An Estimated DSGE Model of the US Economy with an Application to Natural Rate Measures

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Abstract

This paper discusses a monetary dynamic stochastic general equilibrium model of the US economy. The model is designed to capture the most important production and expenditures decisions in the US economy while remaining sufficiently small to allow intuitive storytelling regarding the key drivers of economic fluctuations. We emphasize the role of model-based analyses as vehicles for storytelling by providing several examples of how our model provides stories regarding the nature of fluctuations in recent years that are both similar to and quite dissimilar from conventional accounts – in particular with regard to the evolution of the natural or efficient rates of production and interest. These examples highlight aspects of DSGE models that may benefit substantially from further research.

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1 Introduction

"We should not expect our discipline to be exempt from the pattern of the natural sciences, in which models of different types and levels of detail are used for different purposes. Many, maybe even most, practical applications of the laws of natural science ignore the "microfoundations" of quantum and relativity theory. In applications like weather forecasting or epidemiology, detailed use of data often requires modeling with little explicit guidance from physical theory." Christopher Sims [1989]

"Forecasting based on structural models, my preferred approach, is not the only way to go. Diversity in our profession, as in other professions, should be valued, not just tolerated." Laurence Meyer [1997]

We present an estimated dynamic general equilibrium model of the US economy suitable for addressing several key questions that arise in monetary policy analysis. Relative to most previous models of a similar type, our model is somewhat more disaggregated along dimensions of both aggregate demand and aggregate supply. As discussed below, this is motivated both by a priori reasoning regarding what level of disaggregation is important for capturing the evolution of the US economy and to allow the model to address, at least in some modest respect, questions that have played a large role in policy discussions over the past decade. After presenting these aspects of the model and some of its basic properties, our analysis turns to consider one of the potentially practical uses for our model in policy discussions – its ability to generate economically interpretable estimates of the output gap and natural rate of interest.

Before turning to our model, some brief comments on the applications of our model we see as most likely are in order. We expect DSGE models similar to ours to prove useful in the forecast process, to provide insight into the structural disturbances hitting the economy and their implications for the efficiency of fluctuations, and to illustrate the probable form of good monetary policy. However, we do not expect our model, or close cousins, to replace the Federal Reserve's FRB/US model – a large-scale macroeconometric model. This should be quite clear from our discussion below, and reflects several factors. First, we suspect that the contribution of model-based analyses will be enhanced by consideration of multiple models, i.e., that in some cases we will learn as much about the outlook and its implications for policy when models disagree as when they agree. (For a discussion of the range of models typically consulted in forecasting and policy work by staff at the Federal Reserve, see Reifschneider *et al.* [1997]). Importantly, the robustness of different policy strategies across models with quite different foundations is important given significant differences of opinion regarding the plausibility of different models, suggesting that regular consultation of a range of models is a good strategy (e.g., Levin *et al.* [2003]); diversity is a virtue in model-based analyses. Finally, small models like ours are simply incapable of addressing many of the questions we address with FRB/US on a daily basis.

Returning to our analysis, our first goal in this research is to emphasize that perhaps the most important output for policy purposes of any model is its story regarding how the economy operates. In our experience, policymakers at central banks are not focused on the minute details of a model's forecast or estimates of its structural parameters. Rather, their focus is on what is happening in the economy, and structural models provide a lens through which the key factors shaping the outlook can be more clearly perceived. We attempt to provide examples of this storytelling role for our DSGE model herein.[1]

The model we consider builds on most recent treatments by distinguishing between two production sectors, which differ in their long-run growth rates of technological progress. Our two-sector setup allows us to match key facts regarding secular trends in expenditure and productivity (as discussed in section 2), and may be important for policy analysis because the sectoral source of a given fluctuation in multifactor productivity can be important for the outlook for activity and inflation, as well as the appropriate policy response.

Similarly, our treatment of aggregate demand is more detailed than most treatments. We distinguish between several categories of household expenditure specifically, the consumption of nondurables and services, investment in durables, and investment in residences. This is important because a large body of research has documented that purchases of consumer durables and homes systematically lead business investment and may respond differently to monetary and perhaps other shocks. (For example, the literature on home production has emphasized these facts; a now somewhat-dated-but-still-useful treatment is Greenwood *et al.* [1995]).

However, we would also emphasize that our level of disaggregation comes at a cost. In particular, the resulting model is more complicated – perhaps not in a substantive sense,

[1] This is not meant to imply that related efforts by other researchers have not emphasized this role for DSGE models. Both the IMF's GEM (IMF [2004]) and the SIGMA model (Erceg *et al.* [2005]) used in the Federal Reserve's Division of International Finance have been employed as storytelling vehicles, including in contributions to this conference. Our effort is a bit different in its close link between the story we are telling as a historical decomposition of fluctuations and the role of estimation.

but clearly with regard to size, which can be a barrier to understanding on the part of consumers not immersed in the details of a given model. Moreover, the disaggregated series are typically more volatile. In companion work (not-yet-completed), we intend to compare the fit of our more-detailed model to simpler specifications. Another complication arises with regard to the sources of volatility in the data. The data clearly require as many sources of volatility as variables; therefore, additional variables necessitate the addition of more structural shocks or measurement errors. When two production sectors are modeled, an additional stochastic productivity shock is quite natural; however, it is debatable whether additional preference shocks (for durables and housing) are either appropriate (e.g., from a home production standpoint, probably yes) or particularly informative about the source of variation in these important macroeconomic series. Despite these concerns with enlarging a dynamic general equilibrium model for policy analysis beyond the typical size, we proceed for the reasons outlined below.

The next section provides more detailed motivation for our focus on storytelling and for the size of our model. Section 3 outlines the preference, capital evolution, and production technologies underlying our model while section 4 outlines the model's decentralization; section 5 discusses our estimation strategy and key properties of the model given our parameter estimates. (Edge, Laforte, and Kiley (2005) provides much more detail about these issues). Section 6 presents and discusses our model's estimates of the output gap and the equilibrium real interest rate. Section 7 concludes.

2 Motivation

"A model-based forecast ends with a story. When I was in the private sector and was asked what I did for a living I often responded that I was a storyteller. My experience as a commercial forecaster taught me that clients did not want to be buried in computer output. They demanded a coherent story that tied the forecast together. A model-based forecast has the ability to essentially explain itself." Meyer [1997]

2.1 What Constitutes a Good Model for Monetary Policy Analysis?

This is a hard question, and we will only touch on this broad issue. Models used for policy analysis must be based on plausible assumptions regarding the behavior of agents in the economy; they must make quantitative predictions that can match observed regularities in the data; and they should be capable of providing insight into the effects of changes in policy regime on the dynamics of the macroeconomy.

These are quite weak requirements, and some researchers or policymakers may have more stringent standards for a model of the macroeconomy. It is clear that a diverse set of models, or modeling strategies, satisfies each of these requirements. For example, a vector autoregression can summarize key regularities in the data, provide insight into the effects of modest monetary policy interventions (e.g., monetary policy shocks), and is based on the plausible view that the all variables depend upon a rich set of determinants (i.e., a large set of "states"); a small calibrated New-Keynesian model can match, in broad terms, the relationship between output, inflation, and policy interest rates, is based on clear behavioral assumptions, and respects the Lucas critique by linking the policy regime to the dynamic behavior of all endogenous variables; and large structural macroeconometric models, like the Federal Reserve's FRB/US model, are derived from the core set of neoclassical assumptions regarding household and firm behavior (e.g., the permanent income hypothesis, the neoclassical (Jorgenson) investment model, etc.), are matched closely to the data through (admittedly strong) assumptions regarding dynamic adjustment, and contain a rich description of the monetary transmission mechanism.

We have specified and estimated a moderately-sized dynamic stochastic general equilibrium (DSGE) model for the United States to add to the set of tools that can be used to analyze US fluctuations, and view this addition as a potentially useful complement to other models, like FRB/US, used for policy analysis at the Federal Reserve. A diverse set of models, each with different strengths, can help provide better insight into a range of questions.

The recent literature on DSGE models in a policy context has made significant progress in developing models that meet each of the basic requirements noted above. Importantly, recent research has shown that estimated DSGE models are capable of matching the data for key macroeconomic variables as well as reduced-form vector autoregressions (Smets and Wouters [2004a], Smets and Wouters [2004b], Christiano *et al.* [2005], Altig *et al.* [2004]). We view this as very important, but do not explore the details of our model's fit to the data in this research. Rather, we emphasize the ability of our model to tell "stories" in a policymaking context; Our experience at the Federal Reserve using FRB/US or other models has suggested that the stories told by structural models are perhaps their most important output, and facilitate communication among participants of the forecast and policymaking process.

2.2 Some Motivation for Our Modeling Choices

Our model has been built to provide some insight into US economic fluctuations. One area of particular concern in our analysis is accounting for the trends in certain relative prices and categories of real expenditure apparent in the data. As can be seen from Table 1, expenditures on consumer non-durable goods and non-housing services and residential investment have grown at roughly similar real rates of around 3-1/2 percent over the last 20 years, while consumer durable goods and nonresidential investment have grown at around 6-1/2 percent. The relative price of residential investment to consumer non-durable goods and non-housing services has increased 1/2 percent on average over the last 20 years (with about half of this average increase accounted for by a large swing in relative prices over the last two years). The prices of both consumer durable goods and non-residential investment (relative to consumer non-durable goods and non-housing services) have decreased on average about 3 percent.

A one-sector model, which appears to be the most widely used for DSGE models of the US economy, is clearly unable to deliver predictions for long-term growth and relative price movements that are consistent with the above-mentioned stylized facts. Specifically, one-sector growth models, such as those that form the neoclassical-core of the models developed by Smets and Wouters [2004b] and Altig *et al.* [2004] imply that all non-stationary real variables grow at the same rate, so that over long periods of time the great ratios are evident in the data.

Single sector models also imply that there is only one price in the economy. For many reasons, we might want to avoid this assumption. First, even in the absence of divergent rates of technical progress across sectors, policymakers may be interested in knowing about more than one price index. For example, different price indices sometimes have different degrees of price-stickiness. Under plausible assumptions, policymakers may wish to focus price stabilization efforts on especially sticky prices; for example, if consumer prices are more sticky than investment good prices, stabilization efforts may wish to focus more on consumer prices than investment or GDP prices.

Moreover, we expect that taking account of the trends in relative prices and expenditure along the economy's steady-state growth path is important in model estimation, since the correct attribution of movements in macroeconomic time series to trend or business cycle fluctuations is a central aspect of obtaining reliable estimates of the structural parameters and indeed the sequence of shocks generating observed movements in the data. This latter function of the model can be quite important for policy. For example, a major theme of FOMC discussions in the late 1990s was the role of technological progress, particularly in high-tech equipment and software, as the source of strong growth and low inflation (e.g., Greenspan [1999]). Even the version of the much larger model in use at that time for forecasting and policy analysis at the Federal Reserve Board (the FRB/US model)was deemed lacking because it did not allow for the separate consideration of high-tech equipment and software and other equipment. While we do not venture to disaggregate to such an extent, this experience in a policy context contributes to our view that a significant degree of disaggregation in aggregate supply is necessary to address likely concerns of policymakers. (Of course, each model need not be capable of addressing *all* possible questions; we feel that our setup is a minimal complication given the potential advantages, and expect experience working with the model to provide more insight into whether our disaggregation of production proves valuable or a distraction).

For these reasons, we attempt to model in some detail the production and expenditure decisions that occur throughout the economy while maintaining a modest-sized model. On the production side of the model, we distinguish between the output produced by the government, the household sector, and the business and institutions sector.[2] The government sector produces a single (government services) output, denoted X_t^{cg}, as does the household sector, which produces housing services, denoted X_t^{ch}, from its stock of residential capital. The business and institutions part of the model assumes a two-sector growth structure, with differential rates of technical progress across sectors. The different rates of technological progress induce secular relative price differentials, which in turn lead to different trend rates of growth across the economy's expenditure and production aggregates. This structure is necessary for the model to be consistent with recent differences in the real growth rates of expenditure aggregates and sizeable trends in relative prices.

The disaggregation of production (aggregate supply) leads naturally to some disaggrega-

[2]Note, the US National Income and Product Accounts (NIPA) split production into that of the government sector, household and institutions sector, and the business sector. Our split is more convenient given the breakdown of expenditures in the model.

tion of aggregate demand, specifically the distinction between spending on consumption (or slow-growing) goods and on capital (or fast-growing) goods. Beyond this, however, we assume the following disaggregation for (private domestic) spending. We consider separately spending on consumer non-durable goods and non-housing services E_t^{cnn}, consumer durable goods E_t^{cd}, residential investment E_t^r, and non-residential investment E_t^{nr}. As might be suggested by the long-run real- and nominal-expenditure growth rates reported in Table 1, we assume that the output produced by the consumption (or slow-growing) sector, X_t^{cbi}, is used for consumer non-durable goods and non-housing services, E_t^{cnn}, and residential investment, E_t^r, while the output produced by the capital (or fast-growing) sector, X_t^{kb}, is used for consumer durable goods, E_t^{cd}, and non-residential investment, E_t^{nr}.

While differential trend growth rates are one motivation for the disaggregation of spending, equally important is the well-known fact that the expenditure categories that we consider co-move quite differently with aggregate output. As shown in Table 2, consumer durables and residential investment tend to lead GDP, while non-residential *fixed* investment (not shown) lags. These patterns suggest some differences in the short-run response of each series to structural shocks. One area where this is apparent is the response of each series to monetary-policy innovations. Figures 1 and 2 presents impulse response functions for GDP and the various expenditure categories just highlighted for two samples 1965q1 to 2004q4 and 1984q1 to 2004q4. In the earlier sample, it is very clear that residential investment and consumer durables respond to the monetary policy innovation much more sizably and quickly; for residential investment much of this probably reflects the impact of disintermediation induced by Regulation Q and other restrictions on credit periodically associated with monetary policy changes prior to deregulation in the early 1990s (McCarthy and Peach [2002]) investigate similar issues in more detail). However, even the more recent period shows a more rapid and pronounced response of residential investment and consumer durables to a monetary policy innovation in the post-1984 period, albeit with large standard errors.

Beyond this statistical motivation, our disaggregation of household demand is motivated by two related discussions. First, the home production literature continues to emphasize the distinction in the business cycle properties of household and business investment (e.g., Fisher [2001]), differences that are ignored when these series are aggregated into one investment spending aggregate. Second – and equally importantly – an issue of concern to policymakers more recently has been the divergent movements in household and business investment since the last recession (e.g., Kohn [2003]). We view providing an explanation for these divergent patterns of spending through differential impacts of monetary policy, technology, and preference shocks as a potentially important operational role for our DSGE model.

3 Production, Capital Evolution, and Preferences

In this section we present the production, capital evolution, and preference technologies for our model. The long-run evolution of the economy is determined by differential rates of stochastic growth in the production sectors of the economy, while its short-run dynamics are influenced by various forms of adjustment costs. Adjustment costs to real aggregate variables are captured by the economy's preference, production, and capital evolution technologies presented in this section. Adjustment costs to real sectoral variables and nominal variables are captured in the decentralization of the model presented in the following section.

3.1 The Production Technology

As noted in the previous section our model economy produces four final goods and services:

- Government services, X_t^{cg};
- Housing services, X_t^{ch};
- Slow-growing "consumption" goods and services X_t^{cbi}; and,
- Fast-growing "capital" goods X_t^{kb}.

We consider first the production of the economy's **slow-growing "consumption" goods and services** and **fast-growing "capital" goods**. These final goods are produced by aggregating—according to a Dixit-Stiglitz technology—an infinite number of differentiated inputs. Specifically, final goods production is represented by the function

$$X_t^s = \left(\int_0^1 X_t^s(j)^{\frac{\Theta_t^{x,s}-1}{\Theta_t^{x,s}}} dj \right)^{\frac{\Theta_t^{x,s}}{\Theta_t^{x,s}-1}}, \qquad s = cbi, kb, \tag{1}$$

where the variable $X_t^s(j)$ denotes the quantity of the jth input (obtained from the intermediate goods sector) used to produce final output $s = cbi$ or $s = kb$ while $\Theta_t^{x,s}$ is the stochastic elasticity of substitution between the differentiated intermediate goods inputs used in the production of the consumption or capital goods sectors. Letting $\theta_t^{x,s} \equiv \ln\Theta_t^{x,s} - \ln\Theta_*^{x,s}$ denote the log-deviation of $\Theta_t^{x,s}$ from its steady-state value of $\Theta_*^{x,s}$, we assume that

$$\theta_t^{x,s} = \epsilon_t^{\theta,x,s} \tag{2}$$

where $\epsilon_t^{\theta,x,s}$ is an i.i.d. shock process.

The jth differentiated intermediate good in sector s (which is used as an input in equation 1) is produced by combining each variety of the economy's differentiated labor inputs $\{L_t^s(i,j)\}_{i=0}^1$ with the sector's specific *utilized* non-residential capital stock $K_t^{u,nr,s}(j)$. (Utilized non-residential capital, $K_t^{u,nr,s}(j)$, is equal to the product of *physical* non-residential capital, $K_t^{nr,s}(j)$, and the utilization rate, $U_t^{nr,s}(j)$). A Dixit-Stiglitz aggregator characterizes the way in which differentiated labor inputs are combined to yield a composite bundle of labor, denoted $L_t^s(j)$. A Cobb-Douglas production function then characterizes how this composite bundle of labor is used with capital to produce—given the current level of multifactor productivity MFP_t^s in the sector s—the intermediate good $X_t^s(j)$. The production of intermediate good j is represented by the function:

$$X_t^{m,s}(j) = (K_t^{u,nr,s}(j))^{\alpha}\left(\underbrace{A_t^m Z_t^m A_t^s Z_t^s}_{MFP_t^s} L_t^{x,s}(j)\right)^{1-\alpha} \text{ where } L_t^{x,s}(j) = \left(\int_0^1 L_t^{x,s}(i,j)^{\frac{\Theta_t^{l,s}-1}{\Theta_t^{l,s}}} di\right)^{\frac{\Theta_t^{l,s}}{\Theta_t^{l,s}-1}} \quad s = cbi, kb. \tag{3}$$

The parameter α in equation (3) is the elasticity of output with respect to capital while $\Theta_t^{l,s}$ denotes the stochastic elasticity of substitution between the differentiated labor inputs. Letting $\theta_t^{l,s} \equiv \ln\Theta_t^{l,s} - \ln\Theta_*^{l,s}$ denote the log-deviation of $\Theta_t^{l,s}$ from its steady-state value of Θ_*^{l}, we assume that

$$\theta_t^{l,s} = \epsilon_t^{\theta,l,s} \tag{4}$$

where $\epsilon_t^{\theta,l,s}$ is an i.i.d. shock process.

The level of technology in sector s has two components. The and Z_t^m component represents an economy-wide technology shock, while the Z_t^s term (for $s = cbi, kb$) represents a technology shock that are specific to either the consumption or capital goods sectors. The technology term contain a unit root, that is, they exhibit permanent movements in their levels. We assume that the stochastic process Z_t^s evolves according to

$$\ln Z_t^s - \ln Z_{t-1}^s = \ln\Gamma_t^{z,s} = \ln\left(\Gamma_*^{z,s}\cdot\exp[\gamma_t^{z,s}]\right) = \ln\Gamma_*^{z,s} + \gamma_t^{z,s},\ \ s = cbi, kb, m \tag{5}$$

where $\Gamma_*^{z,s}$ and $\gamma_t^{z,s}$ are the steady-state and stochastic components of $\Gamma_t^{z,s}$. The stochastic component $\gamma_t^{z,s}$ is assumed to evolve according to

$$\gamma_t^{z,s} = \rho^{z,s}\gamma_{t-1}^{z,s} + \epsilon_t^{z,s}. \tag{6}$$

where $\epsilon_t^{z,s}$ is an i.i.d shock process, and $\rho^{z,s}$ represents the persistence of $\gamma_t^{z,s}$ to a shock. In line with historical experience, we assume a more rapid rate of technological progress in capital goods production by calibrating the steady-state growth rate of the non-stationary component of technology in the capital goods sector above that in the consumption goods sector. That is, $\Gamma_*^{z,k} > \Gamma_*^{z,c}(= 1)$, where an asterisk on a variable denotes its steady-state value.[3]

We assume, as in official statistics, that **housing services**, X_t^{ch}, are produced from the economy's stock of residential capital, K_t^r. The production function for consumer housing services is given by

$$X_t^{ch} = \frac{\Gamma_*^{x,cbi} - \beta(1-\delta^r)}{\beta} \cdot K_t^r,$$

Finally, the growth rate of **government services** output, $H_t^{cg} = X_t^{cg}/X_{t-1}^{cg}$, follows an exogenous auto-regressive process.

3.2 Capital Stock Evolution

As already noted, there are three types of *physical* capital stocks in our model economy:

- Non-residential capital, K_t^{nr};
- Residential capital, K_t^r; and,
- Consumer durables capital K_t^{cd}.

Purchases of the economy's fast-growing "capital" good can be transformed into either non-residential capital, K_{t+1}^{nr}, (that can then be used in the production of either the slow-growing "consumption" good or the fast-growing "capital" good) or into the economy's consumer-durable capital stock, K_{t+1}^{cd}, (from which households derive utility). Purchases of the economy's slow-growing "consumption" good can be transformed into residential capital.

The evolution of the economy's three capital stocks are given below. We assume that there is some stochastic element affecting the efficiency of investment—reflected in the term

[3] Our more general model also allows for transitory but persistent technology shocks.

A_t^s, for $s = nr$, cd, and r—in the capital accumulation process. These shocks exhibit only transitory movements from their steady-state unit mean. Letting $a_t^s \equiv \ln A_t^s$ denote the log-deviation of A_t^s from its steady-state value of unity, we assume that:

$$a_t^s = \rho^{a,s} a_{t-1}^s + \epsilon_t^{a,s}, \;\; s = nr, cd, r. \tag{7}$$

We also asssume that not all investment expenditure results in productive capital, since some fraction is absorbed by adjustment costs in the process of installation:

$$\begin{aligned} K_{t+1}^{nr}(k) =& \ (1-\delta^{nr})K_t^{nr}(k) + A_t^{nr}E_t^{nr}(k) \\ & - \frac{100 \cdot \chi^{nr}}{2}\left(\frac{E_t^{nr}(k) - \eta^{nr}E_{t-1}^{nr}(k)\Gamma_t^{x,kb} - (1-\eta^{nr})\widetilde{E}_*^{nr}Z_t^m Z_t^{kb}}{K_t^{nr}}\right)^2 K_t^{nr} \qquad (8) \\ K_{t+1}^{cd}(k) =& \ (1-\delta^{cd})K_t^{cd}(k) + A_t^{cd}E_t^{cd}(k) \\ & - \frac{100 \cdot \chi^{cd}}{2}\left(\frac{E_t^{cd}(k) - \eta^{cd}E_{t-1}^{cd}(k)\Gamma_t^{x,kb} - (1-\eta^{cd})\widetilde{E}_*^{cd}Z_t^m Z_t^{kb}}{K_t^{cd}}\right)^2 K_t^{cd} \qquad (9) \\ K_{t+1}^{r}(k) =& \ (1-\delta^{r})K_t^{r}(k) + A_t^{r}E_t^{r}(k) \\ & - \frac{100 \cdot \chi^{r}}{2}\left(\frac{E_t^{r}(k) - \eta^{r}E_{t-1}^{r}(k)\Gamma_t^{x,cbi} - (1-\eta^{r})\widetilde{E}_*^{r}Z_t^m (Z_t^{kb})^\alpha (Z_t^{cbi})^{1-\alpha}}{K_t^{r}}\right)^2 K_t^{r}. \qquad (10) \end{aligned}$$

The parameter δ^s denotes the depreciation rate for either the non-residential ($s = nr$), consumer durables ($s = cd$), or residential ($s = r$) capital stocks. The term $\widetilde{E}_*^s$ denotes the value of steady-state non-residential ($s = nr$), consumer durables ($s = cd$), or residential ($s = r$) investment spending normalized by the permanent component of technology so as to be constant in the steady state. Note that investment adjustment costs are zero for non-residential capital when $\frac{E_t^{nr}}{Z_t^m Z_t^{kb}} = \frac{E_{t-1}^{nr}}{Z_{t-1}^m Z_{t-1}^{kb}} = \widetilde{E}_*^{nr}$ but rise to above zero, at an increasing rate, as non-residential investment growth moves further away from this. The costs for altering non-residential investment depend on both the level of (growth-adjusted) investment spending from the preceding period as well as the steady-state level of investment spending. The parameter χ^{nr} governs how quickly these costs increase away from the steady-state. The relative values of $\frac{E_t^{cd}}{Z_t^m Z_t^{kb}}$, $\frac{E_{t-1}^{cd}}{Z_{t-1}^m Z_{t-1}^{kb}}$, and $\widetilde{E}_*^{cd}$ have similar implications for the adjustment costs entailed in the accumulation of consumer durables capital, as do the relative values of $\frac{E_t^r}{Z_t^m (Z_t^{kb})^\alpha (Z_t^{cbi})^{1-\alpha}}$, $\frac{E_{t-1}^r}{Z_{t-1}^m (Z_{t-1}^{kb})^\alpha (Z_{t-1}^{cbi})^{1-\alpha}}$, and $\widetilde{E}_*^r$ for the accumulation of residential capital. Similarly, the values of the parameter χ^{cd} and χ^r govern how quickly these costs increase away from the steady-state. Adjustment costs are quite important in models such as ours in ensuring gradual responses of investment to shocks.

3.3 Preferences

The ith household derives utility from four sources:

- Its purchases of the consumer non-durable goods and non-housing services, $E_t^{cnn}(i)$;
- The flow of services from its stock of consumer-durable capital, $K_t^{cd}(i)$;
- The flow of services from its stock of residential capital $K_t^r(i)$; and
- Its leisure time, which is equal to what remains of its time endowment after $L_t^{cbi}(i) + L_t^{kb}(i)$ hours are spent through working.

The preferences of household i are separable over all of the arguments of its utility function. The utility that the household derives from the three components of its goods and services consumption is influenced by its habit stock for each of these consumption components, a feature that has been shown to be important for consumption dynamics in similar models. Household i's habit stock for its consumption of non-durable goods and non-housing services, is equal to a factor h^{cnn} multiplied by its consumption last period $E_{t-1}^{cnn}(i)$). The household's habit stock for its other components of consumption is defined similarly. In summary, the preferences of household i are represented by the utility function:

$$\mathcal{E}_0\sum_{t=0}^{\infty}\beta^t\Big\{\varsigma^{cnn}\Xi_t^{cnn}\ln(E_t^{cnn}(i)-h^{cnn}E_{t-1}^{cnn}(i))+\varsigma^{cd}\Xi_t^{cd}\ln(K_t^{cd}(i)-h^{cd}K_{t-1}^{cd}(i))$$
$$+\varsigma^r\Xi_t^r\ln(K_t^r(i)-h^rK_{t-1}^r(i))-\varsigma^l\Xi_t^l\frac{(L_t^{cbi}(i)+L_t^{kb}(i))^{1+\nu}}{1+\nu}\Big\}. \quad (11)$$

The parameter β is the household's discount factor, ν denotes its inverse labor supply elasticity, while ς^{cnn}, ς^{cd}, ς^r, and ς^l are scale parameter that tie down the ratios between the household's consumption components. The stationary, unit-mean, stochastic variables Ξ_t^{cnn}, Ξ_t^{cd}, Ξ_t^r, and Ξ_t^l represent aggregate shocks to the household's utility of its consumption components and its disutility of labor. Letting $\xi_t^x \equiv \ln\Xi_t^x - \ln\Xi_*^x$ denote the log-deviation of Ξ_t^x from its steady-state value of Ξ_*^x, we assume that

$$\xi_t^x = \rho^{\xi,x}\xi_{t-1}^x + \epsilon_t^{\xi,x}, \qquad x = cnn, cd, r, l. \quad (12)$$

The variable $\epsilon_t^{\xi,x}$ is an i.i.d. shock process, and $\rho^{\xi,x}$ represents the persistence of Ξ_t^x away from steady-state following a shock to equation (12).

4 The Decentralized Economy

We assume the following decentralization of the economy:

- The representative, perfectly competitive firm that exists in each of the economy's two final-goods producing sectors purchases intermediate inputs from the continuum of intermediate goods producers to produce the sector's final goods output.
- Firms in the continuum of intermediate goods producers in both of the economy's intermediate-goods producing sectors rent non-residential capital at a set utilization rate from the representative capital owner, and differentiated types of labor from households. Because each intermediate goods producer is a monopolistically competitive supplier of its own output, it is able to set the price at which it sells its product.
- The representative, perfectly competitive capital owner purchases the output from the fast-growing "capital" final-goods sector and transforms it into either non-residential capital or consumer durables capital. The representative capital owner also purchases the output from the slow-growing "consumption" final-goods and transforms it into residential capital.
- Households in the continuum of consumers purchase the output of the slow-growing "consumption" goods sector, and rent consumer durables capital and residential capital from the capital owner. Because each household is a monopolistically competitive supplier of its own labor, it is able to set the wage at which it supplies its labor services.
- The monetary authority sets the nominal interest rate given an interest rate feedback rule with smoothing of the policy response to endogenous variables.
- The fiscal authority raises taxes in a lump-sum fashion to cover the subsidy outlays that is makes to monopolistically competitive intermedite-goods producing firms and households (in their capacity of labor suppliers) to induce them to supply (in the absence of sticky-prices) at the pareto optimal level. Taxes are also raised to cover the government's purchases of goods and services from the business and institutions sector.
- Foreigners, who are not modeled, pay lump-sum transfers to households equal to the negative of net exports.

We describe in this section the behaviour of all but the last two agents listed above.

4.1 Consumption and Capital Final Goods Producers

The representative, perfectly competitive firm in the consumption good sector owns the production technology described in equation (1) for $s = cbi$, while the representative, perfectly competitive firm in the capital goods sector owns the same technology for $s = kb$. The final-good producer in sector s solves the cost-minimization problem of:

$$\min_{\{X_t^s(j)\}_{j=0}^1} \int_0^1 P_t^s(j) X_t^s(j) dj \text{ subject to } \left(\int_0^1 \left(X_t^s(j) \right)^{\frac{\Theta_t^{x,s}-1}{\Theta_t^{x,s}}} dj \right)^{\frac{\Theta_t^{x,s}}{\Theta_t^{x,s}-1}} \geq X_t^s, \text{ for } s = cbi, kb. \tag{13}$$

4.2 Consumption and Capital Intermediate Goods Producers

Each intermediate-good producing firm $j \in [0, 1]$ and $s = c, k$ owns the production technology described in equation (3). It is convenient to think of the intermediate good producing firm as solving three problems: two factor-input cost-minimization problems and one price-setting profit-maximization problem. The two cost-minimization problems faced by the representative firm in sector s are:

$$\min_{\{L_t^s(i,j)\}_{i=0}^1} \int_0^1 W_t^s(i) L_t^s(i,j) di \text{ subject to } \left(\int_0^1 \left(L_t^s(i,j) \right)^{\frac{\Theta_t^{l,s}-1}{\Theta_t^{l,s}}} di \right)^{\frac{\Theta_t^{l,s}}{\Theta_t^{l,s}-1}} \geq L_t^s(j), \text{ for } s = c, k. \tag{14}$$

and

$$\begin{aligned} &\min_{\left\{L_t^s(j), K_t^{u,nr,s}(j)\right\}} W_t^s L_t^s(j) + R_t^{nr,s} K_t^{u,nr,s}(j) \\ &\text{subject to } \left(A_t^m Z_t^m A_t^s Z_t^s L_t^s(j) \right)^{1-\alpha} \left(K_t^{u,nr,s}(j) \right)^{\alpha} \geq X_t^s(j), \text{ for } s = cbi, kb. \end{aligned} \tag{15}$$

The profit-maximization problem faces by the firm is given by:

$$\begin{aligned} \max_{\{P_t^s(j), X_t^s(j), X_t^s(j)\}_{t=0}^\infty} \mathcal{E}_0 \sum_{t=0}^\infty \beta^t \frac{\Lambda_t^{cnn}}{P_t^{cbi}} \Big\{ & \left(1 + \sigma^{p,s}\right) P_t^s(j) X_t^s(j) - MC_t^s(j) X_t^s(j) - \sigma^{p,s} P_t^s X_t^s \\ & - \frac{100 \cdot \chi^{p,s}}{2} \left(\frac{P_t^s(j)}{P_{t-1}^s(j)} - \eta^{p,s} \Pi_{t-1}^{p,s} - (1 - \eta^{p,s}) \Pi_*^{p,s} \right)^2 P_t^s X_t^s \Big\} \end{aligned}$$

$$\begin{aligned} &\text{subject to } X_\tau^s(j) = \left(\frac{P_\tau^s(j)}{P_\tau^s} \right)^{-\Theta_\tau^{x,s}} X_\tau^s \\ &\text{for } \tau = 0, 1, ..., \infty, \text{ and } s = cbi, kb. \end{aligned} \tag{16}$$

The parameters $\sigma^{p,s}$ in the expressions for the firm's profits represents a subsidy that can be set to $(\Theta_*^{p,s}-1)^{-1}$ so as to ensure a Pareto-optimal flexible price and wage equilibrium. The variable $MC_t^s(j)$ represents the marginal cost of producing a unit of $X_t^s(j)$ while $\sigma^{p,s}P_t^s X_t^s$ represents the tax revenue (raised in a lump-sum fashion) that are needed to payout the production subsidy. The profits function also reflects price setting adjustment costs (the size which depend on the parameter $\chi^{p,s}$ and the lagged and steady-state inflation rate). The constraint against which the firm maximizes its profits is the demand curve it faces for its differentiated good. This demand curve derives from the final goods producing firm's cost-minimization problem.

4.3 Capital Owners

Capital owners possess the technologies described in equations (8) and (9) for transforming the economy's fast-growing "capital" good into either non-residential capital, K_{t+1}^{nr}, or the consumer-durable capital stock, K_{t+1}^{nr}. The also possess the technology described in equation (10) for transforming the economy's slow-growing "consumption" good into the economy's residential capital stock K_{t+1}^{nr}. The investment decision for the economy's three types of capital stock do not interact in any way and so we describe them separately.

In considering its non-residential investment decision, the capital owner solves:

$$\max_{\{E_t^{nr}(k),K_{t+1}^{nr}(k),K_t^{nr,cbi}(k),K_t^{nr,kb}(k)U_t^{cbi}(k),U_t^{kb}(k)\}_{t=0}^{\infty}}$$

$$\mathcal{E}_0\sum_{t=0}^{\infty}\beta^t\frac{\Lambda_t^{cnn}}{P_t^{cbi}}\Big\{R_t^{nr,cbi}U_t^{cbi}(k)K_t^{nr,cbi}(k)+R_t^{nr,kb}U_t^{kb}(k)K_t^{nr,kb}(k)-P_t^{kb}E_t^{nr}(k)$$
$$-\kappa\left(\frac{(U_t^{cbi}(k))^{1+\psi}-1}{1+\psi}\right)P_t^{kb}K_t^{nr,cbi}-\kappa\left(\frac{(U_t^{kb}(k))^{1+\psi}-1}{1+\psi}\right)P_t^{kb}K_t^{nr,kb}\Big\}$$

subject to

$$K_{\tau+1}^{nr}(k)=(1-\delta^{nr})K_\tau^{nr}(k)+A_\tau^{nr}E_\tau^{nr}(k)$$
$$-\frac{100\cdot\chi^{nr}}{2}\left(\frac{E_\tau^{nr}(k)-\eta^{nr}E_{\tau-1}^{nr}(k)\Gamma_t^{y,kb}-(1-\eta^{nr})\widetilde{E}_*^{nr}Z_\tau^m Z_\tau^{kb}}{K_\tau^{nr}}\right)^2K_\tau^{nr}$$

$$K_\tau^{nr,cbi}(k)+K_\tau^{nr,kb}(k)=K_\tau^{nr}(k)$$
$$-\frac{100\cdot\chi^k}{2}\left(\frac{K_\tau^{nr,cbi}(k)}{K_\tau^{nr,kb}(k)}-\eta^k\frac{K_{\tau-1}^{nr,cbi}}{K_{\tau-1}^{nr,kb}}-(1-\eta^k)\frac{\widetilde{K}_*^{nr,cbi}}{\widetilde{K}_*^{nr,kb}}\right)^2\frac{K_\tau^{nr,kb}}{K_\tau^{nr,cbi}}\cdot K_\tau^{nr}.$$

for $\tau=0,1,...,\infty$. (17)

We assume that the capital owner decides on both the amount of capital that it will rent to firms and the rate of utilization at which this capital is used by firms. (Recall, that the firm's choice variables in 15 is utilized capital $K_t^{u,nr,s} = U_t^s K_t^{nr,s}$.) Raising the rate of utilization will boost the capital owners rental income but will incur a cost (reflected in the last two terms in the capital owners profit function). For its consumer durables investment decision, the capital owner solves:

$$
\begin{aligned}
&\max_{\{E_t^{cd}(k), K_{t+1}^{cd}(k)\}_{t=0}^{\infty}\}} \mathcal{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\Lambda_t^{cnn}}{P_t^{cbi}} \left\{ R_t^{cd} K_t^{cd}(k) - P_t^{kb} E_t^{cd}(k) \right\} \\
&\text{subject to} \;\; K_{\tau+1}^{cd}(k) = (1-\delta^{cd}) K_\tau^{cd}(k) + A_\tau^{cd} E_\tau^{cd}(k) \\
&\qquad - \frac{100 \cdot \chi^{cd}}{2} \left(\frac{E_\tau^{cd}(k) - \eta^{cd} E_{\tau-1}^{cd}(k) \Gamma_\tau^{x,kb} - (1-\eta^{cd}) \widetilde{E}_*^{cd} Z_\tau^m Z_\tau^k}{K_\tau^{cd}} \right)^2 K_\tau^{cd} \\
&\text{for } \tau = 0, 1, ..., \infty.
\end{aligned} \tag{18}
$$

while for its residential investment decision, it solves:

$$
\begin{aligned}
&\max_{\{E_t^{r}(k), K_{t+1}^{r}(k)\}_{t=0}^{\infty}\}} \mathcal{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{\Lambda_t^{cnn}}{P_t^{cbi}} \left\{ R_t^{r} K_t^{r}(k) - P_t^{cbi} E_t^{r}(k) \right\} \\
&\text{subject to} \\
&K_{\tau+1}^{r}(k) = (1-\delta^{r}) K_\tau^{r}(k) + A_\tau^{r} E_\tau^{r}(k) \\
&\qquad - \frac{100 \cdot \chi^{r}}{2} \left(\frac{E_\tau^{r}(k) - \eta^{r} E_{\tau-1}^{r}(k) \Gamma_\tau^{x,cbi} - (1-\eta^{r}) \widetilde{E}_*^{r} Z_\tau^m (Z_\tau^{kb})^\alpha (Z_\tau^{cbi})^{1-\alpha}}{K_\tau^{cd}} \right)^2 K_\tau^{cd} \\
&\text{for } \tau = 0, 1, ..., \infty.
\end{aligned} \tag{19}
$$

4.4 Households

The household possesses the utility function—defined over three components of goods and services consumption and leisure—described by equation (11). The representative household solves the problem:

$$\max_{\left\{E_t^{cnn}(i),K_t^{cd}(i),K_t^r(i),\{W_t^s(i),L_t^s(i)\}_{s=cbi,kb},B_{t+1}(i)\right\}_{t=0}^{\infty}}$$

$$\mathcal{E}_0\sum_{t=0}^{\infty}\beta^t\Big\{\varsigma^{cnn}\Xi_t^{cnn}\ln(E_t^{cnn}(i)-h^{cnn}E_{t-1}^{cnn}(i))+\varsigma^{cd}\Xi_t^{cd}\ln(K_t^{cd}(i)-h^{cd}K_{t-1}^{cd}(i))$$
$$+\varsigma^{r}\Xi_t^{r}\ln(K_t^{r}(i)-h^{r}K_{t-1}^{r}(i))-\varsigma^{l}\Xi_t^{l}\frac{(L_t^{cbi}(i)+L_t^{kb}(i))^{1+\nu}}{1+\nu}\Big\}.$$

subject to

$$R_\tau^{-1}B_{\tau+1}(i)=B_\tau(i)+\sum_{s=cbi,kb}(1+\sigma^{w,s})W_\tau^s(i)L_\tau^s(i)+\mathit{Profits}_\tau(i)+\mathit{Govt.\ Transfers}_\tau(i)$$
$$+\mathit{Foreign\ Transfers}_\tau(i)-P_\tau^{cbi}E_\tau^{cnn}(i)-R_\tau^{cd}K_\tau^{cd}-R_\tau^{r}K_\tau^{r}$$
$$-\sum_{s=cbi,kb}\frac{100\cdot\chi^{w,s}}{2}\left(\frac{W_\tau^s(j)}{W_{\tau-1}^s(j)}-\eta^{w,s}\Pi_{\tau-1}^{w,s}-(1-\eta^{p,s})\Pi_*^w\right)^2W_\tau^sL_\tau^s$$
$$-\frac{100\cdot\chi^l}{2}\left(\frac{L_*^{cbi}}{L_*^{cbi}+L_*^{kb}}\cdot W_\tau^{cbi}+\frac{L_*^{kb}}{L_*^{cbi}+L_*^{kb}}\cdot W_\tau^{kb}\right)$$
$$\times\left(\frac{L_\tau^{cbi}(i)}{L_\tau^{kb}(i)}-\eta^l\frac{L_{\tau-1}^{cbi}}{L_{\tau-1}^{kb}}-(1-\eta^l)\frac{L_*^{cbi}}{L_*^{kb}}\right)^2\frac{L_\tau^{kb}}{L_\tau^{cbi}}.$$

$$L_\tau^{cbi}(i)=\left(\frac{W_\tau^{cbi}(i)}{W_\tau^{cbi}}\right)^{-\Theta_\tau^{l,cbi}}L_\tau^{cbi},\text{ and }L_\tau^{kb}(i)=\left(\frac{W_\tau^{kb}(i)}{W_\tau^{kb}}\right)^{-\Theta_\tau^{l,kb}}L_\tau^{kb},\quad\text{for }\tau=0,1,...,\infty.\quad(20)$$

The parameter $\sigma^{w,s}$ in the households utility funtion is a subsidy to labor that can be set to $\sigma^{w,s}$ to ensure that the economy's level of steady-state labor (and consequently output) is Pareto optimal. The household's budget constraint reflects wage setting adjustment costs (the size of which depend on the parameter $\chi^{w,s}$ and the lagged and steady-state wage inflation rate). The constraint against which the household maximizes its utility is the demand curve it faces for its differentiated labor. This demand curve derives from the first of the intermediate goods producing firm's cost-minimization problems.

4.5 Monetary Authority

The central bank sets monetary policy in accordance with an Taylor-type interest-rate feedback rule. Policymakers smoothly adjust the actual interest rate R_t to its target level $\bar{R}_t$

$$R_t=(R_{t-1})^{\phi^r}\left(\bar{R}_t\right)^{1-\phi^r}\exp\left[\epsilon_t^r\right],\quad(21)$$

where the parameter ϕ^r reflects the degree of interest rate smoothing, while ϵ_t^r represents a monetary policy shock. The central bank's target nominal interest rate $\bar{R}_t$ is given by:

$$\bar{R}_t = \left(\Pi_t^{p,gdp}/\Pi_*^{p,gdp}\right)^{\phi^{\pi,gdp}} \left(\Delta\Pi_t^{p,gdp}\right)^{\phi^{\Delta\pi,gdp}} \left(H_t^{gdp}/H_*^{gdp}\right)^{\phi^{h,gdp}} \left(\Delta H_t^{gdp}\right)^{\phi^{\Delta h,gdp}} R_*. \quad (22)$$

where R_* denotes the economy's steady-state nominal interest rate (which is equal to $(1/\beta)\Pi_*^{p,c}\Gamma_*^{z,m}(\Gamma_*^{z,kb})^{\alpha}(\Gamma_*^{z,cbi})^{1-\alpha}$) and $\phi^{\pi,gdp}$, $\phi^{\Delta\pi,gdp}$, $\phi^{h,gdp}$, and $\phi^{\Delta h,gdp}$ denote the weights in the feedback rule. GDP growth, denoted by H_t^{gdp}, is given by:

$$\begin{aligned}
H_t^{gdp} = & \left(\frac{\Gamma_t^{x,cbi}\cdot \widetilde{X}_t^{cbi}}{\widetilde{X}_{t-1}^{cbi}}\right)^{\frac{1}{2}\cdot\frac{P_t^{cbi}X_t^{cbi}}{P_t^{cbi}X_t^{cbi}+P_t^{kb}X_t^{kb}+P_t^{cbi}X_t^{gf}}+\frac{1}{2}\cdot\frac{P_{t-1}^{cbi}X_{t-1}^{cbi}}{P_{t-1}^{cbi}X_{t-1}^{cbi}+P_{t-1}^{kb}X_{t-1}^{kb}+P_{t-1}^{cbi}X_{t-1}^{gf}}} \\
& \times \left(\frac{\Gamma_t^{x,kb}\cdot \widetilde{X}_t^{kb}}{\widetilde{X}_{t-1}^{kb}}\right)^{\frac{1}{2}\cdot\frac{P_t^{kb}X_t^{kb}}{P_t^{cbi}X_t^{cbi}+P_t^{kb}X_t^{kb}+P_t^{cbi}X_t^{gf}}+\frac{1}{2}\cdot\frac{P_{t-1}^{kb}X_{t-1}^{kb}}{P_{t-1}^{cbi}X_{t-1}^{cbi}+P_{t-1}^{kb}X_{t-1}^{kb}+P_{t-1}^{cbi}X_{t-1}^{gf}}} \\
& \times \left(\frac{\Gamma_t^{x,cbi}\cdot \widetilde{X}_t^{gf}}{\widetilde{X}_{t-1}^{gf}}\right)^{\frac{1}{2}\cdot\frac{P_t^{cbi}X_t^{gf}}{P_t^{cbi}X_t^{cbi}+P_t^{kb}X_t^{kb}+P_t^{cbi}X_t^{gf}}+\frac{1}{2}\cdot\frac{P_{t-1}^{cbi}X_{t-1}^{gf}}{P_{t-1}^{cbi}X_{t-1}^{cbi}+P_{t-1}^{kb}X_{t-1}^{kb}+P_{t-1}^{cbi}X_{t-1}^{gf}}}, \quad (23)
\end{aligned}$$

where $\widetilde{X}_t^{cbi}$ and $\widetilde{X}_t^{kb}$ denote the stationary counterparts of X_t^{cbi} and X_t^{kb}, and $\widetilde{X}_t^{gf}$ represent stationary un-modelled output (that is, GDP other that E_t^{cnn}, E_t^{cd}, E_t^{r}, and E_t^{nr}). Stationary un-modeled output, which is equal to nominal un-modeled output deflated by prices from the slow-growing "consumption" goods sector, is exogenous and is assumed to follow the process:

$$\ln \widetilde{X}_t^{gf} - \ln \widetilde{X}_*^{gf} = \rho^{x,gf}\left(\ln \widetilde{X}_t^{gf} - \ln \widetilde{X}_*^{gf}\right) + \epsilon^{x,gf}.$$

The inflation rate of the GDP deflator, represented by $\Pi_t^{p,gdp}$, is defined implicitly by:

$$\Pi_t^{p,gdp}H_t^{gdp} = \frac{P_t^{gdp}X_t^{gdp}}{P_{t-1}^{gdp}X_{t-1}^{gdp}} = \frac{\widetilde{X}_t^{cbi} + \widetilde{P}_t^{kb}\widetilde{X}_t^{kb} + \widetilde{X}_t^{gf}}{\widetilde{X}_{t-1}^{cbi} + \widetilde{P}_{t-1}^{kb}\widetilde{X}_{t-1}^{kb} + \widetilde{X}_{t-1}^{gf}}$$

where $\widetilde{P}_t^{kb}$ is equal to the stationary relative price of fast-growing "capital" goods to slow-growing "consumption" goods.[4]

[4]Deflating nominal un-modeled output by the prices from the slow-growing "consumption" goods sector, means that the model's GDP and the GDP deflator, even in their non-linear form, will diverge from NIPA estimates. This difference in definitions is captured by our assumption of measurement error for these series, which also reflects the fact that (i) we assume the same deflator for consumer non-durable goods and non-housing services and residential investment and likewise for consumer durable goods and non-residential investment and (ii) we estimate a log-linearized model that implies a divergence due to the use of steady-state—rather than, chained—weights in aggregation.

4.6 Summary

Our presentation of the model has purposefully been quite terse, and a companion piece provides more detail. However, our presentation highlights several important points. First, our model, while considering production and expenditures decisions in a bit more detail, is very similar to many others in the literature. In addition, our economy is subject to a rich set of productivity, preference, and markup shocks. Finally, our model includes a large number of adjustment costs in order to slow the response of endogenous variables to fundamentals. Alternative modeling frameworks may also be consistent with the data on this latter dimension, such as the rational inattention hypothesis of Sims [2003], but considerable work needs to be done in order to bring such models to the data.

5 Properties of the Model

We take a log-linear approximation to our model, cast this resulting dynamical system in its state space representation for the set of (in our case 11) observable variables, use the Kalman filter to evaluate the likelihood of the observed variables, and form the posterior distribution of the parameters of interest by combining the likelihood function with a joint density characterizing some prior beliefs. Since we do not have a closed-form solution of the posterior, we rely on Markov-Chain Monte Carlo (MCMC) methods. A companion piece provides detail regarding the model, the prior beliefs regarding structural parameters, and the posterior distribution of these parameters. In this section, we highlight some of the key properties of our model, focusing in particular on key parameters influencing the model's dynamic behavior and their relationship to specifications in the Federal Reserve's FRB/US model.

The model is estimated using 11 data series. The series, each from the Bureau of Economic Analysis's National Income and Product Accounts except where noted, are:

1. Nominal gross domestic product.
2. Nominal consumption expenditure on nondurables and services excluding housing services.
3. Nominal consumption expenditure on durables.
4. Nominal residential investment expenditure.

5. Nominal business investment expenditure, which equals nominal gross private domestic investment minus nominal residential investment.
6. GDP price inflation.
7. Inflation for consumer nondurables and services.
8. Inflation for consumer durables.
9. Hours, which equals hours of all persons in the non-farm business sector from the Bureau of Labor Statistics; we scale up this measure of hours by the ratio of nominal spending in our model to nominal non-farm business sector output in order to model a level of hours more appropriate for the total economy.
10. Wage inflation, which equals compensation per hour in the non-farm business sector from the Bureau of Labor Statistics.
11. The federal funds rate, from the Federal Reserve Board.

In the estimated model that we present here we make the following modifications:

- We assume that the parameters capturing wage and price adjustment costs are identical across sectors, that is, $\chi^{p,cbi} = \chi^{p,kb}$, $\eta^{p,cbi} = \eta^{p,kb}$, $\chi^{w,cbi} = \chi^{w,kb}$, and $\eta^{w,cbi} = \eta^{w,kb}$. In addition, we assume that there is only one markup shock process for the overall labor market, so that $\theta_t^l = \theta_t^{l,c} = \theta_t^{l,k}$.
- We assume no inter-sectoral adjusment costs for capital, that is, we set the parameter χ^k to zero.[5]
- We assume that there are no subsidies, that is $\sigma^{w,s} = \sigma^{p,s}$, which means that Pareto optimality does not obtain in the flexible wage and price economy.
- To ensure that output aggregates to GDP we include government and foreign demand in our exogenous un-modeled output variable X_t^{gf}. We also assume that the government and foriegn sectors do not demand any of the output produced by the business and institutions sector. The economy's production of housing services X_t^{ch} and government services X_t^{cg} are also included in un-modeled output.
- Finally, we have imposed measurement error processes, denoted η_t, for all of the observed series used in estimation except the nominal interest rate and the aggregate

[5]Attempts to estimate the inter-sectorial adjustment cost coefficient associated with capital, χ^k, have been unfruitfull in the sense that, based on the current choice of model and data, the best specification is the one assuming that χ^k is equal to 0.

hours series. In all cases, the measurement errors explain less than 5 percent of the observed series.[6]

5.1 Key Parameters

Our model contains a large number of calibrated and estimated parameters, and we refer the interested reader to a companion piece for a more detailed presentation of parameter estimates and other aspects of our estimation results. However, Figure 3 presents the data used in estimation along with one-step-ahead forecasts and illustrates reasonable success of the model in tracking fluctuations in most serires. We focus herein on a few important parameters that drive the dynamic behavior of our model and are related to some important controversies in macro-modeling. All of the model's parameters are reported in the Tables 3 to 5.

Turning first to preference and adjustment cost parameters related to household decisions, the set of parameters related to habit persistence (the h parameters for each type of consumption in our utility function) are uniformly large. For nondurables and services excluding housing, the habit parameter (at the posterior mode) is about 0.8 – close to the value in Fuhrer [2000] and other DSGE models of the United States. For durables expenditure, the habit parameter takes on a similar value (at the posterior mode). Most DSGE models do not consider durables expenditure, and hence it is not immediately obvious that this value lies near any sort of consensus; however, we view this parameter as quite plausible within the context of our model, as habit persistence for the stock of durable goods will make utility from this flow (partially) dependent on the level of durable investment, thereby smoothing the growth rate in this series relative to the negative autocorrelation implied by the model absent habits (e.g., Mankiw [1982]). The habit parameter is not quite as large for housing (at about 1/2 at the posterior mode). However, investment adjustment costs are estimated to be very significant for residential investment and of modest importance for consumer durables, and both these factors contribute to "hump-shaped" responses of these series to monetary policy shocks. (In fact, it appears from simulations of the posterior distribution of parameters that habit persistence and adjustment costs for consumer durables are closely related). The adjustment cost parameters are a bit hard to interpret.

[6] There is one exception which is consumption growth; issues associated with the ability of DSGE models to explain consumption are also observed in Smets and Wouters [2004b].

It is perhaps easier to think of the implications of these parameters for the elasticity of investment with respect to the capital-stock specific measure of marginal q; this elasticity is about one for consumer durables and about 1/7 for residential investment.

While an important role for habit persistence is quite standard in DSGE models, we would note some skepticism regarding the structural interpretation of these parameters (among at least some of the authors). In particular, microeconomic evidence (Dynan [2000]) and some macroeconomic evidence (Kiley [2005a]) suggests that the support for habit persistence is quite weak; nonetheless, it plays a very important role in the dynamics of our DSGE model.

With regard to other preference parameters, we consider the estimate of the inverse of the labor supply elasticity, at around 3 at the posterior mode, as consistent with microeconomic evidence (Abowd and Card [1989]) and results from earlier DSGE models with sticky wages. The sticky wage assumption is important in this regard, as it allows households to be "off" their labor supply schedule in the short-run; in flexible wage models, the labor supply elasticity typically must be much larger to generate the required volatility in hours.

With regard to other adjustment cost parameters, we estimate significant costs to the change in investment flows for business investment (as well as the investment in household stocks noted above), a standard result; these costs imply an elasticity of investment to marginal q of about 2/5. We also find an important role for the sectoral adjustment costs to labor: In our multisector setup, shocks to productivity or preferences in one sector of the economy will result in a strong shift of labor towards that sector – an undesirable implication given the high sectoral comovement in the data. The adjustment costs to the sectoral mix of labor input ameliorate this potential problem, as in Boldrin *et al.* [2001].

Finally, adjustment costs to prices and wages are both estimated to be important, although prices appear "stickier" than wages. Our quadratic costs of price adjustment can be translated into frequencies of price adjustment consistent with the Calvo model; these are about six quarters for prices and just over one quarter for wages. With regard to the importance of indexation, we find only a modest role for lagged inflation in our adjustment cost specification (around 1/3), equivalent to modest indexation to lagged inflation in other sticky-price specifications. This differs from some other estimates, perhaps because of the focus on a more recent post-1983 sample (similar to results in (Kiley [2005b]) and Laforte [2005]).

Before turning to some model properties, we would like to emphasize the close relationship between the role of adjustment costs in our DSGE model and the structure of the FRB/US model. Estimated DSGE models like ours have increasingly relied on adjustment costs to the growth of investment and to changes in inflation (through mechanisms like dynamic indexation and/or rule-of-thumb price-setting, which result in similar first-order conditions to those in an adjustment cost framework) in order to match the hump-shaped response of these variables to fundamentals. This framework has been standard at the Federal Reserve within the FRB/US model since at least the important contribution of Tinsley [1993], which emphasized the role of this type of adjustment cost in matching the data for many series. Of course, the nature of these adjustment costs has long been a criticism of the FRB/US model from academic researchers, and many current DSGE models, including our own, share this deficiency.

5.2 Important Properties

We now turn to some of the properties of our model. Table 6 presents forecast error variance decompositions at various (quarterly) horizons at the posterior mode of the parameter estimates for key variables and shocks. Looking first at output growth, it is clear that technology shocks – to economywide productivity, the productivity in the fast-growing sector, and to the efficiency of investment – explain the overwhelming fraction of output fluctuations. The importance of these aggregate supply disturbances is not surprising in this class of models and given our specification. Interestingly, such shocks are much more important in our DSGE model than in the Federal Reserve's FRB/US model; we view this as a strength of our model, as the importance of aggregate supply innovations for high frequency fluctuations in output is standard in the academic literature and the addition of a model with this property to the toolkit used in policy analysis can only help expand the range of "stories" considered in forecasting and policy work. Technology shocks similarly dominate the variance decomposition for inflation at all but the shortest horizons (where transitory markup shocks are important).

Unsurprisingly, monetary policy shocks contribute very little to the variance decomposition on any variable; of course, this does not imply that monetary policy is unimportant, as the policy rule has significant effects on model properties. As we will see in the next section, there have been very important discretionary shifts in monetary policy (shocks) over our period, despite the unimportance of this factor overall for variance decompositions.

Figure 4 presents the impulse responses of key variables to a monetary policy innovation. In a policy context, it is obviously important that our model capture the conventional wisdom regarding the effects of such shocks, and it is apparent that our model does. In particular, both household and business expenditures on durables (consumer durables, residential investment, and business investment) respond strongly (and with a hump-shape) to a contractionary policy shock, with more muted responses by nondurables and services consumption; each measure of inflation responds gradually, albeit probably more quickly than in some analyses based on vector autoregressions.

6 Storytelling with the Output Gap and Natural Rate of Interest

With our rather terse summary of some of the key properties of our model behind us, we now turn to some aspects of "storytelling" in the context of our model. As we emphasized earlier, we view the stories embedded in our model as perhaps their key potential contribution to the forecasting and policymaking process, as it is these stories that connect – or possibly disconnect – the output of our model to the intuition and analysis brought to the policymaking process by staff not directly connected to day-to-day model operations. We provide several examples of such storytelling below. In some cases, the stories told by our DSGE model appear to be very similar to "conventional" wisdom; in others, the story from our model differs significantly from some other views, and this may indicate problems with the conventional wisdom or with our model.

6.1 The Output Gap, Recessions, and Monetary Policy

The first topic we discuss is the evolution of the output gap over our sample period. In our DSGE context, we define the level of potential output as the level that would prevail absent wage and price rigidities and abstracting from shocks to markups. This definition is standard in the New-Keynesian and related DSGE literature (Woodford [2004], Neiss and Nelson [2003]).

For comparison purposes, we will also consider a measure of potential output and the output gap based on the FRB/US model. This series takes a more traditional view of potential output as a smoothly evolving series. In particular, potential is based on a production function; total factor productivity in the potential series is a smoothed series for measured total factor productivity (with the smoothing achieved through a Kalman filter on actual TFP); the capital stock in the potential series is the actual measured capital stock; and labor input in the potential series is a smoothed series, more akin to our DSGE model's notion of steady-state labor input.

Figure 5 graphs the output gap from our model and the FRB/US model's output gap from 1984 to 2004. It is immediately apparent that the two series capture some of the same stories that have been prominent factors in monetary policy decisions over this period. Perhaps most importantly, both series show relatively sharp movements of output below potential in the early 1990s and in 2001 – consistent with the well-known dating of recessions around those times by the National Bureau of Economic Research (NBER).

One reaction to this finding might be that this is a pretty weak story to hold up as an example illustrating that our DSGE model has some reasonable properties. However, we view the quasi-success of our model in capturing sharp downward movements in the output gap in the neighborhood of NBER recessions as both important and addressing a criticism that has been made of much simpler New-Keynesian models. For example, in the bare-bones New-Keynesian model with only sticky prices, the output gap is proportional to labor's share of income (e.g., Woodford [2004]). It is well-known that labor's share of income, in the United States, has tended to rise, or at least not fall sharply, in NBER recessions (Rotemberg and Woodford [1999], Rudd and Whelan [2005a]), and this tendency has led some to sharply criticize the New-Keynesian model as failing to connect to the basic discussion of economic activity in terms of recognizable expansions and contractions (e.g., Rudd and Whelan [2005a], Rudd and Whelan [2005b]).

Our model also tells an interesting story regarding the role of monetary policy in mitigating the depth of each recession. Figure 6 plots our DSGE model's measure of the output gap and the contribution to the output gap of monetary policy shocks, i.e., deviations of policy from the standard rule. According to the model, monetary policy shocks acted to raise output toward potential – to a significant extent – in both the early 1990s and from 2001 to 2004. This should be unsurprising to even casual observers of policy behavior at that time. But our model says a bit more: when potential output is measured by the efficient level of output, as in DSGE models like ours, it is also possible to clearly state that such discretionary policy shocks were probably welfare enhancing. We strongly suspect policymakers would tend to agree, as presumably that explains why these (estimated) discretionary moves occurred. (In addition, there is another issue which some of the recent literature has addressed: The form of optimal policy in a model like ours. An optimal policy may perform much better than the historical rule, and may not require the types of discretionary policy shocks we measure over history in order to maintain output near its potential level. While we view investigations along these lines (such as Levin *et al.* [2005]) as very interesting, we defer such questions within the context of our model for future research).

Finally, our model also tells an interesting story regarding output relative to potential over the late 1990s. Returning to Figure 5, our DSGE measure of the output gap remains negative for much of the 1990s, whereas the measure in FRB/US turns very positive around the mid-1990s. At first glance, such a discrepancy could suggest sharply different stories from the two models. In fact, the stories are fairly similar. In our DSGE model, output below potential tends to be associated with low or falling inflation (although the connections are not immediate with both sticky prices and wages, as emphasized in Erceg *et al.* [2000]). In FRB/US, output above potential need not be associated with rising inflation; in particular, strong productivity growth will initially tend to boost output above its steady-state level in FRB/US while leading to decelerating inflation. In fact, the stories from FRB/US and the DSGE model are even more similar; both models link inflation to labor's share of income.

6.2 Potential Output

The view of growth over the past twenty years that emerges from the DSGE model becomes more significantly different from conventional wisdom or the view embedded in FRB/US once some other issues are considered. The evolution of potential output, and the associated stories regarding the role of "aggregate supply" disturbances in macroeconomic fluctuations, is one important area of disagreement. As noted earlier, our DSGE model attributes the overwhelming majority of fluctuations to technology shocks, whether those are shocks to total factor productivity or the efficiency of investment. Models like FRB/US attribute much more of the short-run variation in aggregate expenditure to "aggregate demand" shocks, typically measured as residuals in the determination of key components of expenditure.

This is apparent in the graph of the output gap in Figure 5, which is much smoother in our DSGE model than FRB/US. In terms of overall volatility, our measure of potential (flexible- price) output has a standard deviation of 0.5 percent per quarter – the same level as actual output growth. This implies that most movements in output are close to being efficient. On the one hand, this result may not be particularly surprising given the existing literature on this topic, and Hall [2005] has argued that policymakers should perhaps absorb this lesson. But some policymakers are skeptical (see Bean [2005]).

Our view is that the potential for large, high frequency fluctuations in the efficient level of output has been well documented by a substantial literature, starting with Kydland and Prescott [1982] and leading to modern, New-Keynesian DSGE models with very much a real-business cycle flavor. Given this tradition, this view should be represented among the set of models used for policy analysis. But we also view this as only one possible story. Another plausible story is that told by a traditional model like FRB/US. And yet another would be a New-Keynesian DSGE model in which fluctuations do not primarily reflect changes in productivity but rather reflect shifts in the degree of distortions in the economy (as suggested in Mankiw [2005]). Our DSGE model has shocks to markups, one type of shock to the degree of distortions in the economy. Whether fuller development of related disturbances would result in a model that captures "conventional" wisdom regarding high frequency fluctuations in output and inflation is an important research project.

6.3 The Natural Rate of Interest

We close our review of stories with a discussion of the natural rate of interest. Attention to such a concept has surged over the past decade. In the academic community, a significant factor has been the work of Woodford [2004], who provides a masterful overview of monetary policy in the core New-Keynesian model and illustrates the role of the flexible-price equilibrium measure of the real interest rate in policy. For example, in a very simple model with one distortion (sticky prices), policymakers can implement the efficient outcome, with stable inflation, by following a rule that sets the real interest rate equal to its natural rate and promises to respond sufficiently to any move in inflation. While this academic work may have influenced policymakers to some extent, a greater interest in the "equilibrium" or "neutral" policy rate in recent years is perhaps more likely attributable to the prolonged period of low real interest rates following the 2001 recession; in late 2005, it is still common to hear Wall Street economists worrying about the level of the neutral policy rate in the

United States.

Figure 7 presents our DSGE model's measure of the natural rate of interest and the actual real federal funds rate (implied by the actual nominal funds rate and expected inflation from our DSGE model). The natural rate of interest implied by our model is very volatile: its standard deviation is 80 basis points, and the standard deviation of the actual real funds rate is only 60 basis points. (Neiss and Nelson [2003] present estimates of the natural rate of interest for the United Kingdom and similarly find a very high level of volatility). We suspect that this story may be considered implausible by at least some policymakers. For example, Laubach and Williams [2003] estimate the equilibrium funds rate essentially by a smoothed version of actual real interest rates in a reduced-form model that seems more related to the view on the natural rate expressed in Committee [1999].

Beyond its plausibility to policymakers, there may be more fundamental issues related to fluctuations in the natural rate of interest and their role in the policy process in the typical DSGE model like ours. In particular, our model relies on habit persistence to generate persistent, hump-shaped responses of key expenditure variables to fundamentals. It is well-known that this specification of preferences has some unpalatable asset pricing implications, i.e., these models imply too much volatility in the risk-free real interest rate (Boldrin *et al.* [2001]). While some research in asset pricing has addressed this concern in a partial equilibrium framework (Campbell and Cochrane [1999]), the problem is much more difficult to address in general equilibrium (Uhlig and Ljungqvist [2004], Uhlig [2004]), because the fluctuations in consumption observed in the data cannot be taken as given but rather must be explained. Given the concerns we expressed earlier regarding habit persistence for other reasons, we view research on quantitative DSGE models that tries to link financial market and business cycle behavior (as started in, for example, Uhlig [2004]) as quite important.

7 Conclusions

We close our analysis with our plan for future analyses based on our DSGE model. We expect the model to provide a useful toolbox for addressing several questions.

One area is forecasting. A DSGE model provides a parsimonious framework in which to identify the structural disturbances driving the economic outlook, and the form of these disturbances – productivity, preference, and markup shocks – differs somewhat from those in a more traditional model like the FRB/US model, where it is often expenditure "residuals" that drive short-run fluctuations. Effectively interacting with this alternative view requires a great degree of disaggregation, as our interactions with colleagues regarding the outlook for expenditure typically takes place at an even greater level of detail than that contained in our DSGE model. We expect experience to provide more insight into the degree to which the alternative language of our DSGE model proves helpful in communication with policymakers.

We also expect the DSGE model's view that a significant fraction of fluctuations reflect the near-efficient response of the economy to fundamental shocks to provide a very different language within which the policy discussion can be framed. However, we anticipate significant resistance to this view from many colleagues: The mainstream view within policy circles remains one in which a significant fraction of fluctuations is viewed as inefficient. In this respect, the mainstream lies much closer to Bean [2005] and Mankiw [2005] than Hall [2005].

This latter controversy provides the key question for future research: How sensitive are our DSGE models predictions regarding the efficiency of significant high-frequency fluctuations in activity to changes in assumptions regarding the types of shock impinging on the economy or the frictions in certain markets? It is obvious that this result would be overturned if the most important sources of volatility were disturbances to the degree of distortions in the economy rather than those to productive efficiency. But estimated DSGE models require much more than simply the theoretical possibility that some alternative shock accounts for high-frequency volatility; they require that such shocks be capable of explaining the patterns observed in the data better than the productivity and preference shocks. It is not obvious how to include a rich set of such shocks to distortions, and whether the data would find a signficant role for such shocks if they were included.

In may be more straightforward to include alternative model frictions in DSGE models like ours. For example, our specification of the labor market, while quite standard in DSGE models, may prove a bit orthogonal to the concerns of policymakers and the public more generally. Most glaringly, we do not distinguish between the intensive and extensive margins of adjustment for hours, and hence have no meaningful measure of unemployment in our model. Related models have begun to incorporate search or other labor market frictions into quantitative DSGE models suitable for monetary policy analysis, and extensions of our model along this dimension may prove valuable.

Finally, we alluded in section 6 to concerns regarding the asset pricing implications of our model. It is quite clear that the asset pricing implications of any DSGE model are important for monetary policy analysis, as the policy interest rate is one of the economy's key asset prices. Further investigations of model features that help explain asset price, activity, and inflation fluctuations are central to policy discussions, especially given the prominence of asset price and wealth fluctuations on activity in the United States in recent years (e.g., Greenspan [2005]). Inclusion of frictions in asset markets may provide an additional deviation from the competititive neoclassical benchmark model that contributes to inefficiency in economic fluctuations and hence brings the predictions of a DSGE model closer to the intuition of some policymakers.

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	Average Real Growth Rate	Average Nominal Growth Rate	Average Price Change
Consumer non-durable goods and non-housing services	$3\frac{1}{4}$ percent	$6\frac{1}{4}$ percent	n.a.
Consumer housing services	$2\frac{1}{2}$ percent	$6\frac{1}{4}$ percent	$\frac{3}{4}$ percent
Consumer durable goods	$6\frac{3}{4}$ percent	$6\frac{1}{2}$ percent	-3 percent
Res. investment goods	$3\frac{3}{4}$ percent	$7\frac{1}{2}$ percent	$\frac{1}{2}$ percent
Non-res. investment goods	$6\frac{1}{4}$ percent	$6\frac{1}{4}$ percent	$-2\frac{3}{4}$ percent

Table 1: Average Growth and Relative Price Changes (1984q1 to 2004q4). Note: Average price change is relative to consumer non-durable goods and non-housing services prices.

	-4	-3	-2	-1	0	+1	+2	+3	+4
Cons. non-dur. goods & non-hous. services	−0.03	0.08	0.23	0.28	0.43	0.37	0.28	0.28	0.18
Cons. dur. goods	0.10	0.06	0.14	0.25	0.32	0.06	0.06	0.08	0.07
Res. inv. goods	0.15	0.19	0.34	0.31	0.44	0.15	-0.08	-0.12	-0.15
Non-res. inv. goods	0.12	0.01	0.17	0.14	0.61	0.31	0.26	−0.09	−0.02

Table 2: Cross Correlations: GDP and Major Private Expenditure Components

ψ	$\theta^{cbi,p}$	$\theta^{kb,p}$	$\theta^{l,w}$	η^{nr}	η^{cd}	η^{r}
5	7.000	7.000	7.000	1.000	1.000	1.000
β	δ	δ_{cd}	δ_{ch}	$h^{*,gf}$	α	-
0.990	0.030	0.055	0.004	0.250	0.260	-

Table 3: Calibrated Parameters

	Prior Distribution			Posterior Distribution				
Parameter	Type	Mean	S.D.	Mode	S.D.	10th perc.	50th perc.	90th perc.
h	B	0.500	0.122	0.794	0.055	0.717	0.794	0.862
h^{cd}	B	0.500	0.122	0.811	0.147	0.388	0.568	0.777
h^{r}	B	0.500	0.122	0.502	0.120	0.348	0.510	0.663
ν	G	2.000	1.000	2.443	0.915	2.124	3.168	4.537
r_{π}	N	2.000	1.000	3.686	0.488	3.021	3.570	4.277
r_{y}	N	0.500	0.400	0.208	0.029	0.170	0.209	0.243
$r_{\triangle\pi}$	N	0.500	0.400	-0.059	0.081	-0.163	-0.061	0.043
$r_{\triangle y}$	N	0.500	0.400	-0.091	0.028	-0.128	-0.095	-0.058
χ^{p}	G	2.000	1.000	2.217	0.673	2.191	2.951	3.878
χ^{H}	G	2.000	1.000	0.790	1.204	0.615	1.777	3.760
χ^{w}	G	2.000	1.000	0.696	0.691	0.634	1.271	2.384
χ^{nr}	G	2.000	1.000	0.660	0.242	0.548	0.817	1.160
χ^{cd}	G	2.000	1.000	0.191	0.159	0.296	0.521	0.708
χ^{r}	G	6.000	1.000	8.967	2.565	7.408	10.165	13.988
η^{H}	B	0.500	0.224	0.563	0.207	0.299	0.624	0.853
η^{p}	B	0.500	0.224	0.332	0.136	0.198	0.378	0.551
η^{w}	B	0.500	0.224	0.264	0.140	0.150	0.321	0.507
ρ_{R}	B	0.750	0.112	0.901	0.017	0.877	0.900	0.919
$\rho_{\xi,cnn}$	B	0.750	0.112	0.766	0.094	0.651	0.792	0.882
$\rho^{a,nr}$	B	0.750	0.112	0.887	0.031	0.853	0.893	0.929
$\rho^{a,cd}$	B	0.750	0.112	0.827	0.096	0.564	0.691	0.808
$\rho^{\xi,cd}$	B	0.750	0.112	0.793	0.112	0.590	0.753	0.882
$\rho^{\xi,r}$	B	0.750	0.112	0.790	0.109	0.591	0.755	0.875
$\rho^{gf,y}$	B	0.750	0.112	0.981	0.012	0.957	0.976	0.988
ρ^{L}	B	0.750	0.112	0.944	0.030	0.887	0.934	0.965
$\rho^{z,k}$	B	0.750	0.112	0.792	0.092	0.607	0.749	0.842
$\rho^{z,m}$	B	0.500	0.150	0.308	0.074	0.199	0.295	0.390
$\rho^{a,r}$	B	0.500	0.150	0.425	0.085	0.331	0.439	0.554

Table 4: Estimated Parameters

Parameter	Prior Distribution			Posterior Distribution				
	Type	Mean	S.D.	Mode	S.D.	10th perc.	50th perc.	90th perc.
$\sigma_{\xi,b}$	I	3.000	2.000	1.755	0.404	1.441	1.849	2.470
$\sigma_{\xi,cd}$	I	3.000	2.000	2.457	2.658	2.095	3.704	7.699
$\sigma_{\xi,r}$	I	3.000	2.000	2.446	1.586	1.939	3.248	5.899
$\sigma_{gf,y}$	I	1.000	2.000	1.585	0.154	1.428	1.613	1.826
$\sigma_{\xi,l}$	I	3.000	2.000	2.357	1.067	2.303	3.342	5.033
σ_R	I	0.200	2.000	0.110	0.011	0.100	0.112	0.128
$\sigma_{z,k}$	I	0.500	2.000	0.410	0.202	0.356	0.539	0.848
$\sigma_{z,m}$	I	0.500	2.000	0.834	0.076	0.752	0.844	0.943
$\sigma_{\theta,y,cbi}$	I	0.500	2.000	0.522	0.155	0.492	0.668	0.899
$\sigma_{\theta,y,kb}$	I	0.500	2.000	0.416	0.157	0.317	0.486	0.716
$\sigma_{\theta,l}$	I	0.500	2.000	0.605	0.079	0.513	0.598	0.713
$\sigma_{a,r}$	I	4.000	2.000	8.241	2.581	6.509	9.082	13.237
$\sigma_{a,cd}$	I	2.000	2.000	1.855	1.746	2.487	4.740	7.050
$\sigma_{\xi,i}$	I	4.000	2.000	5.353	1.140	4.744	6.060	7.682

Table 5: Estimated Variances

Shocks	Horizon	$\triangle y_t$	X_t^{cbi}	X_t^{kb}	L_t^{Agg}	Π_t^c	Π_t^{GDP}	R_t
$\epsilon_t^{\xi,cnn}$	1	0.01	0.15	0.02	0.03	0.00	0.00	0.01
	4	0.00	0.23	0.02	0.02	0.01	0.01	0.03
	12	0.00	0.27	0.02	0.01	0.02	0.01	0.03
$\epsilon_t^{\xi,cd}$	1	0.00	0.00	0.01	0.01	0.00	0.00	0.00
	4	0.00	0.00	0.01	0.01	0.00	0.00	0.01
	12	0.00	0.00	0.00	0.00	0.00	0.00	0.01
$\epsilon_t^{\xi,r}$	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\epsilon_t^{h,gf}$	1	0.23	0.00	0.01	0.02	0.01	0.01	0.07
	4	0.06	0.00	0.01	0.02	0.03	0.03	0.04
	12	0.04	0.00	0.00	0.01	0.03	0.02	0.01
$\epsilon_t^{\xi,l}$	1	0.01	0.00	0.02	0.03	0.03	0.03	0.00
	4	0.05	0.01	0.03	0.10	0.07	0.06	0.00
	12	0.05	0.10	0.06	0.35	0.05	0.04	0.00
ϵ_t^{R}	1	0.02	0.00	0.03	0.05	0.02	0.03	0.57
	4	0.01	0.00	0.02	0.04	0.07	0.06	0.09
	12	0.00	0.01	0.00	0.01	0.10	0.08	0.01
$\epsilon_t^{z,kb}$	1	0.00	0.00	0.18	0.10	0.01	0.06	0.03
	4	0.00	0.00	0.16	0.11	0.04	0.15	0.11
	12	0.13	0.05	0.08	0.05	0.06	0.25	0.09
$\epsilon_t^{z,m}$	1	0.46	0.72	0.02	0.23	0.26	0.32	0.02
	4	0.51	0.52	0.01	0.11	0.65	0.59	0.01
	12	0.56	0.35	0.00	0.00	0.69	0.54	0.00
$\epsilon_t^{\theta,y,cbi}$	1	0.00	0.00	0.00	0.01	0.64	0.48	0.11
	4	0.00	0.01	0.00	0.01	0.06	0.03	0.06
	12	0.00	0.01	0.00	0.00	0.00	0.00	0.01
$\epsilon_t^{\theta,y,kb}$	1	0.00	0.00	0.01	0.00	0.00	0.02	0.00
	4	0.00	0.00	0.01	0.01	0.00	0.00	0.00
	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\epsilon_t^{\theta,l}$	1	0.00	0.00	0.00	0.01	0.02	0.02	0.00
	4	0.01	0.00	0.00	0.02	0.02	0.02	0.00
	12	0.00	0.01	0.00	0.02	0.00	0.00	0.00
$\epsilon_t^{a,r}$	1	0.01	0.04	0.00	0.01	0.00	0.00	0.01
	4	0.00	0.04	0.00	0.01	0.00	0.00	0.01
	12	0.00	0.03	0.00	0.00	0.00	0.00	0.01
$\epsilon_t^{a,cd}$	1	0.04	0.01	0.11	0.09	0.01	0.01	0.04
	4	0.02	0.01	0.07	0.08	0.03	0.03	0.12
	12	0.00	0.03	0.01	0.02	0.03	0.03	0.06
$\epsilon_t^{a,nr}$	1	0.19	0.07	0.60	0.40	0.00	0.01	0.12
	4	0.33	0.16	0.67	0.47	0.01	0.02	0.52

Figure 1: VAR Impulse Response Functions (1967q1 to 2004q4).

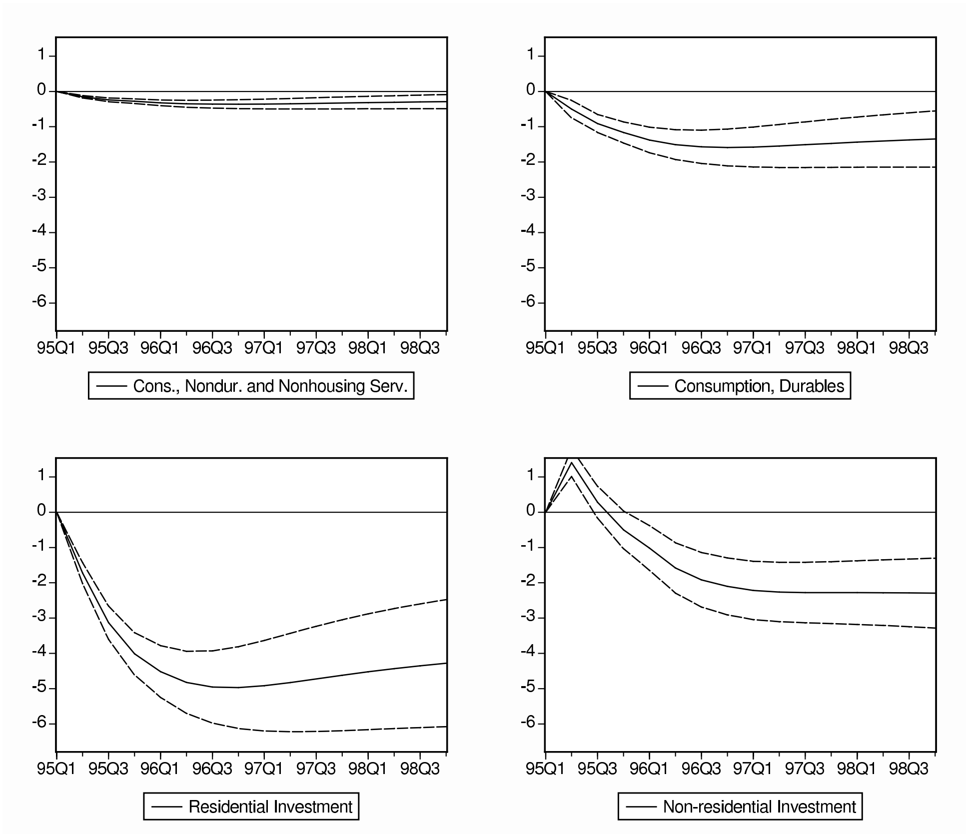


Figure 2: VAR Impulse Response Functions (1984q1 to 2004q4).

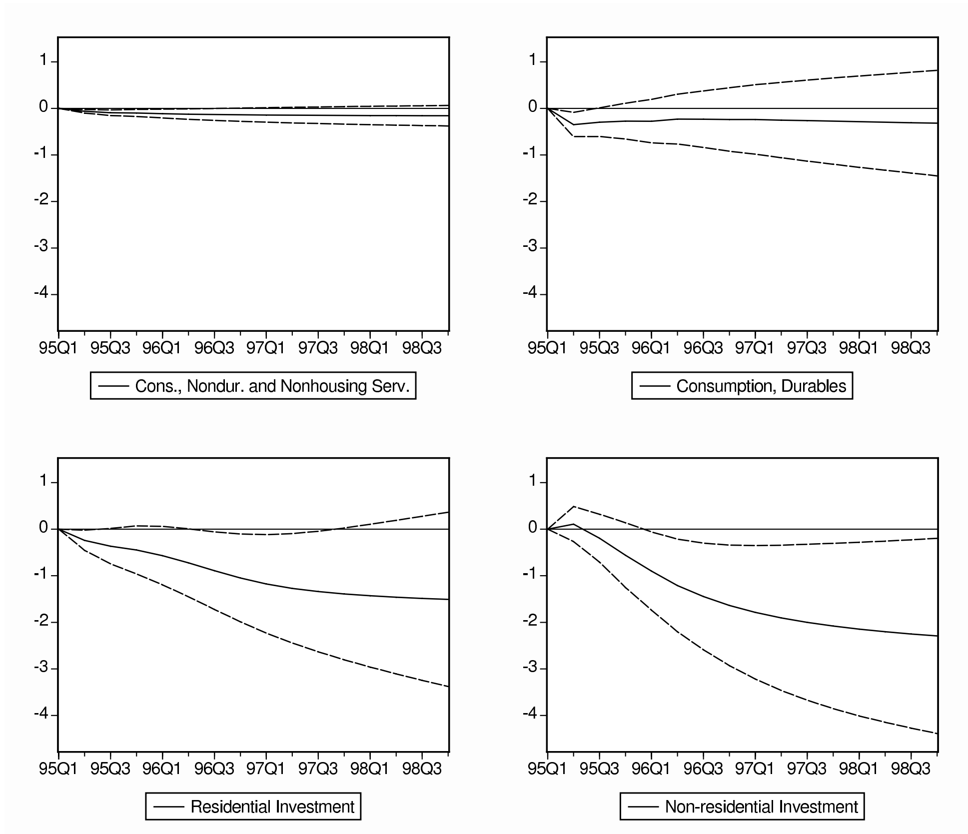


Figure 3: Observable series: realized paths and one-step ahead forecasts.

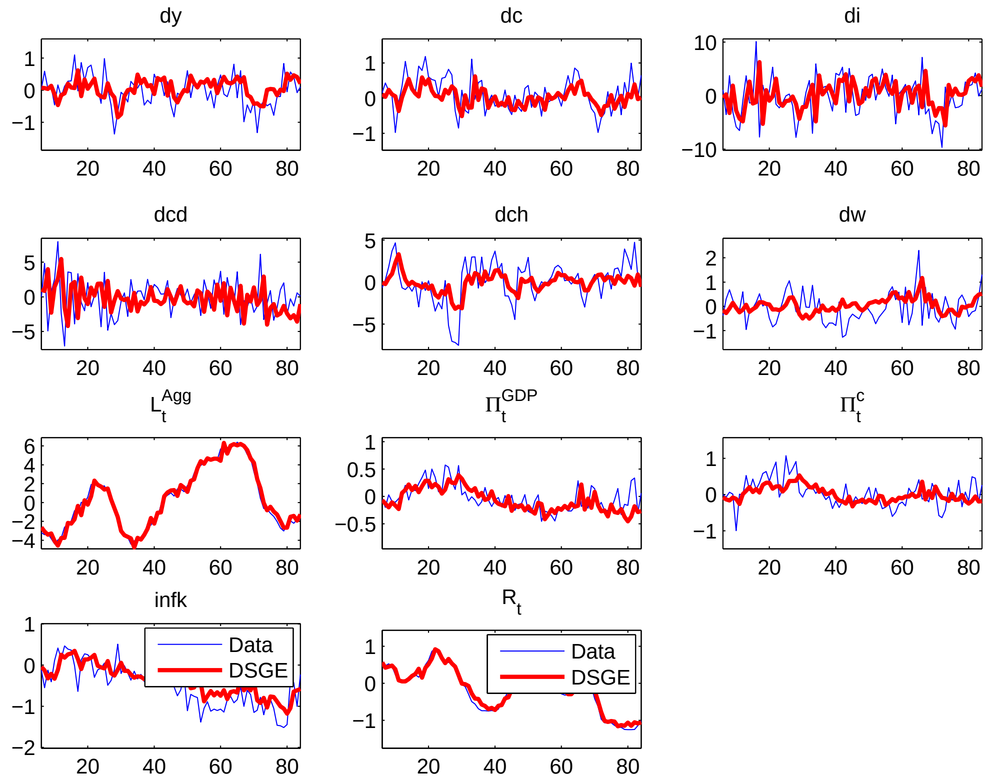
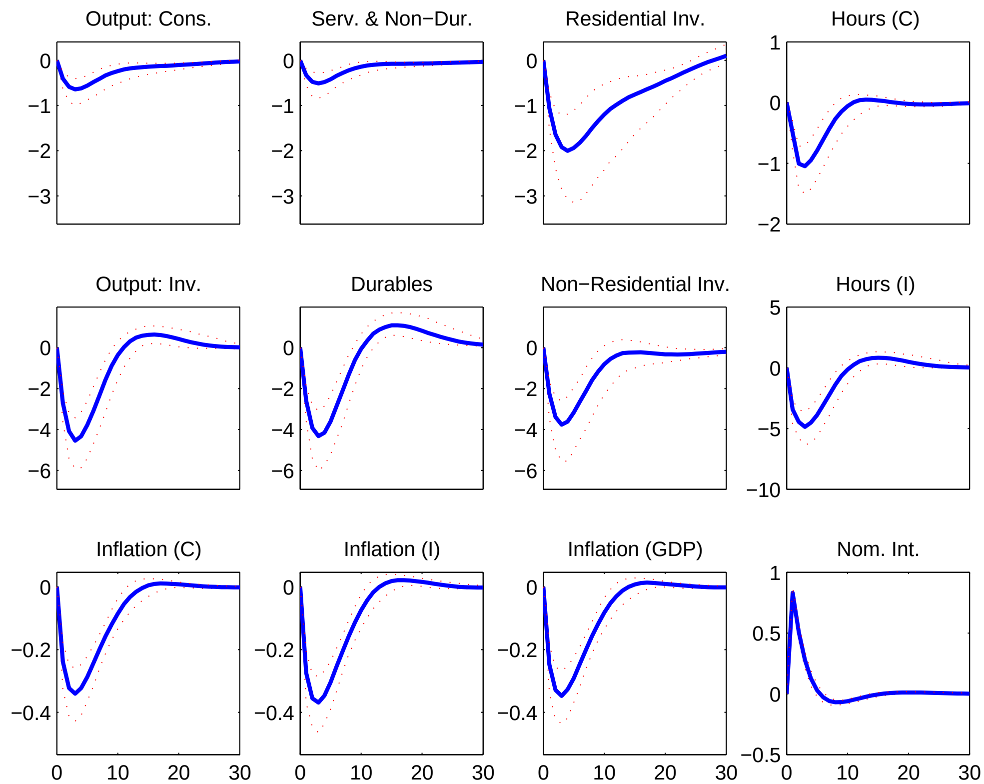


Figure 4: Impulse Responses: Monetary Policy Shock



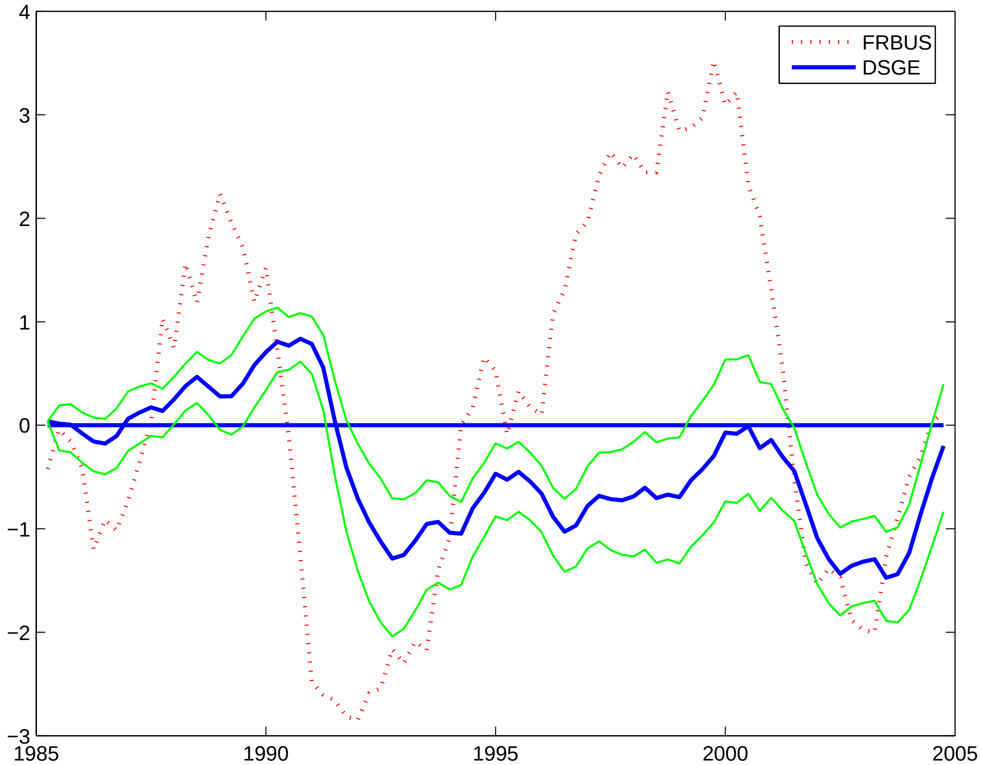


Figure 5: Output Gap Measures

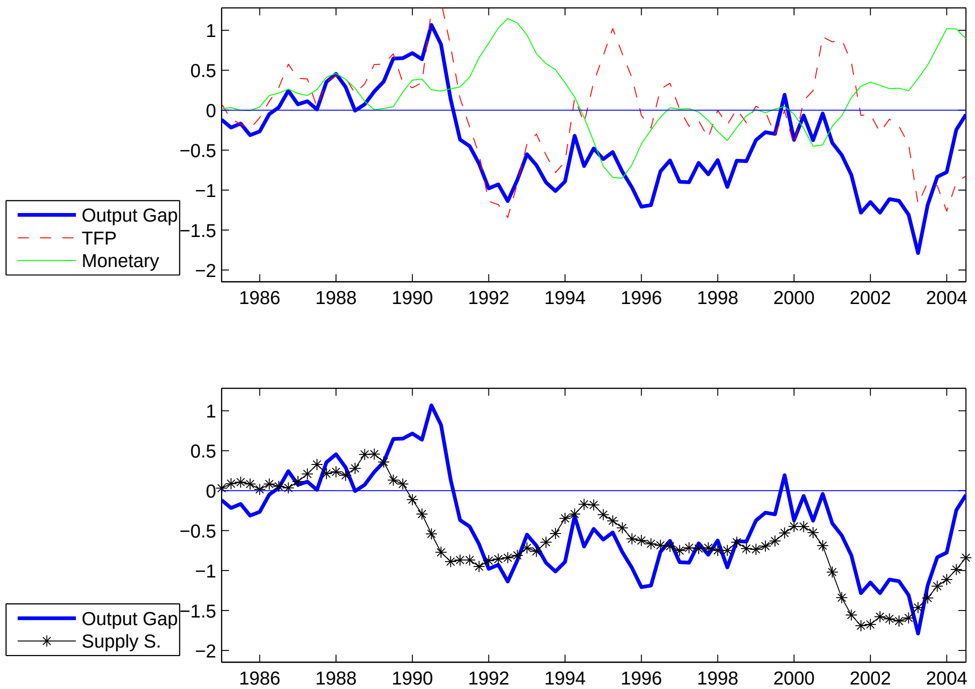


Figure 6: Output Gap: Historical Decompostion for Key Shocks. The supply shocks are the investment-goods permanent technology shock, the labor supply shock and the stationary investment-specific shocks.

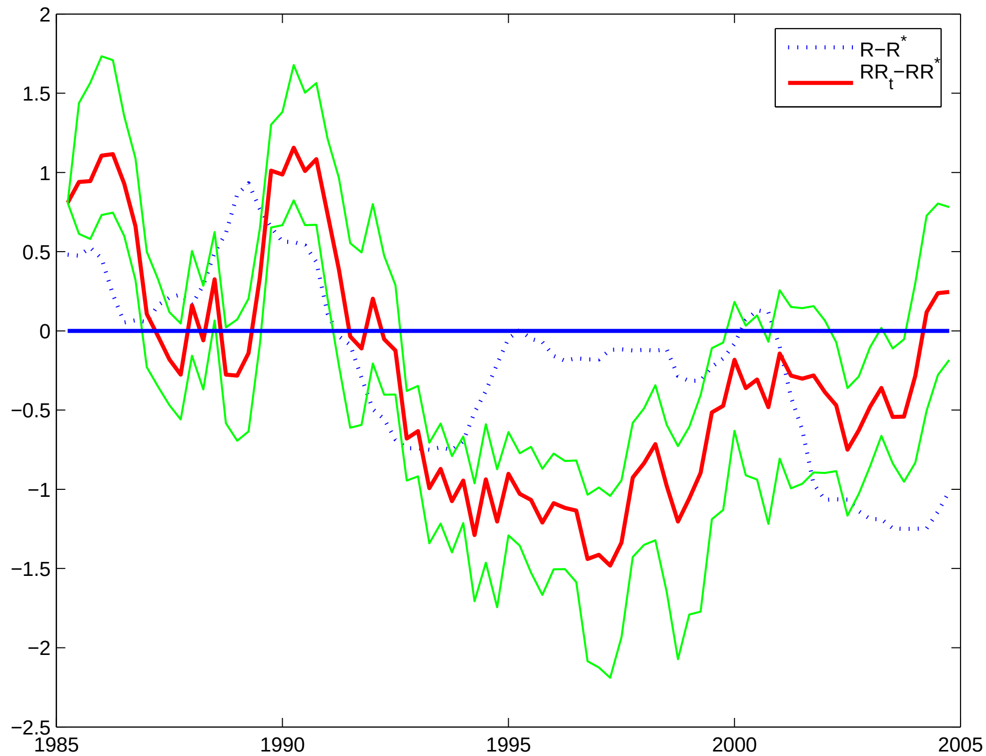


Figure 7: Natural Rate. The blue line shows the nominal interest rate. The 90% confidence bands is associated to the natural real nature as defined by the flex-price economy.