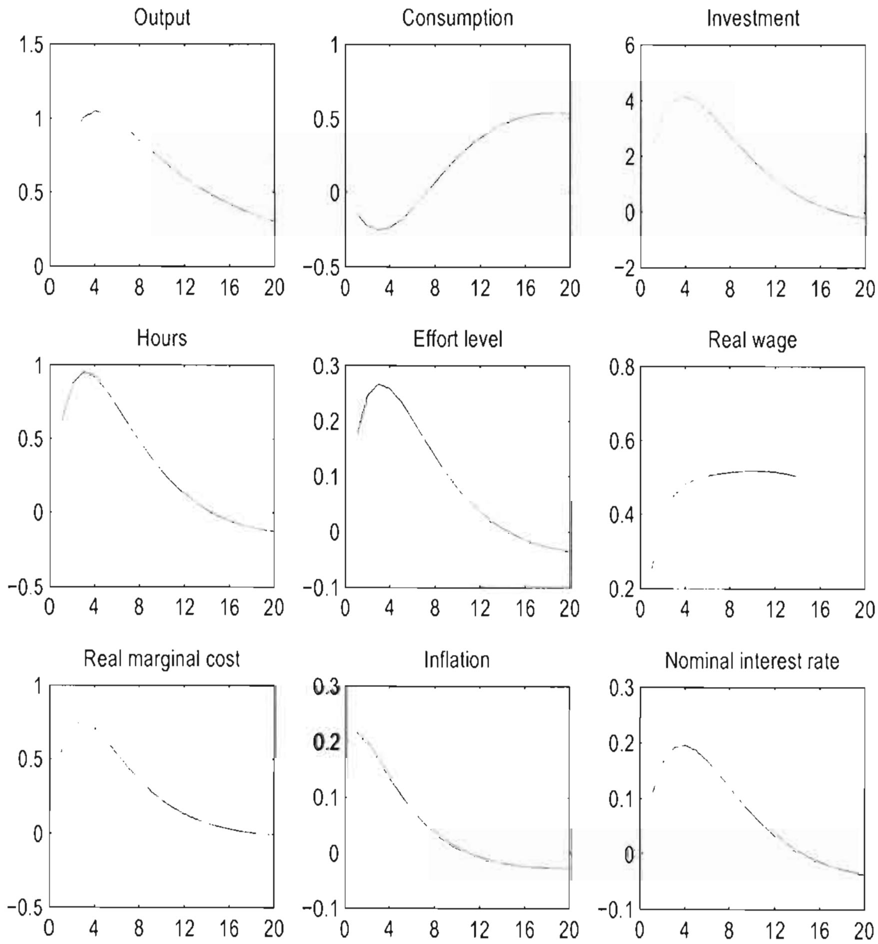


Figure 3.7: Impulse Responses to a Positive Investment-Specific Shock



Appendix

This appendix briefly shows how the Phillips curve equation (3.16) is derived. First, recall that $\varepsilon(1)$ denotes the demand elasticity of intermediate good i evaluated at the steady state. We linearize the first-order condition for the finished-good firm's problem (3.9), the no-profit condition for the finished-good firm (3.15), and the first-order condition for the optimal price of the intermediate-good firm (3.14). These equations are:

$$y_{i,t+\tau} - y_{t+\tau} = -\varepsilon(1)(p_t^* - p_{t+\tau}), \tag{i}$$

$$p_t^* - p_t = \frac{\xi}{(1-\xi)}\pi_t. \tag{ii}$$

$$\frac{1}{(1-\beta\xi)}(p_t^* - p_t) = E_t \sum_{\tau=0}^{\infty}(\beta\xi)^\tau [mc_{i,t+\tau} + p_{t+\tau} - p_t - \varphi_1(p_t^* - p_{t+\tau})]. \tag{iii}$$

where

$$\varphi_1 = \left(\frac{1 + \left(1 + \frac{G'''(1)}{G''(1)}\right)\varepsilon(1)}{\varepsilon(1) - 1}\right).$$

Eichenbaum and Fisher (2004, appendix) show that $1 + \left(1 + \frac{G'''(1)}{G''(1)}\right)\varepsilon(1) = \epsilon$, where ϵ is the percent change in the elasticity of demand due to a one percent change in the relative price of the good, evaluated at the steady state. From the household's first-order conditions, we have :

$$(1 + \eta_e)e_{i,t+\tau} = (1 + \eta_h)h_{i,t+\tau}. \tag{iv}$$

The real marginal cost of firm i is related to the aggregate real marginal cost by:

$$mc_{i,t+\tau} = mc_{t+\tau} - \varphi_2(p_t^* - p_{t+\tau}). \tag{v}$$

where

$$\varphi_2 = (\varepsilon(1) - 1)\left[\frac{A - B}{(1 + \alpha(A - B))^{I^F}} - 1\right], \qquad A = \left(\frac{1 + \eta_h}{1 - \alpha}\right), \qquad B = \left(\frac{(1 + \eta_h)^2}{(2 + \eta_h + \eta_e)(1 - \alpha)}\right).$$

where I^F is an indicator function taking a value of 1 if capital is homogenous and mobile across firms, and a value of 0 if capital is fixed. Note that as $\eta_e \longrightarrow \infty$, then $B \longrightarrow 0$.

Substituting (i), (ii), (iv) and (v) in (iii) and rearranging, we obtain equation (3.16) in chapter 3:

$$\pi_t = \beta E_t \pi_{t+1} + \Gamma mc_t,$$

where $\Gamma = \frac{(1-\beta\xi)(1-\xi)}{\xi}\varphi^{-1}$, and $\varphi = 1 + \varphi_1 + \varphi_2$.

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