ESSAYS IN MACROECONOMICS

By

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Abstract

This dissertation has three self-contained chapters in macroeconomics. In the first chapter, I develop a two-sector dynamic stochastic general equilibrium (DSGE) model where the housing sector is subject to search and matching frictions. These frictions amplify the response of residential construction to all economic shocks. Further, the interest rate spread between mortgages and risk free bonds transmits monetary policy to the housing market. An expansionary monetary policy shock reduces this spread, increasing the demand for homeownership and spurring new residential construction. I test the qualitative predictions of the DSGE model by estimating a factor-augmented vector autoregression and identifying the structural monetary policy shocks with an external instrument. Consistent with the DSGE model, an expansionary monetary policy shock reduces the interest rate spread between mortgages and Treasury bonds.

In the second chapter, I study time series models for forecasting residential investment. I estimate standard univariate and multivariate models and propose an error correction model (ECM) based on the stock-flow relationship of housing starts, completions and units under construction. The root mean squared prediction errors (RMSPEs) of the models are compared along with the RMSPEs of the Survey of Professional Forecasters (SPF) and the Federal Reserve's Greenbook. For the 1981:Q3 to 2013:Q2 sample, the ECM improves upon the competing time series models and makes modest improvements to the SPF. For the 1981:Q3 to 2007:Q4 sample, the ECM performs comparably to the Greenbook.

In the third chapter, I study the implication of two stylized facts of the U.S. economy. First, nominal prices in the services sector change less frequently than those in the goods sector. Second, the size of the services sector relative to the goods sector has increased over the last 50 years. In a two-sector new Keynesian model, these facts imply that interest rate shocks should have a larger impact on output in more recent time periods. In contrast to this implication, impulse response functions of U.S. GDP to Federal Funds rate shocks estimated using both vector autoregressions and factor-augmented vector autoregressions are larger in the 1959 to 1979 time period than in the 1983 to 2007 time period.

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Chapter 1

Housing Search and Fluctuations in Residential Construction

1.1 Introduction

Fluctuations in residential construction are an important component of the U.S. business cycle. They were central to the 2002-2007 economic expansion and the 2008-2009 recession, and historically, they have been large compared to fluctuations in other sectors of the economy. From 1947 to 2013, the standard deviation in annual residential growth was 5.5 times that of gross domestic product, and it was roughly twice that of durable goods consumption and non-residential investment. Further, residential investment is the component of gross domestic product that "contributes most to weakness before recessions" (Leamer, 2007), it typically makes large contributions to recoveries (McCracken, 2011), and it has been repeatedly shown to be highly responsive to monetary policy shocks.[1] For these reasons, policy-makers have recognized the importance of housing markets for transmitting monetary policy. Frederic Mishkin (2007), then a member of the Board of Governors of the Federal Reserve, wrote

> [T]he housing market is of central concern to monetary policy makers. To achieve the dual goals of promoting price stability and maximum sustainable employment, monetary policy makers must understand the role that housing plays in the monetary transmission mechanism if they are to appropriately set policy instruments.

More recently, Janet Yellen (2014) highlighted the stimulation of the housing market as a goal of the Federal Reserve's low interest rates:

> Although we [the Federal Reserve] work through financial markets, our goal is to help Main Street, not Wall Street. By keeping interest rates low, we are trying to make homes more affordable and revive the housing market.

Motivated by the importance of residential construction to U.S. business cycles, the objective of this paper is to understand why housing construction is so responsive to economic shocks. I approach this objective in two steps. First, I construct and calibrate a theoretical dynamic stochastic general equilibrium (DSGE) model in order to provide intuition for the behavior of residential construction as well as other housing market variables. Second, I estimate a factor-augmented vector autoregession model and document that the empirical impulse

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[1] For examples, see Bernanke and Gertler (1995), Edge (2000), Barsky, House, and Kimball (2003), Bańbura, Giannone, and Reichlin (2010), Luciani (2013).

response functions of housing construction and other housing market variables to a monetary policy shock are consistent with the qualitative predictions of the DSGE model.

The DSGE model is a two-sector new Keynesian model. The first sector is standard in the new Keynesian literature and is populated by monopolistic firms that produce non-durable consumption goods and face Calvo (1983) pricing rigidities. These rigidities provide a role for monetary policy, which operates by setting the short-term risk-free interest rate according to a Taylor (1993) style rule. The second sector in the model is populated by residential investment firms that produce durable houses. However, my modelling of this sector is distinct from the previous new Keynesian literature. The common approach to modelling residential investment is to treat it similarly to neoclassical capital accumulation and have households scale up or down their individual housing stocks in response to economic shocks.[2] In contrast to this focus on the intensive margin of housing, I model housing adjustment along the extensive margin. I assume that houses exist in discrete units of one size and that households only get utility from occupying one housing unit at a time. The decision for households is not how much housing stock to accumulate; it is whether to rent or own the housing unit they occupy. When households decide to buy a house, they do so through a time-consuming searching and matching process, and when households match with a house, they purchase it with a long-term mortgage that is subject to administrative costs.[3]

[2]For standard DSGE models with housing, see Davis and Heathcote (2005) for a real business cycle model or Carlstrom and Fuerst (2010) and Iacoviello and Neri (2010) for new Keynesian models. The Federal Reserve Board's DSGE model also includes residential investment treated in manner parallel to capital investment, and Edge, Kiley, and Laforte (2007) provide details.

[3]To my knowledge, Ungerer (2012) is the only other paper that includes searching, matching and bargaining in the housing market of a new Keynesian model. However, Ungerer (2012) maintains a fixed quantity of housing and cannot model fluctuations in residential construction.

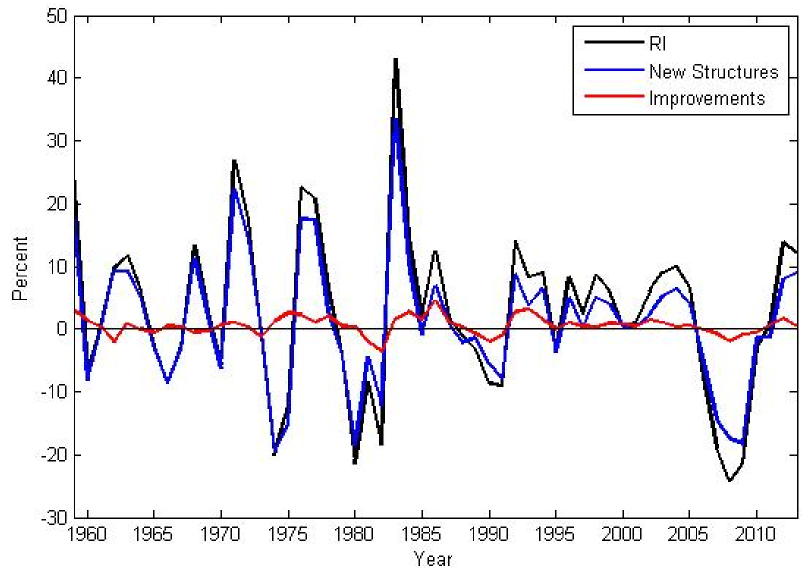

Figure 1.1: Percent growth in residential investment and the contribution of new structures and improvements to existing structures to residential investment growth.

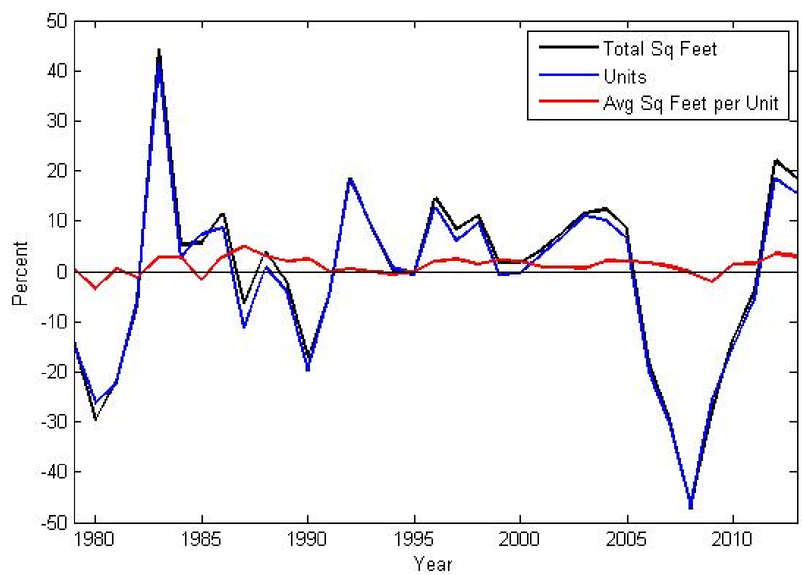

Figure 1.2: Percent growth in total square footage of new single-family houses sold and the contribution of the number of units and the average square feet per unit to total square footage growth.

My motivation for deviating from the neoclassical accumulation view of housing comes from three empirical facts. First, fluctuations in residential investment growth are driven largely by the construction of new housing and not by improvements to existing housing.[4] As evidence of this, Figure 1.1 displays the annual percentage growth of residential investment and the contribution from new structures and improvements to residential investment growth. New structures track total residential investment much more closely than improvements and contribute roughly 50 times the variance to residential investment growth than improvements do. Second, fluctuations in the total square footage of new housing units is driven almost entirely by the number of new units built and not by the average square footage per unit. As evidence of this, Figure 1.2 shows the annual percent growth in the total square footage of new single-family houses sold and the contribution from new units sold and the average square footage per unit sold to total square footage growth.[5] It shows that growth in the number of units sold contributes roughly 100 times more variance to total square footage growth than does growth in average square feet per unit. Third, housing units designated as seasonal, as occasional use or as being occupied by persons with a usual residence elsewhere have historically averaged less than 5% of the total housing stock.[6] This suggests that households rarely acquire multiple housing units for their own private use.

[4]Improvements is a broad category that is defined as additions, alterations, and major replacements to structures subsequent to their completion. It includes but is not limited to the finishing of attics and basements, the remodelling of bathrooms and kitchens, the additions of garages and in-ground pools, any repairs that extend the life of the structure such as a new roof, and even the addition of new housing units to an existing structure. The data in Figure 1.1 are from the BEA's national income and product table 5.4.2.

[5]This figure is based on the decomposition of total square feet sold into the number of units sold times the average square feet per unit. Data are from the Census Bureau's historical series on new residential sales.

[6]Data are annual from 1965 to 2013 from the Census Bureau's annual estimates of housing inventory: http://www.census.gov/housing/hvs/data/histtabs.html.

The DSGE model yields four primary results. First, without search frictions, monetary, preference and productivity shocks will not cause the number of housing units under construction to deviate from its steady-state. Hence, search frictions are the central mechanism that allows economic shocks to generate large fluctuations in residential construction. This result is consistent with previous literature,[7] and the intuition for it is as follows. As matching efficiency decreases (as average search times increase), houses act less like substitutes with each other because they are less likely to match with each other's potential buyers. This causes the marginal value of new housing to be less responsive to the number of new houses built, and larger fluctuations in new housing units are needed to equate the marginal value of new houses to the marginal cost of building a new house.

Second, in the baseline calibration of the DSGE model, shocks to both monetary policy and productivity in the non-durables sector generate larger responses in residential construction spending than in non-durable consumption spending. This result suggests that empirically reasonable levels of search frictions can generate the large fluctuations in residential construction observed in the data and can support the claim that housing drives the business cycle (Leamer, 2007).

Third, monetary policy is transmitted to the housing sector by mortgages. While this is a common explanation of the monetary transmission mechanism, it often relies on Jorgenson's (1963) neoclassical user cost of capital framework, which motivates households to adjust their private housing stocks.[8] In contrast mortgage rates in my model do not impact existing homeowners. Rather, they impact the households that are on the margin between wanting

[7]Both Head, Lloyd-Ellis, and Sun (2014) and Hedlund (2014) have found that search frictions in the housing sector amplify the response of housing construction to economics shocks.

[8]For example, McCarty and Peach (2002), Mishkin (2007) and Boivin, Kiley, and Mishkin (2010) all argue that mortgage rates impact housing markets by influencing the user cost of housing capital.

to rent and wanting to own. In the model, the administrative costs of mortgages generate an interest rate spread between mortgage rates and long-term risk-free rates. Following an expansionary monetary shock, this interest spread falls, making it relatively cheap to finance a house and increasing the total surplus of a housing match. This incentivizes more households to begin searching to buy a house and spurs the construction of new houses.

The fourth result is that residential construction and the production of non-durable goods co-move positively following a monetary policy shock. Hence, the DSGE model does not suffer from the counterfactual features of new Keynesian models described in Barsky, House, and Kimball (2007). They show that when flexibly-priced durable goods, such as houses, are added to an otherwise standard new Keynesian model, the model predicts that durable goods production should *fall* in response to an expansionary monetary policy shock while non-durable production rises. The intuition for this response is that the relative price of durable to non-durable goods rises following an expansionary shock, and because households do not need to purchase new durable goods every period in order to get utility from them, households can substitute their purchases of durable goods to the future when they will be relatively cheaper.

My model's ability to overcome this counterfactual feature of new Keynesian models is a result of not treating housing similarly to neoclassical capital accumulation. Individual households do not adjust their stock of housing based on the relative price of new housing and non-durable goods. Rather, because households choose between staying in rental housing and searching for a house to buy, a cut in interest rates incentivizes more households to search for a house to buy by increasing the value of a housing match. In earlier work, Carlstrom and Fuerst (2010) and Iacoviello and Neri (2010) show that sticky wages can also overcome the Barsky, House, and Kimball (2007) result. Thus, my model provides an additional mechanism to help new Keynesian models match the empirical features of housing markets.

In order to increase its tractability and the clarity of its results, the DSGE model in this paper has several stylized features. The model uses linear dis-utility of labor, assumes no defaults on mortgages, does not allow the monetary authority to engage in quantitative easing by purchasing mortgage debt, and calibrates rather than estimates parameter values. However, the DSGE model still yields many qualitative predictions about the behavior of housing construction and many other housing market variables. To test the DSGE model's predictions following monetary policy shocks, I estimate a factor-augmented vector autoregression (FAVAR), which allows me to incorporate many housing market variables into one statistical model without degrees of freedom limitations. I then follow Stock and Watson (2012) and Mertens and Ravn (2013) and identify the structural policy shocks with an external instrument, where the instrument is constructed as in Romer and Romer (2004). Finally, I generate the empirical impulse response functions (IRFs) for comparison against the DSGE model.

Consistent with the transmission effect in the DSGE model, I show that the interest rate spread between 30-year mortgages and 10-year treasury bonds falls following an expansionary monetary policy shock.[9] I document that an expansionary monetary policy shock generates an increase in real residential construction spending, and that the peak response of residential construction spending is roughly five times the response of non-durable consumption. Further, real house prices, real rental prices, the number of new houses sold, and the homeownership rate all rise after an expansionary monetary policy shock while the time that

[9]Similar results are documented in Gertler and Karadi (2014).

houses spend on the market falls. These last two responses cannot be explained by models of neoclassical housing accumulation as there is no concept of a homeownership rate or time on the market in those models. However, the direction of all of these empirical responses are consistent with DSGE model presented in this paper.

The rest of the paper proceeds as follows. Section 1.2 provides a literature review. Section 1.3 describes the DSGE model, and Section 1.4 discusses its equilibrium and the importance of search frictions. Section 1.5 calibrates the DSGE model and presents the numerical results. Section 1.6 discusses the methodology for estimating the FAVAR and identifying monetary policy shocks, and it presents the empirical IRFs of housing market variables to monetary policy shocks. Section 1.7 concludes and notes directions for future research.

1.2 Literature Review

The DSGE model in this paper follows in the spirit of Davis and Heathcote (2005), Barsky, House, and Kimball (2007), Carlstrom and Fuerst (2010) and Iacoviello and Neri (2010) by using a separate production technology for the housing sector than in other sectors. Davis and Heathcote (2005) is a real business cycle model that introduced this feature, which did not previously exist in the home production literature (for example, see Gomme, Kydland, and Rupert (2001)). Barsky, House, and Kimball (2007), Carlstrom and Fuerst (2010) and Iacoviello and Neri (2010) introduce new Keynesian features, which include but are not limited to sticky prices and interest rate policy, to the Davis and Heathcote (2005) model.

The model presented in this paper is also heavily indebted to the long and active literature that uses searching and matching models to study housing markets. Early papers in this literature are Stull (1978), Yinger (1981), Wheaton (1990) and Williams (1995). More recent papers include but are not limited to Krainer (2001), Krainer and LeRoy (2002), Albrecht et al. (2007), Caplin and Leahy (2011), Ungerer (2012), Díaz and Jerez (2013), Albrecht, Gautier, and Vroman (2014), and Ngai and Tenreyro (2014). These papers apply the labor search models of Peter A. Diamond, Dale T. Mortensen and Christopher A. Pissarides to study the pricing, liquidity and vacancy characteristics of housing. However, the majority of these papers have a constant housing stock and none of them have endogenous housing construction. Thus, they cannot address the observed volatility in residential construction.

In addition to this housing search literature, there is a small recent literature that includes both housing search and endogenous housing construction. These papers are Head and Lloyd-Ellis (2012), Karahan and Rhee (2013), Head, Lloyd-Ellis, and Sun (2014) and Hedlund (2014). All of these papers are real business cycle models, and none of them study monetary policy. To my knowledge, the model presented in this paper is the first to include housing search, endogenous residential construction and monetary policy.

The structure of the long-term mortgages in this paper closely follows Garriga, Kydland, and Sustek (2013). As in their paper, I assume that a fraction of the price paid to buy housing is financed by long-term, geometrically decaying mortgages. However, Garriga, Kydland, and Sustek (2013) do not use administrative costs as a friction in their mortgage market. Rather, they assume that households have limited access to risk-free bond markets, and this limited access to risk-free markets gives monetary policy influence in the housing market. Further, Garriga, Kydland, and Sustek (2013) do not include sticky prices, and mortgage rates provide the only nominal rigidity in their model. Calza, Monacelli, and Stracca (2013) include both sticky-prices and long-term mortgages in their model; however, they do not use the geometrically decaying mortgages as in Garriga, Kydland, and Sustek (2013) or in this paper.

1.3 The DSGE Model

Five types of agents populate the economy:

- **Households:** There is a measure one of households, indexed by $h \in [0, 1]$. Households get utility from non-durable consumption goods and dis-utility from providing labor to firms, which is the only factor of production in the economy. Further, households get utility from occupying one housing unit, which can either be owned by that household or rented.[10] They buy housing through random bilateral matching and bargaining, and they pay a fraction of the purchase price by borrowing a mortgage. Households own all of the firms in the economy as well as the financial intermediary.

- **Investment firms:** There is an arbitrarily large measure of housing investment firms that use labor to build new housing. Investment in housing takes one period so that investment in period t becomes available for sale in period $t + 1$. Housing is built in discrete units, and investment firms can only hold one house at a time in inventory.

- **Financial intermediary:** There is a financial intermediary whose sole purpose is to make mortgage loans and collect mortgage payments. Extending a mortgage requires real administrative costs, and the financial intermediary's optimal choice for mortgage loans determines the interest rate on mortgages.

- **Non-durable consumption firms:** Following conventional new Keynesian models, there are two types of non-durable consumption firms. First, there is a continuum of intermediate-goods firms that produce unique goods, and both the firms and their

[10] Households will be allowed to own many housing units, but they only receive utility from occupying one housing unit at a time.

goods are indexed by $i \in [0,1]$. These intermediate-goods firms are monopolistic and face nominal rigidities in the form of Calvo (1983) pricing. Second, there are final-goods firms that aggregate the intermediate goods according to Dixit and Stiglitz (1977) and sell the aggregated bundle in a competitive market.

- **Monetary authority:** The monetary authority sets the nominal interest rate on risk-free bonds that are traded by consumers according to a Taylor (1993) style rule.

1.3.1 Households

There is a continuum of households, indexed by $h \in [0,1]$. The utility function of household h is

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\ln(C_t(h) - \nu C_{t-1}) + \gamma_{H,t}(h) - \gamma_N N_t(h) \right],$$

where $\beta \in (0,1)$ is the subjective discount factor, $C_t(h)$ is non-durable consumption and $N_t(h)$ is labor provided for household h. Following Smets and Wouters (2003), non-durable consumption follows an external habit, where C_t denotes aggregate consumption and ν gives the degree of habit persistence.

The variable $\gamma_{H,t}(h)$ gives the instantaneous utility from housing for household h, depending on whether it owns or rents the house it occupies. This variable follows

$$\gamma_{H,t}(h) = \begin{cases} \gamma_{H,r} & \text{if household } h \text{ is renter} \\ \gamma_{H,o,t} + \gamma_{H,r} & \text{if household } h \text{ is owner-occupier} \end{cases} \tag{1.1}$$

where $\gamma_{H,r}$ is the instantaneous utility from renting, and $\gamma_{H,o,t}$ is the premium that households get from being owner-occupiers. Both $\gamma_{H,o,t}$ and $\gamma_{H,r}$ are the same across households, and

$\gamma_{H,o,t}$ is a stochastic process that follows

$$\ln(\gamma_{H,o,t}) = (1 - \rho_H)\ln(\bar{\gamma}_{H,o}) + \rho_H \ln(\gamma_{H,o,t-1}) + \xi_{H,t} \tag{1.2}$$

while $\gamma_{H,r}$ is constant over time. Because $\gamma_{H,o,t}$ is non-negative, it motivates the desire of households to be owner-occupiers of housing.

The labor market is competitive, and households take the nominal wage of W_t as given. Every household can split their labor to produce non-durable goods and housing investment

$$N_t(h) = \int_0^1 N_{X,t}(i,h)di + N_{I,t}(h), \tag{1.3}$$

where $N_{X,t}(i,h)$ is household h's labor provided to non-durable goods firm i and $N_{I,t}(h)$ is household h's labor provided for housing investment. Households also trade risk-free bonds amongst one another in a competitive market with a gross interest rate of $R_{f,t}$. The budget for household h is

$$P_t C_t(h) + R_{f,t}^{-1} B_t(h) + \text{spending on housing}_t = W_t N_t(h) + B_{t-1}(h) + \text{dividends}_t.$$

I discuss how households spend on housing in depth below.

Household h's first-order conditions yield an Euler equation for consumption

$$\frac{1}{P_t(C_t(h) - \nu C_{t-1})} = \beta R_{f,t}\mathbb{E}_t\left[\frac{1}{P_{t+1}(C_{t+1}(h) - \nu C_t)}\right]$$

and an optimal consumption-labor condition of

$$\gamma_N(C_t(h) - \nu C_{t-1}) = \frac{W_t}{P_t}.$$

Because $C_t(h)$ is the only variable in the consumption-labor condition that depends on h, all households choose the same quantity of consumption. This result is from the linear disutility of labor, which generates the result that all households fully offset any wealth effects through their labor market choices. This allows me to treat households homogenously for the purposes of consumption, and it allows me to solve for the equilibrium of aggregate variables without having to track the distribution of wealth across households. Thus, the Euler equation and optimal consumption-labor condition for households are

$$\frac{1}{P_t(C_t - \nu C_{t-1})} = \beta R_{f,t}\mathbb{E}_t\left[\frac{1}{P_{t+1}(C_{t+1} - \nu C_t)}\right] \tag{1.4}$$

and

$$\gamma_N(C_t - \nu C_{t-1}) = \frac{W_t}{P_t}. \tag{1.5}$$

1.3.2 Evolution of Home Ownership

Households can take one of three states with respect to housing. They can be owner-occupiers, in which case they own the house they occupy, they can be non-searching renters, in which case they rent the house they occupy and are not trying to become owner-occupiers, or they can be searching renters, in which case they rent the house they occupy but are trying to become owner-occupiers. I denote the measure of owner-occupiers, the measure of non-searching renters, and the measure of searching renters by $H_{o,t}$, $H_{r,t}$ and $H_{s,t}$, respectively.

Because there is a measure one of total consumers in the economy, it must be the case that

$$1 = H_{o,t} + H_{s,t} + H_{r,t}. \tag{1.6}$$

In between periods $t-1$ and t a fraction $\delta \in (0,1)$ of houses depreciate completely, and a fraction $\chi_r \in (0,1)$ of owner-occupiers separate from their house and become renters. The depreciation of houses provides a role for new residential construction. The separation from houses, although not explicitly modelled, is meant to stand in for factors that cause households to become mismatched with a house, such as changes in employment location. It is included because existing home sales make up the bulk of total home sales in the U.S, and it is standard in the housing search literature. Depreciation and separation imply that there is a measure of $(1-\delta)(1-\chi_r)H_{o,t-1}$ owner-occupiers at the beginning of period t.

All households that are not owner-occupiers rent housing in a competitive rental market, and there is no homelessness. Non-searching renters choose to rent this period and enter the following period as non-searching renters. Searching renters that do not match with a house stay searching renters in the following period.[11] Searching renters that match with a house become owner occupiers. In addition, a fraction $\chi_{s,t}$ of non-searching renters in period t decide to become searching renters in that period. This implies that the measure of households searching to buy a house at the beginning of period t is $H_{s,t-1} + \chi_{s,t}H_{r,t-1} + \chi_{s,t}[1-(1-\delta)(1-\chi_r)]H_{o,t-1}$.

On the supply side of the housing market, there is a stock of housing that is not owner-occupied, denoted by U_t. In between periods $t-1$ and t a fraction δ of these houses depreciate,

[11] I assume that searching renters do not revert back being non-searching renters in the previous period. The idea is that households may require several consecutive periods of search in order to find a house.

a measure $(1-\delta)\chi_r H_{o,t-1}$ of houses become mismatched, and new houses invested in in period $t-1$, denoted I_{t-1}, becomes available for sale. This implies that the stock of housing that is not owner-occupied at the beginning of period t is $(1-\delta)(U_{t-1}+\chi_r H_{o,t-1})+I_{t-1}$. I assume that rental housing cannot also be marketed as a house available for sale, and a measure $H_{s,t}+H_{r,t}$ of housing units must be taken off the market and rented. This implies that the measure of houses available for sale is $(1-\delta)(U_{t-1}+\chi_r H_{o,t-1})+I_{t-1}-H_{s,t}-H_{r,t}$.

Market tightness is the ratio of households searching for a house to the number of houses available for sale, and it is given by

$$\tau_t = \frac{H_{s,t-1}+\chi_{s,t}H_{r,t-1}+\chi_{s,t}[1-(1-\delta)(1-\chi_r)]H_{o,t-1}}{(1-\delta)(U_{t-1}+\chi_r H_{o,t-1})+I_{t-1}-H_{s,t}-H_{r,t}} \tag{1.7}$$

I follow Díaz and Jerez (2013) by using an urn-ball matching function that is scaled by scaled by an efficiency parameter ζ.[12] This implies that the fraction of houses available for sale that are sold is given by

$$G_t = \zeta\left(1-e^{-\tau_t}\right). \tag{1.8}$$

The fraction of searching households that find a house is given by

$$F_t = \frac{G_t}{\tau_t}. \tag{1.9}$$

[12]For ease of notation, let $\mathcal{B}$ be the number of buyers in the market (the numerator in Equation (1.7)), and let $\mathcal{S}$ be the number of sellers (the denominator in Equation (1.7)). Then, the urn-ball matching function takes the form

$$\mathcal{M}(\mathcal{B},\mathcal{S}) = \mathcal{S}\left(1-e^{-\frac{\mathcal{B}}{\mathcal{S}}}\right),$$

where $\mathcal{M}(\mathcal{B},\mathcal{S})$ denotes the measure of houses sold, given a measure of buyers and sellers. For $\mathcal{B}\geq 0$ and $\mathcal{S}\geq 0$, this function has the standard properties that it is increasing both arguments, it is homogeneous of degree one, and $\mathcal{M}(0,\mathcal{S})=\mathcal{M}(\mathcal{B},0)=0$. Given homogeneity of degree one, the fraction of houses for sale that actually get sold, which is $\mathcal{M}(\mathcal{B},\mathcal{S})/\mathcal{S}$, can be re-written in terms of market tightness: $\mathcal{M}(\tau,1)=1-e^{-\tau}$. Similarly, the fraction of buyers that find a house is $\tau\mathcal{M}(\tau,1)=1-e^{-\tau}$.

The virtue of this matching function is that $G_t \to 0$ and $F_t \to \zeta$ as $\tau_t \to 0$, and $G_t \to \zeta$ and $F_t \to 0$ as $\tau_t \to \infty$. Thus, for any non-negative measures of buyers and sellers and for $\zeta \in [0,1]$, F_t and G_t are between zero and one, and I interpret F_t and G_t as the probabilities that a searching renter buys a house and that a seller sells a house, respectively. The number of houses that are sold every period is given by

$$S_t = F_t\{H_{s,t-1} + \chi_{s,t}H_{r,t-1} + \chi_{s,t}[1-(1-\delta)(1-\chi_r)]H_{o,t-1}\}, \tag{1.10}$$

which is the probability of buying a house times the number of households searching for a house.

The evolution of natural renters is

$$H_{r,t} = (1-\chi_{s,t})[1-(1-\delta)(1-\chi_r)]H_{o,t-1} + (1-\chi_{s,t})H_{r,t-1}, \tag{1.11}$$

and the evolution of searching renters is

$$H_{s,t} = (1-F_t)\{H_{s,t-1} + \chi_{s,t}H_{r,t-1} + \chi_{s,t}[1-(1-\delta)(1-\chi_r)]H_{o,t-1}\}. \tag{1.12}$$

Given the evolutions of $H_{s,t}$ and $H_{r,t}$, $H_{o,t}$ evolves according to Equation (1.6). Finally, the stock of housing that is not owner-occupied evolves according to

$$U_t - H_{s,t} - H_{r,t} = (1-G_t)[(1-\delta)(U_{t-1} + \chi_r H_{o,t-1}) + I_{t-1} - H_{s,t} - H_{r,t}]. \tag{1.13}$$

1.3.3 Mortgages and Financial Intermediaries

Following Garriga, Kydland, and Sustek (2013), I assume that all households use a mortgage to finance part of the price of housing. Given a house price of Q_t, a household that purchases a house pays $(1-\theta)Q_t$ and borrows θQ_t in period t, where $1-\theta$ is the fraction of the down payment. Because all households have the same level of consumption, Q_t will be the same for all households as discussed in the bargaining protocol below. Thus, all households that buy a house in period t borrow θQ_t.

Once a household has a loan, it repays a fraction η of the principal every period. In addition, the household pays interest on the principal every period of $R_{m,t} - 1$, where $R_{m,t}$ is the fixed gross nominal interest rate on mortgages. This set-up yields a stream of geometrically decaying nominal mortgage payments of $(1-\eta)^{j-1}(R_{m,t} - 1 + \eta)\theta Q_t$ for period $t + j$, where $j = 1, 2, \ldots$.

Households get mortgages from the financial intermediary. I deviate from the framework of Garriga, Kydland, and Sustek (2013) by assuming that each mortgage requires a real administrative cost of $\kappa_1 S_t$ on the part of the intermediary.[13] Because the administrative cost for each mortgage increases with the total number of houses sold, S_t, we can interpret the financial intermediary has having increasing marginal costs in administering mortgages. In the searching equilibrium below, this assumption ensures that the system of equations yields a unique steady-state and satisfies the Blanchard and Kahn (1980) conditions when

[13] I assume that the administrative costs use up non-durable consumption goods.

it is log-linearized.[14]

In order to extend one additional mortgage, the financial intermediary must reduce its dividend payments to households by $\theta Q_t + P_t \kappa_1 S_t$ in period t. Once the mortgage is extended, it then receives the stream of mortgage repayments that can be used to increase future dividends to households. Because the financial intermediary is owned by households, it converts all dividend payments into utility using the Lagrange multiplier of the households' budget constraint. Thus, in the eyes of the financial intermediary, extending mortgages costs the households utility today in exchange for additional future utility, and it extends mortgages in period t up to the point where the utility cost of one mortgage today equals that mortgage's future utility increase. Mathematically, this condition is

$$\begin{aligned} &\frac{1}{P_t(C_t - \nu C_{t-1})}(\theta Q_t + P_t \kappa_1 S_t) \\ &\qquad = \beta \mathbb{E}_t \left[\frac{1}{P_{t+1}(C_{t+1} - \nu C_t)} \right] (R_{m,t} - 1 + \eta)\theta Q_t \\ &\qquad + \beta^2 \mathbb{E}_t \left[\frac{1}{P_{t+2}(C_{t+2} - \nu C_{t+1})} \right] (1 - \eta)(R_{m,t} - 1 + \eta)\theta Q_t + ... \end{aligned}$$

To ease analysis of this condition, I collect $(R_{m,t} - 1 + \eta)\theta Q_t$ on the right-hand side and re-write the condition as

$$\theta \frac{Q_t}{P_t} + \kappa_1 S_t = (R_{m,t} - 1 + \eta)\theta \frac{Q_t}{P_t} V_{\eta,t} \tag{1.14}$$

[14] The intuition for why increasing marginal administrative costs stabilizes the equilibrium is as follows. Consider a hot housing market where there are a lot of searching households and houses available for sale. This increases the number of house sales. When sales go up, marginal administrative costs increase. This increase in costs will increase mortgage rates and incentivize fewer households to search, cooling the market. The converse of this reasoning also holds in cold housing markets with few searching households and houses for sale.

where

$$V_{\eta,t} = \mathbb{E}_t \left[\beta \frac{P_t(C_t - \nu C_{t-1})}{P_{t+1}(C_{t+1} - \nu C_t)} + \beta^2 (1-\eta) \frac{P_t(C_t - \nu C_{t-1})}{P_{t+2}(C_{t+2} - \nu C_{t+1})} + \dots \right].$$

These equations determine the gross interest rate on mortgages, $R_{m,t}$.

The variable $V_{\eta,t}$ can be re-written as

$$V_{\eta,t} = \mathbb{E}_t \left[\beta \frac{C_t - \nu C_{t-1}}{\Pi_{t+1}(C_{t+1} - \nu C_t)} + \beta^2 (1-\eta) \frac{C_t - \nu C_{t-1}}{\Pi_{t+1}\Pi_{t+2}(C_{t+2} - \nu C_{t+1})} + \dots \right],$$

where $\Pi_t = P_t / P_{t-1}$ is inflation of non-durable goods prices. Here, we can see that $V_{\eta,t}$ converts the nominal mortgage payments with geometric decay of η into real, present-value terms by dividing the payments by products of inflation and scaling them by the stochastic discount factors of the households. For ease of analysis, $V_{\eta,t}$ can be written in recursive form as

$$V_{\eta,t} = \beta \mathbb{E}_t \left[\frac{C_t - \nu C_{t-1}}{\Pi_{t+1}(C_{t+1} - \nu C_t)} \right] + \beta(1-\eta) \mathbb{E}_t \left[\frac{C_t - \nu C_{t-1}}{\Pi_{t+1}(C_{t+1} - \nu C_t)} V_{\eta,t+1} \right]. \tag{1.15}$$

To better understand how $V_{\eta,t}$ impacts the pricing of $R_{m,t}$, I log-linearize Equation (1.15) around the non-stochastic steady-state. This, along with the log-linarized Euler equation in (1.4), yields

$$\hat{V}_{\eta,t} = -\hat{R}_{f,t} + \beta(1-\eta)\Pi^{-1} \mathbb{E}_t \hat{V}_{\eta,t+1},$$

where " ˆ " denotes log-deviations from the steady-state and Π is steady-state inflation. Solving this forward yields

$$\hat{V}_{\eta,t} = - \sum_{j=0}^{\infty} \left[\beta(1-\eta)\Pi^{-1} \right]^j \mathbb{E}_t \hat{R}_{f,t+j}. \tag{1.16}$$

This implies that to a first-order approximation, $V_{\eta,t}$ discounts the mortgage payments by the future expected stream of discounted one-period risk-free interest rates. Thus, the pricing of $R_{m,t}$ in Equation (1.14) is partially determined by the expected future stream of risk-free rates, giving monetary policy influence over mortgage rates.

In addition to converting mortgage payments with decay of η into a real present discounted value, $V_{\eta,t}$ can convert any nominal stream of payments with decay η into its real present discounted value. Consider a risk-free bond that costs 1 unit of account today and repays a fraction, η, of the principal every period in the future along with an interest payment of $R_{\eta,t} - 1$ on the outstanding principal, where $R_{\eta,t}$ is the gross interest rate. Then, the households will invest in this bond until the marginal cost of doing so equals the marginal benefit. Mathematically, this optimality condition is

$$\begin{aligned}\frac{1}{P_t(C_t - \nu C_{t-1})} &= \beta \mathbb{E}_t \left[\frac{1}{P_{t+1}(C_{t+1} - \nu C_t)} \right] (R_{\eta,t} - 1 + \eta) \\ &\quad + \beta^2 \mathbb{E}_t \left[\frac{1}{P_{t+2}(C_{t+2} - \nu C_{t+1})} \right] (1 - \eta)(R_{\eta,t} - 1 + \eta) + ...,\end{aligned}$$

which is equivalent to

$$1 = (R_{\eta,t} - 1 + \eta) V_{\eta,t}. \tag{1.17}$$

Log-linearizing this equation around the non-stochastic steady-state and applying Equation (1.16) yields

$$r_{\eta,t} = \left[1 - \beta(1-\eta)\Pi^{-1}\right] \sum_{j=0}^{\infty} \left[\beta(1-\eta)\Pi^{-1}\right]^j \mathbb{E}_t r_{f,t+j}. \tag{1.18}$$

Thus, $V_{\eta,t}$ prices long-term risk-free interest rates to be weighted expected sums of future short-term interest rates in a manner that is consistent with the expectations hypothesis of the term structure, and monetary policy can influence long-term bond rates by adjusting the path of short-term rates.

Finally, Equations (1.14) and (1.17) yield

$$\theta \frac{Q_t}{P_t} + \kappa_1 S_t = \theta \frac{Q_t}{P_t} \left(\frac{R_{m,t} - 1 + \eta}{R_{\eta,t} - 1 + \eta} \right). \tag{1.19}$$

This shows that the administrative costs, κ_1, generate a wedge between the nominal payments on mortgages, $R_{m,t} - 1 + \eta$, and the nominal payments on risk-free debt with the same term structure, $R_{\eta,t} - 1 + \eta$. Because the interest rates on both mortgages and long-term risk-free bonds are influenced by monetary policy, this wedge will also be influenced by monetary policy.

1.3.4 Investment Firms

The production technology for a house is given by

$$\bar{H} = A_{I,t} N_{I,t}, \tag{1.20}$$

where $\bar{H}$ is the size of a house, $A_{I,t}$ is the productivity of labor in the housing market, and $N_{I,t}$ is the amount of labor needed to build one house. I assume that a housing investment firm can only invest in one house at a time. Because all investment firms share this technology, all investment firms that build a house in period t use $N_{I,t} = \bar{H}/A_{I,t}$ of labor. Thus, total labor used to build houses in period t is $N_{I,t} I_t$, where I_t is the number of new houses started in period t. The random variable $A_{I,t}$ follows

$$\ln(A_{I,t}) = (1 - \rho_I) \ln(\bar{A}_I) + \rho_I \ln(A_{I,t-1}) + \xi_{I,t}. \tag{1.21}$$

In addition to the labor costs of investment, there is a real adjustment cost of $\iota(I_t - I_{t-1})/I_{t-1}$ imposed on all investment firms that build a house in period t.[15]

To finance the construction of a house, investment firms get equity injections from (that is, they pay negative dividends to) households, and then repay the households when the houses sell. Thus, to provide financing to one additional investment firm, a household must give up $W_t\bar{H}/A_{I,t} + P_t\iota(I_t - I_{t-1})/I_{t-1}$ units of account. In return, it gets the utility value of owning an investment firm when that investment firm has a house available for sale, which I denote by $\beta\mathbb{E}_t J_{t+1}$.[16] I assume that there is free entry of new housing firms, and that households finance new housing investment until the utility cost of one extra house equals the utility benefit. Formally, the free entry condition is

$$\frac{1}{P_t(C_t - \nu C_{t-1})}\left[\frac{W_t\bar{H}}{A_{I,t}} + P_t\iota\frac{I_t - I_{t-1}}{I_{t-1}}\right] = \beta\mathbb{E}_t J_{t+1}. \tag{1.22}$$

Firms with a house can rent them or try to sell them. If the firm tries to sell, there is a probability G_t that it does and gets a nominal house price of Q_t. If the firm rents, it does so in a competitive market with a nominal rental price of $P_{r,t}$. Houses listed for rent are not available for sale. Thus, J_t is given by

$$\begin{aligned} J_t = \max\Bigg\{ &\frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta(1-\delta)\mathbb{E}_t J_{t+1}, \\ &G_t\frac{Q_t}{P_t(C_t - \nu C_{t-1})} + (1 - G_t)\beta(1-\delta)\mathbb{E}_t J_{t+1}\Bigg\}. \end{aligned} \tag{1.23}$$

[15] As with the administrative cost faces by the financial intermediary, I assume that the adjustment cost uses up non-durable consumption goods.

[16] Because housing investment takes one period to become available for sale, the household gets an expected discounted benefit from investing today.

The first expression in the maximum function is the value if the firm rents, and the second expression in the maximum function is the value if the firm tries to sell.

1.3.5 Valuing Housing

For households, the utility benefits of owning at the beginning of period t is

$$\begin{aligned} V_{o,t} = \gamma_{H,o,t} + \gamma_{H,r} + \beta(1-\delta)(1-\chi_r)\mathbb{E}_t V_{o,t+1} \\ + \beta[1-(1-\delta)(1-\chi_r)]\mathbb{E}_t V_{r,t+1} + \beta(1-\delta)\chi_r \mathbb{E}_t J_{t+1}, \end{aligned} \tag{1.24}$$

which is the instantaneous utility of being an owner-occupier, the expected value of staying an owner-occupier from period t to $t+1$, the expected value of becoming a renter from period t to $t+1$ (either through depreciation or separation), and the expected value of the empty house if separation occurs without depreciation. For ease of modelling, I treat a separated house as reverting back to an investment firm with a continuation value of $\beta\mathbb{E}_t J_{t+1}$. The idea is that when a household has a house that it does not want to live in, it can either rent it to other households or sell it in exactly the same way that an investment firm would. Hence, separation effectively grants the household ownership of an investment firm that has already built a house.

Searching renters pay a utility cost of κ_2 for every period that they search for a house. The value of entering period t as a searching renter is

$$\begin{aligned} V_{s,t} = -\kappa_2 + (1-F_t)\left[\gamma_{H,r} - \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta\mathbb{E}_t V_{s,t+1}\right] \\ + F_t\left[V_{o,t} - \frac{(1-\theta)Q_t}{P_t(C_t-\nu C_{t-1})} - \frac{\theta Q_t}{P_t(C_t - \nu C_{t-1})}(R_{m,t} - 1 + \eta)V_{\eta,t}\right]. \end{aligned} \tag{1.25}$$

The the second term on the right-hand side of Equation (1.25) is the expected value of not buying a house, which is the probability of not matching times the utility from not matching. The third term on the right-hand side of Equation (1.25) is the expected value buying a house, where $V_{o,t}$ is the value of owning a house, $(1-\theta)Q_t/(P_t(C_t - \nu C_{t-1}))$ is the utility value of a down payment, and $(\theta Q_t/(P_t(C_t - \nu C_{t-1})))(R_{m,t} - 1 + \eta)V_{m,t}$ is the utility cost of mortgage repayments.

The value of entering period t as a non-searching renter is

$$V_{r,t} = \max\left\{\gamma_{H,r} - \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta \mathbb{E}_t V_{r,t+1}, V_{s,t}\right\}. \tag{1.26}$$

Equation (1.26) reflects the choice faced by non-searching renters. The first term in the maximization is the value of staying a non-searching renter, and the second term is the value of becoming a searching renter.

1.3.6 Consumption Goods, Inflation and Monetary Policy

In this subsection, I briefly summarize the remainder of the model, which covers the production of non-durable consumption goods, inflation of non-durable goods prices and monetary policy. These features of the model closely follow the standard New Keynesian set up, and I provide a full characterization in Appendix A of this chapter.

Consumption goods are produced in two steps. First, monopolistic intermediate-goods firms use labor to produce unique intermediate goods, indexed by $i \in [0, 1]$. Second, competitive final-goods firms bundle the intermediate goods according to a Dixit and Stiglitz (1977) aggregator and sell a homogeneous final good. Final-good firms produce final goods according to a constant elasticity of substitution aggregator

$$X_t = \left[\int_0^1 X_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1.27}$$

where X_t is the final good, $X_t(i)$ is the good produced by intermediate firm i, and $\epsilon > 1$ is the elasticity of substitution. This yields the standard demand function for good i, which is

$$X_t(i) = \left[\frac{P_t(i)}{P_t} \right]^{-\epsilon} X_t, \tag{1.28}$$

where $P_t(i)$ is the price of intermediate good i and P_t is a price index given by

$$P_t = \left[\int_0^1 P_t(i)^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}. \tag{1.29}$$

Intermediate-goods firms face Calvo (1983) pricing rigidities, where a measure $\alpha \in [0, 1]$ of consumption firms keep their price from the previous period and a measure $1-\alpha$ re-optimize their price. The production function for intermediate good firm i is

$$X_t(i) = A_{X,t} N_{X,t}(i), \tag{1.30}$$

where $N_{X,t}(i) = \int_0^1 N_{X,t}(i,j)dj$ is the labor used by firm i, and $A_{X,t}$ is aggregate productivity of non-durable goods that follows

$$\ln(A_{X,t}) = (1-\rho_X)\ln(\bar{A}_X) + \rho_X \ln(A_{X,t-1}) + \xi_{X,t}. \tag{1.31}$$

The monetary authority follows a Taylor (1993) style rule. To implement this rule, I define gross domestic product (GDP) to be

$$Y_t = C_t + \frac{P_{r,t}}{P_t}(H_{o,t} + H_{s,t} + H_{r,t}) + RS_t + \kappa_1 S_t^2.$$

The first term is simply non-durable consumption. The second term is the real rental services provided by housing, which includes both the imputed rent for owner-occupied dwellings, $P_{r,t}H_{o,t}/P_t$, and the rental services paid for by renting households, $P_{r,t}(H_{s,t} + H_{r,t})/P_t$. I include both terms in order to be consistent with Bureau of Economic Analysis's treatment of housing services.[17] The third term is real residential construction spending, and the fourth term is the administrative costs of mortgages. Because the number of households equals one, GDP can be written as

$$Y_t = C_t + \frac{P_{r,t}}{P_t} + RS_t + \kappa_1 S_t^2. \tag{1.32}$$

I define real residential construction spending to be the real wages plus adjustment costs spent on the building of housing units times the number of housing units built

$$RS_t = \frac{W_t \bar{H}}{P_t A_{I,t}} I_t + \iota \frac{I_t - I_{t-1}}{I_{t-1}} I_t. \tag{1.33}$$

Then, the policy rule is

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi}\right)^{\psi_\pi} \left(\frac{Y_t}{Y}\right)^{\psi_Y}\right]^{1-\rho_r} e^{\xi_{R,t}} \tag{1.34}$$

[17]The Bureau of Economic Analysis writes "PCE for housing services includes both the monetary rents paid by tenants and an imputed rental value for owner-occupied dwellings (measured as the income the homeowner could have received if the house had been rented to a tenant). This treatment is designed to make PCE (and GDP) invariant to whether the house is rented by a landlord to a tenant or is lived in by the homeowner." See http://www.bea.gov/national/pdf/chapter5.pdf for more details.

where $\xi_{R,t}$ is white noise and variables without time subscripts denote steady-states. The parameter ρ_r governs the persistence of the of the interest rate, and the parameters ψ_π and ψ_Y govern the monetary authority's response to inflation and GDP gaps.

1.4 Equilibrium

Equilibrium in the non-durable goods market, the labor market and the risk-free bonds market requires market clearing:

$$X_t = C_t + \iota \frac{I_t - I_{t-1}}{I_{t-1}} I_t + \kappa_1 S_t^2, \tag{1.35}$$

$$N_t = N_{X,t} + N_{I,t}, \tag{1.36}$$

where $N_{X,t} = \int_0^1 N_{X,t}(i)di$, and

$$B_t = 0. \tag{1.37}$$

1.4.1 Non-Searching and Searching Equilibria

In the housing market, there are two potential equilibria. First, there is an equilibrium where housing investment firms only supply their houses to the rental market and all households are non-searching renters. I call this equilibrium the *non-searching equilibrium.* The intuition for this equilibrium is as follows. If houses are only supplied to the rental market, then the probability that a searching renter matches with a house is $F_t = 0$. Thus, the household would face the utility cost of searching but be guaranteed to stay a renter. In this case, the household is better off by simply renting in the first place and not searching for a house to buy. Thus, no households search. When no households search, then the probability that an investment firm can sell a house is $G_t = 0$. If an investment firm makes its house available for sale, it forgoes the rental income but is guaranteed not to sell the house. In this case, the firm is better off renting the house and collecting the rental income. Thus, all investment firms rent their houses.

While this equilibrium is theoretically possible, it does not realistically characterize the housing market. Thus, the remainder of the paper focuses on the second equilibrium, which I call the *searching equilibrium*. In this equilibrium, the fraction of non-searching renters that become searching renters, $\chi_{s,t}$, adjusts so that renting households are indifferent between searching and not searching. From Equation (1.26), this implies

$$V_{r,t} = V_{s,t} \tag{1.38}$$

and

$$V_{r,t} = \gamma_{H,r} - \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta \mathbb{E}_t V_{r,t+1}. \tag{1.39}$$

The indifference in Equation (1.38) arises because if $V_{s,t} > V_{r,t}$, then more households would begin searching, market tightness would increase, the probability of buying a house would fall, and $V_{s,t}$ would fall. If $V_{s,t} < V_{r,t}$, then fewer household would begin searching, market tightness would decrease, the probability of buying a house would increase, and $V_{s,t}$ would rise.[18]

Similarly, in the searching equilibrium, investment firms are indifferent between renting

[18]There is the possibility of a corner solutions where $V_{s,t} > V_{r,t}$ even when all renters search (that is, when $\chi_{s,t} = 1$). However, the solution in the calibrated steady-state below is interior (that is, $\chi_{s,t} \in (0, 1)$), and I solve the model with log-linearization so that only states of the world within a neighborhood of the steady-state are analyzed. For this reason, I only consider the interior equilibrium going forward and leave the study of corner solutions for future research.

their houses and trying to sell their houses. From Equation (1.23), this implies

$$J_t = \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta(1-\delta)\mathbb{E}_t J_{t+1} \tag{1.40}$$

and

$$J_t = G_t \frac{Q_t}{P_t(C_t - \nu C_{t-1})} + (1-G_t)\beta(1-\delta)\mathbb{E}_t J_{t+1}. \tag{1.41}$$

This indifference comes from the competitive rental market and free entry into both the rental and sales markets. Because there is a measure of $H_{s,t} + H_{r,t}$ of renting households, investment firms must supply exactly $H_{s,t} + H_{r,t}$ houses to the rental market for it to clear. To achieve this, the rental price adjusts so that investment firms are indifferent between supplying to the rental and sales markets. If they were not indifferent, then they could freely switch to the other market, which would then violate market clearing in the rental market.

For buyers in a match, the consumer surplus is

$$CS_t = V_{o,t} - \frac{(1-\theta)Q_t}{P_t(C_t - \nu C_{t-1})} - \frac{\theta Q_t}{P_t(C_t - \nu C_{t-1})}(R_{m,t} - 1 + \eta)V_{\eta,t} - V_{s,t}, \tag{1.42}$$

which is the utility benefit of owning a house less the less the utility cost of the down payment, the utility cost of the mortgage payments, and the opportunity cost of not staying a searching renter. For sellers in a match, the producer surplus is

$$PS_t = \frac{Q_t}{P_t(C_t - \nu C_{t-1})} - \beta(1-\delta)\mathbb{E}_t J_{t+1}, \tag{1.43}$$

which is the utility value of the sales price less the opportunity cost of not keeping the house. In the steady-state of the calibration below, both consumer and producer surpluses are positive, implying that both buyers and sellers benefit from trading houses once they are in a match and that trades occur in equilibrium.

Adding the consumer and producer surpluses yields the total surplus. Using Equations (1.42) and (1.43) and applying Equation (1.17) yields a total surplus that can be written as

$$\begin{aligned} TS_t = {} & V_{o,t} - V_{s,t} - \beta(1-\delta)\mathbb{E}_t J_{t+1} \\ & + \frac{\theta Q_t}{P_t(C_t - \nu C_{t-1})} - \frac{\theta Q_t}{P_t(C_t - \nu C_{t-1})} \frac{R_{m,t} - 1 + \eta}{R_{\eta,t} - 1 + \eta}. \end{aligned} \tag{1.44}$$

The first line on the right-hand side of Equation (1.44) gives the standard definition of total surplus, which is the value that the household gets from buying a house, $V_{o,t} - V_{s,t}$, less the opportunity cost to the investment firm of selling a house, $\beta(1-\delta)\mathbb{E}_t J_{t+1}$. The second line of Equation (1.44) introduces the effects of mortgages into the total surplus. From the optimal mortgage pricing condition in Equation (1.19), it is the case that this term is zero when the administrative costs of mortgages are zero. Thus, the administrative costs allow the spread between the mortgage payments and payments of risk-free debt with the same term structure to directly influence the total surplus of a match. Because $(R_{m,t} - 1 + \eta)/(R_{\eta,t} - 1 + \eta)$ enters with a negative sign, reducing this spread increases total surplus and increasing the spread reduces total surplus. Thus, because monetary policy can influence this spread, it can influence the total surplus gained from buying and selling houses.

To close the equilibrium, I assume that house prices are determined through a bargaining protocol where a fraction ω of the total surplus is received by house buyers and a fraction $(1 - \omega)$ is received by house sellers. Formally, I assume that $CS_t = \omega TS_t$ and $PS_t =$

$(1-\omega)TS_t$. This implies that house prices adjust so that

$$(1-\omega)CS_t = \omega PS_t. \tag{1.45}$$

Given that the consumer and producer surpluses are simply a fraction of the total surplus, monetary policy can then impact these variables in the same way that it impacts total surplus in Equation (1.44) above. Thus, by changing the total surplus of a housing match, monetary policy can change consumer surplus and influence how many households begin searching for a house to buy.

The equations that characterize the searching equilibrium are provided in Appendix B of this chapter, which also shows that the steady-state of the searching equilibrium is unique. To solve the model, I log-linearize around the steady-state, and given the calibration below, the Blanchard and Kahn (1980) conditions are satisfied. However, before discussing the calibration and numerical results. I first address a more general result on the importance of search frictions.

1.4.2 The Importance of Search Frictions

The time-consuming searching and matching frictions in the model are central to understanding why residential construction is so volatile and highly responsive to economic shocks. To highlight this, I compare the searching equilibrium to an extreme case of the model with no searching frictions, where $F_t = 1$ and $G_t = 1$ for all t. That is, I dispense with the matching function in Equation (1.8) and assume that all searching renters match in the current period with a probability of 1 and that all residential investment firms are able to sell a house in the current period with a probability 1. In this case of no search frictions, Equations (1.6), (1.7), (1.9), (1.11), (1.12) and (1.13) yield

$$I_{t-1} = \delta.$$

Thus, without search frictions, residential construction is fixed at the rate of depreciation and neither monetary, preference, nor productivity shocks effect it. The reason for this result is that when all households can perfectly match with a house and all houses can perfectly match with households, then the number of houses will always equal the population of households. Given, the constant quantity of households in the model, this implies that the residential construction only exists to replace depreciated houses.[19] Thus, search frictions are essential for economic shocks to impact the quantity of houses under construction in the model, and the searching and matching frictions amplify residential construction spending.

In line with this result, Equations (1.12) and (1.13) will also yield

$$H_{s,t} = 0$$

and

$$U_t = H_{r,t}.$$

These results imply that there are never searching renters at the end of a period because they are all able to match with a house and that all houses that are not owner occupied get used in the rental market because no houses go unoccupied.

To understand why search frictions influence the number of houses under construction,

[19] Allowing for trend population growth, as in Head, Lloyd-Ellis, and Sun (2014), will not substantially change this results. Housing construction will still be constant, but it will be larger in order to cover both depreciation and provide housing units for new households.

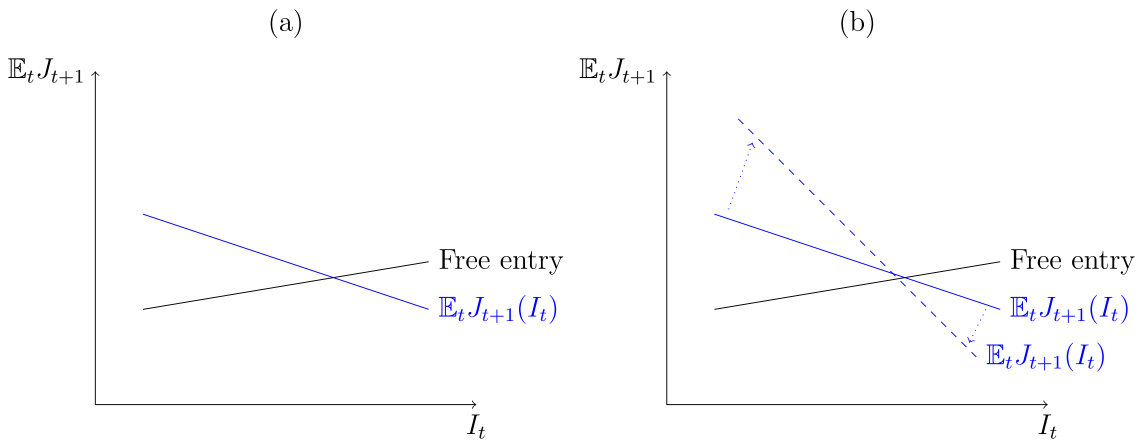

Figure 1.3: Panel (a) displays the two curves summarizing the problem for housing investment firms. Panel (b) displays the change in the problem when matching efficiency increases.

it is helpful to further consider the problem facing residential investment firms. The first component of the problem is that the number of new houses built, I_t, reduces the expected value of a house in the next period, $\mathbb{E}_t J_{t+1}$. This is because an increase in I_t leads to an increase in the number of houses available for sale in period $t+1$, driving down the market tightness and the house selling rate, which leads to a lower expected value of an additional house. I denote this relationship by $\mathbb{E}_t J_{t+1}(I_t)$. The second component of the problem for residential investment firms is the free entry condition of residential construction. Because of free entry, investment firms add new housing until the marginal cost of a new house equals the expected marginal benefit. Equations (1.5) and (1.22) imply that this free entry condition is

$$\beta \mathbb{E}_t J_{t+1} = \frac{\gamma_N \bar{H}}{A_{I,t}} + \frac{\iota(I_t - I_{t-1})}{I_{t-1}(C_t - \nu C_{t-1})} \tag{1.46}$$

so that $\mathbb{E}_t J_{t+1}$ is increasing with I_t as a result of the adjustment costs.

Panel (a) of Figure 1.3 displays the two components of the problem of investment firms.

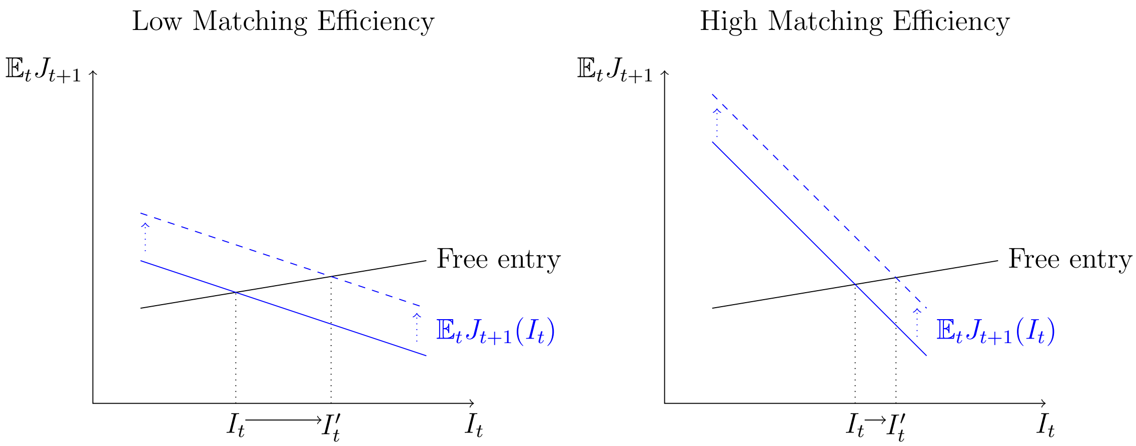

Figure 1.4: A shift in the $\mathbb{E}_t J_{t+1}(I_t)$ curve under low and high matching efficiency.

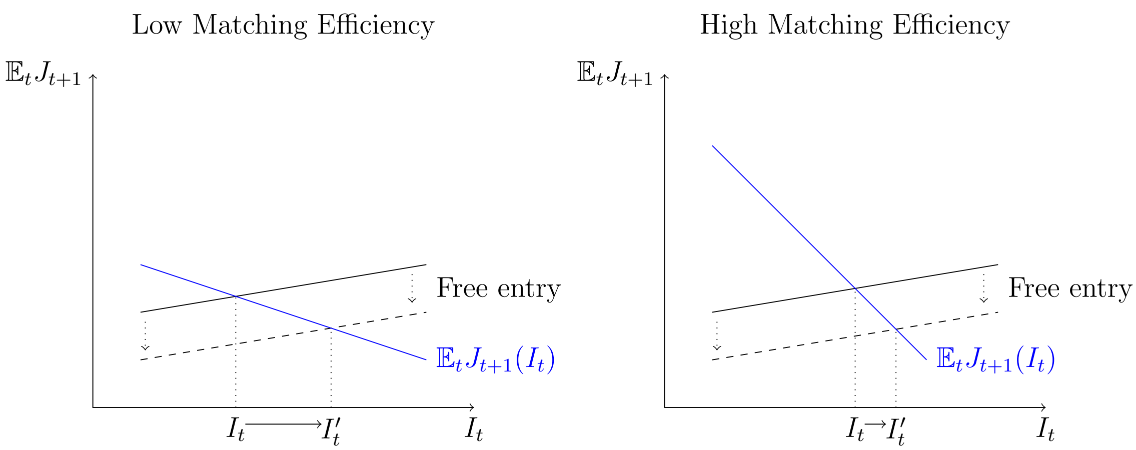

Figure 1.5: A shift in the free entry curve under low and high matching efficiency.

It shows that firms invest in new housing up to the point where $\mathbb{E}_t J_{t+1}(I_t)$ intersect with the free entry condition. That is, investment firms choose I_t to satisfy

$$\beta \mathbb{E}_t J_{t+1}(I_t) = \frac{\gamma_N \bar{H}}{A_{I,t}} + \frac{\iota(I_t - I_{t-1})}{I_{t-1}(C_t - \nu C_{t-1})}. \tag{1.47}$$

An increase in matching efficiency (a decrease in search frictions) causes the $\mathbb{E}_t J_{t+1}(I_t)$ curve to steepen as in panel (b) of Figure 1.3. The reason for this is that as matching efficiency increases, houses act like closer substitutes and are more likely to match with and take away potential buyers from each other. This means that the first house built will have a greater impact on the value of the second house built, causing the marginal value of housing to fall more quickly. In the extreme case where $F_t = 1$ and $G_t = 1$ for all t, then the $\mathbb{E}_t J_{t+1}(I_t)$ curve turns vertical at $I_t = \delta$, yielding the above result that the number of houses under construction will be constant at the rate of depreciation.

With a steeper $\mathbb{E}_t J_{t+1}(I_t)$ curve, shifts in either curve generate smaller movements in I_t, as demonstrated in Figures 1.4 and 1.5. This is because when $\mathbb{E}_t J_{t+1}(I_t)$ is steep, it takes smaller movements in I_t for the free entry condition in Equation (1.47) to equate the benefit of one additional house to its marginal cost. Figure 1.4 shows a shift in the $\mathbb{E}_t J_{t+1}(I_t)$ curve under low and high matching efficiency. With higher matching efficiency, the change is smaller for both I_t and $\mathbb{E}_t J_{t+1}$. Figure 1.5 shows a shift in the free entry under low and high matching efficiency. With higher matching efficiency, the change in I_t is smaller but the change in $\mathbb{E}_t J_{t+1}$ is larger. In the extreme case of $F_t = 1$ and $G_t = 1$ where $\mathbb{E}_t J_{t+1}(I_t)$ is vertical, shifts in either curve no impact on the level of investment.

1.5 Numerical Results of the Model

1.5.1 Calibration

The model has 26 parameters to calibrate. I calibrate them to monthly data, using 1984:1 to 2008:6 as a baseline time period for many of the parameters. This corresponds to the sample period of the factor-augmented vector autoregression presented in the next section. I calibrate the parameters in three blocks. The first block is calibrated on a parameter-by-parameter basis. Given the first block, I calibrate the second block jointly to match steady-state targets. Finally, given the first two blocks, I calibrate the last block to match characteristics of the empirical impulse response functions in the next section. Table 1.1 provides a summary of the parameters and their baseline values.

In the first block of parameters, I calibrate steady-state inflation, Π, to be 2% in order to match the the Fed's target inflation rate. Given this, I calibrate the subjective discount factor, β, to give a steady-state risk-free interest rate of 4.8%, which was the average yield of the 3-month treasury bill from 1984:1 to 2008:6. For the degree of habit persistence, ν, I use the estimated parameter from Edge, Kiley, and Laforte (2007) and Christiano, Trabandt, and Walentin (2010), which is 0.77, raised to the one-third power to convert from a quarterly to a monthly frequency. Next, I calibrate the probability of not changing non-durables prices, α, to give a mean price duration of 7.2 months, which is consistent with Klenow and Malin (2010).[20] I calibrate ϵ so that $\epsilon/(\epsilon - 1) = 1.2$, yielding a steady-state price mark-up of

[20]Klenow and Malin (2010) report that the mean posted price duration for non-durable goods is 5.8 months and that for non-shelter services is 9.4 months. Given a weight of 48.6% on non-durable goods and a weight of 29.7% on services, also reported in Klenow and Malin (2010), this yields a weighted average of 7.2 months.

Table 1.1: Summary of Baseline Calibration

Parameter	Description	Value
Parameters calibrated individually:		
Π	Steady-state inflation	1.0017
β	Household discount factor	0.9978
ν	Habit persistence	0.9166
α	Probability of no price change for non-durables	0.8611
ϵ	Elasticity of substitution for non-durables	6
ψ_π	Policy response to inflation gap	1.5
ψ_y	Policy response to output gap	0.05
ρ_r	Persistence of policy rule	0.9546
δ	Housing depreciation	0.0011
χ_r	Probability of owner-occupiers separating	0.0058
ω	Bargaining weight	0.5
θ	Fraction of house price borrowed	0.85
η	Principal repayment	0.02
$\bar{A}_X$	Steady-state non-durable productivity	1
$\bar{A}_I$	Steady-state housing labor productivity	1
ρ_H	Persistence of housing preference shocks	0.95
ρ_I	Persistence of housing productivity shocks	0.95
ρ_X	Persistence of non-durable productivity shocks	0.95
Parameters calibrated jointly to steady-state moments:		
$\bar{\gamma}_{H,o}$	Steady-state owner-occupier premium	0.3555
$\gamma_{H,r}$	Renter utility	1.1662
γ_N	Dis-utility of labor	10.503
$\bar{H}$	Size of a house	35.11
ζ	Matching efficiency	0.6057
κ_1	Administrative costs	594.4
κ_2	Utility cost of search	1.0778
Parameters calibrated to empirical IRFs:		
ι	Degree of housing investment costs	0.0099

20%. This is a common value in the new Keynesian literature.[21] I calibrate the policy responses to the GDP gap and the inflation gap, ψ_y and ψ_π, to be 0.05 and 1.5. These values are consistent with the new Keynesian literature. For example, chapter 3 of Galí (2008) sets ψ_y equal to 0.5 divided by the number of period in a year (which is 12 in this case) and $\psi_\pi = 1.5$, and Christiano, Trabandt, and Walentin (2010) estimate $\psi_y = 0.07$ and $\psi_\pi = 1.43$. For the persistence of the policy rule, ρ_r, I use 0.87 from Christiano, Trabandt, and Walentin (2010) raised to the one-third power to convert from quarterly to monthly. To calibrate depreciation, Equations (1.7), (1.9), (1.11), (1.12) and (1.13) yield

$$\delta = \frac{I}{H_o + U}$$

in the steady-state. Because $H_o + U$ represents the entire housing stock (both owner-occupied and not owner-occupied), depreciation equals the steady-state ratio of housing units that get built to the entire housing stock. Thus, I set $\delta = 0.0011$, which reflects the monthly of average of housing starts provided in the Census's new residential construction data divided by the average housing inventory provided in the Census's housing vacancies and homeownership data.[22] To calibrate the rate of separation, χ_r, I use migration data from the Current Population Survey, which indicates that about 8% of owner-occupiers moved per year from 1988 to 2008.[23] Thus, given the value of δ, I set χ_r to solve $1 - ((1-\delta)(1-\chi_r))^{12} = 0.08$. I calibrate the bargaining weight, ω, to be 0.5, which puts equal weight on the buyers and

[21] See, for example, the calibration in chapter 3 of Galí (2008) or the estimation in Christiano, Trabandt, and Walentin (2010).

[22] This yields an annualized depreciation rate of 1.3%, which falls in the the 1% to 3% range noted in Davis and Van Nieuwerburgh (2014).

[23] Migration data can be found at http://www.census.gov/hhes/migration/data/cps/historical.html. Dieleman, Clark, and Deurloo (2000) use data from the American Housing Survey that yields similar values.

the sellers in the bargaining protocol. I calibrate the fraction of the house price borrowed, θ, to be 0.85. This suggests that households can borrow slightly more than the standard 20% down payment, and it is the parameter value used in Iacoviello and Neri (2010). I set $\eta = 0.02$ which implies that 99.9% of the mortgage principal is paid off after 30 years. I normalize the steady-state productivity of labor in both the non-durables and housing sectors to $\bar{A}_X = \bar{A}_I = 1$. For the persistence of housing preference shocks and productivity shocks in both the housing and non-durables sectors, I set $\rho_H = \rho_I = \rho_X = 0.95$. This captures the high level of persistence of shocks commonly estimated in new Keynesian DSGE models (Iacoviello and Neri, 2010).

The second block of parameters, which I calibrate jointly, includes $\bar{\gamma}_{H,o}$, the steady-state utility premium from being an owner-occupier, $\gamma_{H,r}$, the utility value of renting a house, γ_N, the dis-utility of labor, $\bar{H}$, the size of a housing unit, ζ, the efficiency parameter of the matching function, κ_1, the administrative cost of mortgages, and κ_2, the utility cost of searching for a house. I calibrate these 7 parameters to 7 steady-state values. First, I set $H_o = 0.658$, which corresponds to an average homeownership rate of 65.8%. Second, I set $V_r = 1$. This normalization ensures that V_r, V_s and V_o are all non-negative and that log-linearizations can be taken. Third, I normalization of $N = 1$. Fourth, I set the ratio $Q/(PY)$ to 27. The idea behind this value is that it takes 27 months of GDP per household to pay for the price of a house. To compute this value, I use annual data from 1984 to 2008. Over this period, the ratio of the average sales price of a new house to GDP per capita is about 6. Given an average number people per household of 2.62 over this sample, it takes a little under 2.3 years or about 27 months of GDP per household to pay for a house.[24] Fifth

[24] Historical data about the size of households is from the Census Bureau: http://www.census.gov/hhes/families/data/households.html.

and sixth, I target $1/F = 2.7$ and $1/G = 2.5$ so that searching renters expect to search for 2.7 months before buying a house and that houses average 2.5 months on the market. This is from Genesove and Han (2012), who use survey data from the National Association of Realtors from 1987 to 2008 and show that the average search time for a house is a little under 12 weeks and the average selling time of a house is a little under 11 weeks.[25] Seventh, I target a net interest rate on mortgages of 8.3%, which corresponds to the average interest rate on 30-year conventional mortgages.

Finally, I calibrate the investment adjustment cost, ι, so that the peak of the theoretical impulse response of I_t in the DSGE model matches the peak of the empirical impulse response for housing total housing units under construction construction in Section 1.6 below. This peak is 0.78%, and it requires $\iota = 0.0099$. This suggests that model would give even larger residential construction responses to economic shocks without the presence of adjustment costs.

1.5.2 Housing Market Shocks

In this subsection, I examine the shocks to the owner-occupier premium and to the productivity of labor in the housing market. I use these housing market shocks to highlight the effects of changes in searching and matching frictions. To do so, I compare the baseline calibration listed in Table 1.1 to a calibration where the matching efficiency, ζ, is increased by 50% over the baseline. This higher level of ζ implies that households expect to search for

[25]Formally, Genesove and Han (2012) provide a median buyer search time of 8.1 or 8.2 weeks and a median seller time of 7.3 or 7.6 weeks, depending on the survey they present. Because the geometric distribution used in this paper to estimate average search times does not provide a unique mapping from median to mean search times, I convert from median to mean using the exponential distribution. This provides a mean buyer search time of 11.7 or 11.8 weeks and a mean selling time of 10.5 or 11 weeks. I then convert to months using one month = 52/12 weeks.

1.8 months before buying a house and that investment firms expect to wait for 1.7 months before selling a house, instead of the 2.7 and 2.5 months, respectively, under the baseline calibration. I refer to latter calibration as the "high matching efficiency" calibration.

Figure 1.6 displays the impulse response functions of the value of a house, J_t, and the number of houses under construction, I_t, to a 1% increase in the owner-occupier premium with months on the horizontal axis and percent deviations on the vertical axis. The solid blue line displays the baseline calibration and the red triangles display the high matching efficiency calibration. An increase in the owner-occupier premium raises the value of houses for any given level of investment. This gives a vertical shift in the $\mathbb{E}_t J_{t+1}(I_t)$ curve as in Figure 1.4 above. Consistent with both panels of Figure 1.4, Figure 1.6 shows that both J_t and I_t are more responsive under the baseline calibration than with the high matching efficiency calibration, indicating that higher matching efficiency reduces the responsiveness of housing investment to shifts in the $\mathbb{E}_t J_{t+1}(I_t)$ curve.

Figure 1.7 displays the impulse response functions of the value of a house, J_t, and the number of houses under construction, I_t, to a 1% increase in labor productivity in the housing sector with months on the horizontal axis and percent deviations on the vertical axis. The solid blue line displays the baseline calibration and the red triangles display the high matching efficiency calibration. Inspecting Equation (1.46), we can see that an increase in labor productivity in the housing sector will shift down the free entry condition as in Figure 1.5 above. Consistent with both panels of Figure 1.5, Figure 1.7 shows that the drop in J_t is more muted under the baseline calibration than with higher matching efficiency. In addition, it shows that the increase in I_t is larger under the baseline calibration than with the higher matching efficiency. This highlights that the responsiveness of housing investment to shifts in the free entry condition are smaller when matching efficiency increases.

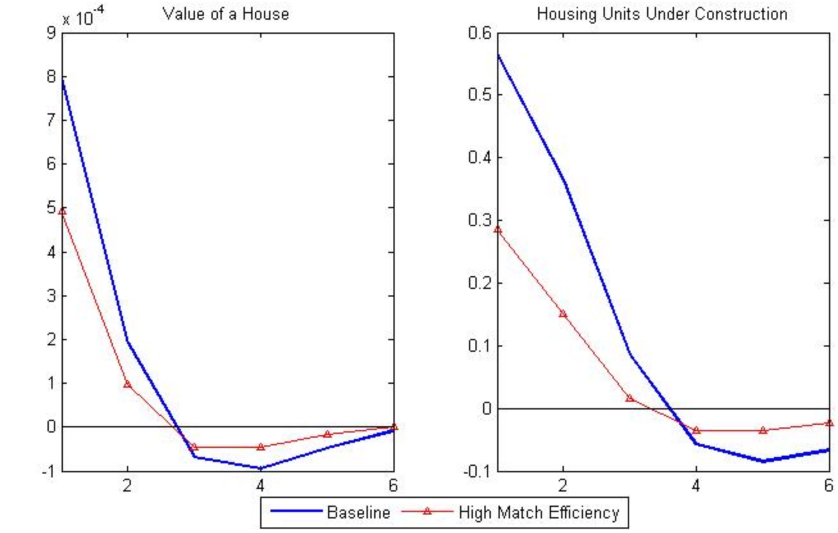

Figure 1.6: Theoretical impulse response functions to a 1% increase in the owner-occupier premium. The baseline calibration is displayed as a solid blue line, and the calibration with higher matching efficiency is displayed with the red triangles. Both panels have number of months along the horizontal axis and percent deviations from the steady-state on the vertical axis.

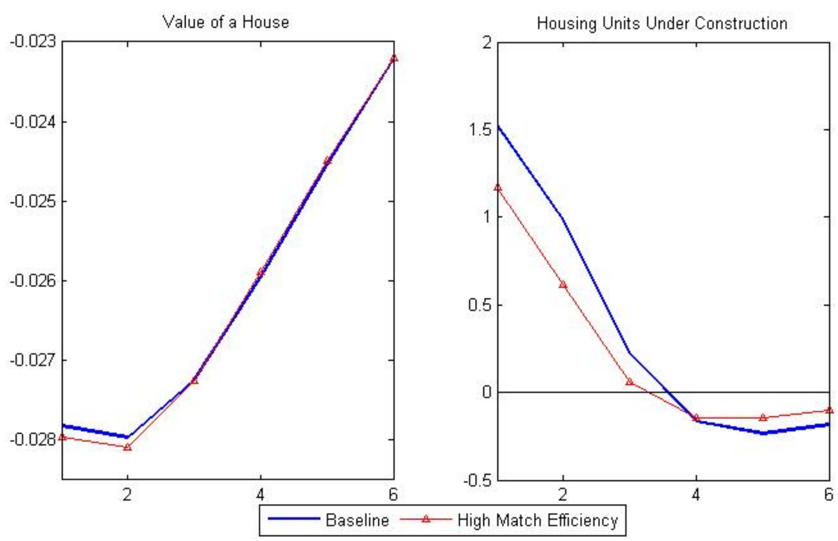

Figure 1.7: Theoretical impulse response functions to a 1% increase in labor productivity in the housing sector. The baseline calibration is displayed as a solid blue line, and the calibration with higher matching efficiency is displayed with the red triangles. Both panels have number of months along the horizontal axis and percent deviations from the steady-state on the vertical axis.

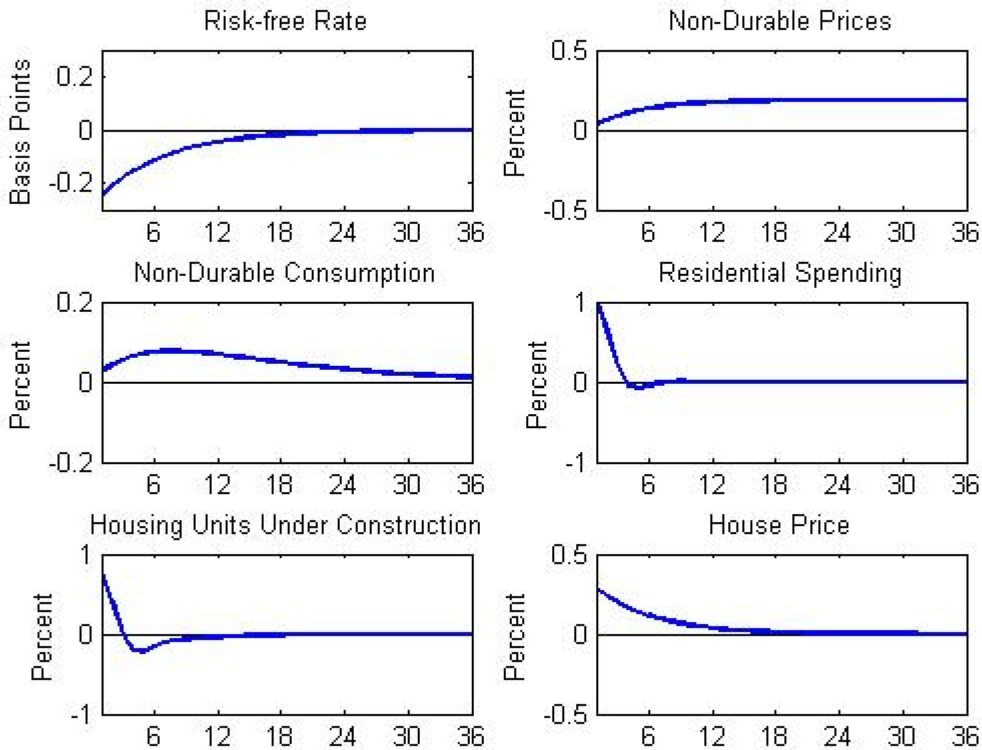

Figure 1.8: Theoretical impulse response functions to a monetary policy shock normalized to an annualized 25 basis point reduction in the risk-free rate. All panels show months on the horizontal axis. The vertical axis of the risk-free rate panel shows the deviation from the steady-state in annualized basis points, and the non-durables prices panel shows the percent deviation from trend prices. All other panels display percent deviation from the steady-state.

1.5.3 Monetary Policy Shocks

Figure 1.8 displays the IRFs of six variables to an expansionary monetary policy shock that is normalized to an annualized 25 basis point reduction in the risk-free rate. Consistent with standard new Keynesian models, this shock generates a permanent rise in non-durable prices relative to their trend, and it generates an increase in non-durable consumption where the hump shape results from the external habit. In addition, this expansionary shock generates a jump in residential spending and housing units under construction along with an increase in real house prices. Two additional results from Figure 1.8 are important to note. First, consistent with the previous empirical literature and the empirical results of Section 1.6 below, the response of residential investment spending is much larger than the response in consumption. Part of this is due to the calibration of habit persistence and the cost to adjusting residential investment,[26] but it also indicates that the baseline level of search frictions are sufficiently large to generate the observed magnitude in residential spending fluctuations. Second, both non-durable consumption and residential investment spending expand following a drop in the risk-free rate. This result suggests that even though house prices are flexible in every period, the model does not suffer from the counterfactual results that Barsky, House, and Kimball (2007) highlighted in new Keynesian models. Previous research has suggested that sticky wages can overcome the Barsky, House, and Kimball (2007) results (Carlstrom and Fuerst, 2010; Iacoviello and Neri, 2010), so this model provides additional mechanisms to help new Keynesian models explain the observed empirical features.

Figure 1.9 displays eight additional IRFs of housing market variables to a monetary policy shock normalized so that the risk-free rate falls by an annualized 25 basis points. This group of IRFs provides the intuition for how monetary policy is transmitted to the housing sector, and it provides variables that can be compared to the empirical IRFs in Section 1.6 below in addition to those from Figure 1.8. Following a drop to the risk-free rate, the interest rate spread between mortgages and long-term bonds falls.[27] This reduces the spread between mortgage payments and the payments on long-term bonds, which then

[26]Carlstrom and Fuerst (2010) also find that habit persistence and costs to adjusting residential investment are important to matching the size of the responses in non-durable consumption and residential investment to a monetary policy shock.

[27]To be comparable to the empirical IRFs below, Figure 1.9 displays this spread as the annualized basis points of the long-term mortgage rate less the annualized basis points of the long-term risk-free bond.

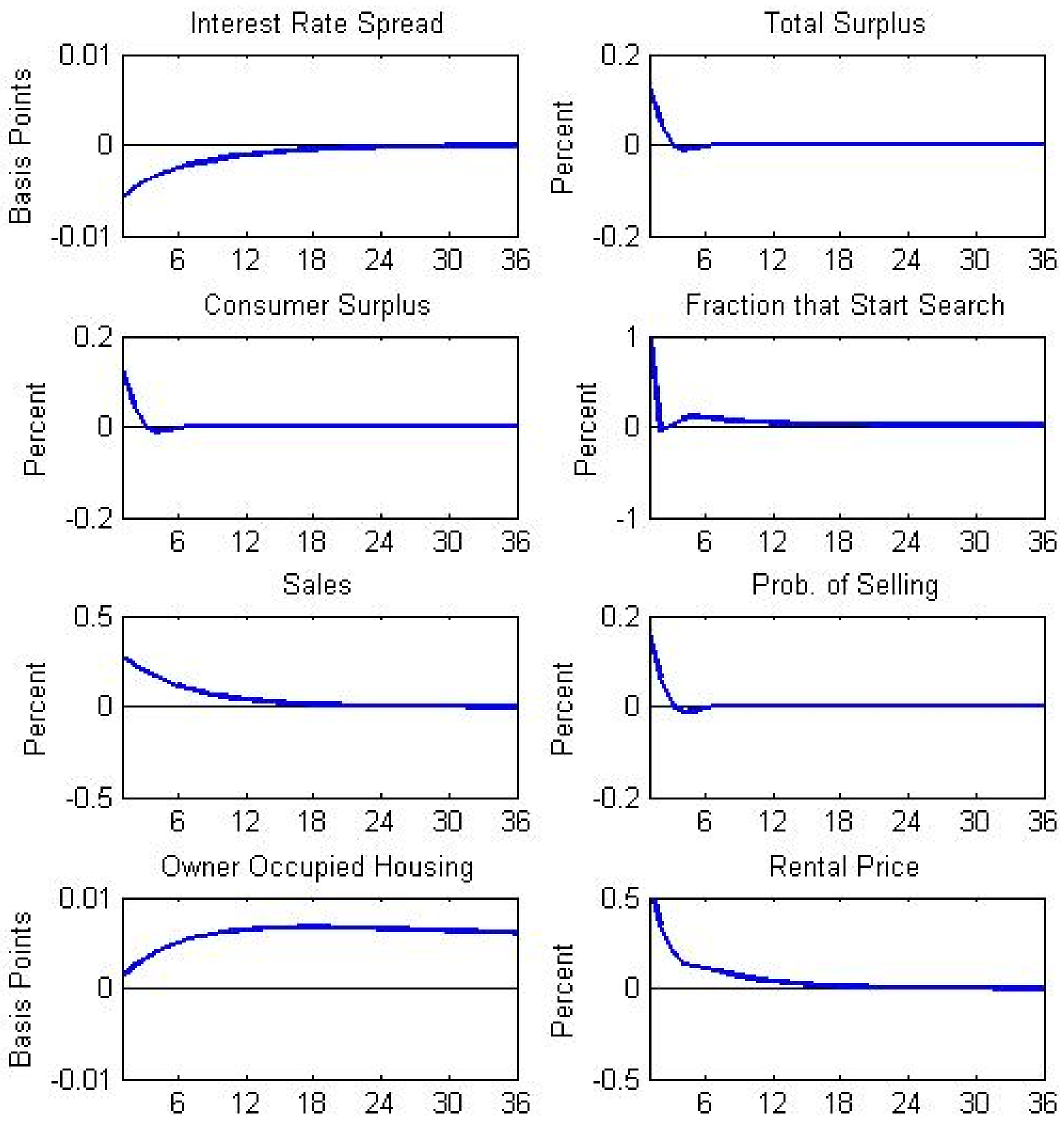

Figure 1.9: Theoretical impulse response functions to a monetary policy shock normalized to an annualized 25 basis point reduction in the risk-free rate. All panels show months on the horizontal axis. The vertical axis of the interest rate spread panel shows the deviation from the steady-state in annualized basis points, and the owner-occupied housing panel shows the deviation from the steady-state in basis points. All other panels display percent deviation from the steady-state.

increases the total surplus of a housing match as implied in Equation (1.44). The increase in total surplus leads to an increase in consumer surplus via bargaining, incentivizing a jump in the number of households that begin searching to buy a house. This causes house sales to rise, the probability of selling a house to rise and the level of owner-occupied housing to rise. In addition, despite the fact that fewer households rent their housing units, rental prices for housing rise. This is because the value to residential investment firms of supplying their houses for sale has risen due to higher real sale prices and higher selling probability. Thus, rental prices must rise in order to incentivize residential investment firms to supply housing to the rental market.

1.5.4 Non-Durable Productivity Shocks

Figure 1.10 displays the IRFs of six variables to a 1% increase in labor productivity in the non-durables sector. Consistent with supply-side shocks, this leads to a drop in the price level of non-durable goods from its trend. However, all other variables resemble the results of a monetary policy shock. The risk-free rate falls and non-durable consumption rises. In addition, residential spending and housing units under construction jump while real house prices rise. Two additional results from Figure 1.10 are important to note. First, despite the fact that the shock here is to non-durable consumption, residential construction spending has a larger peak response. This suggests that even in the absence of housing market and monetary shocks, we should expect residential construction to be more volatile than non-durable consumption. Second, the peak in residential spending leads the peak in non-durable consumption, causing residential investment to lead total GDP (not pictured). The leading nature of residential investment is a recurring observation about the U.S. business

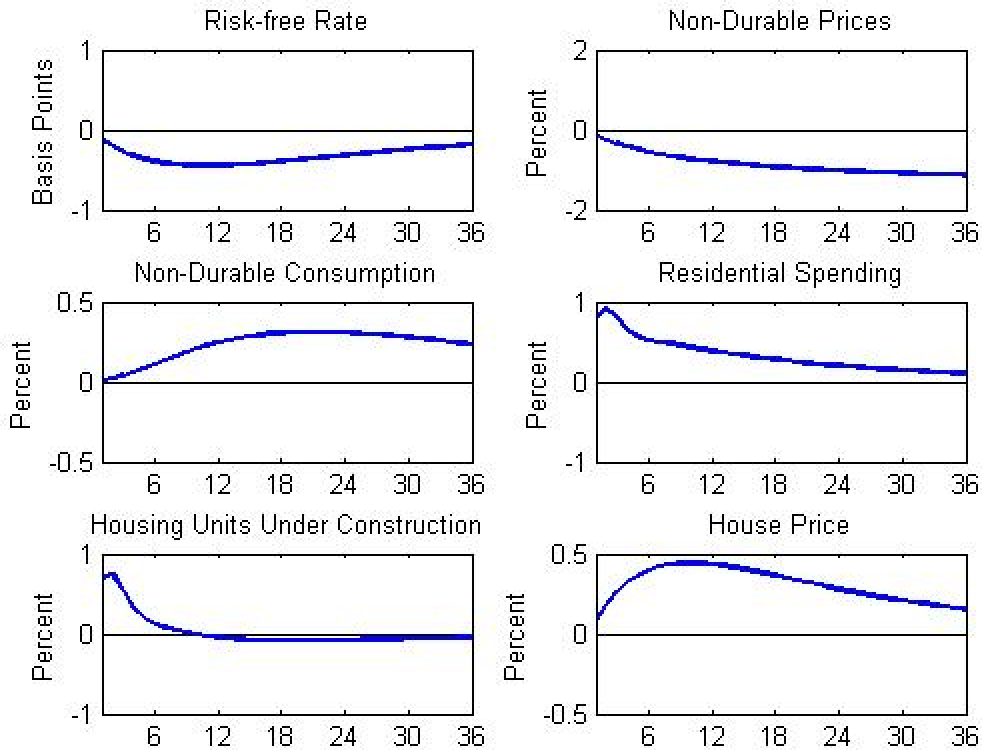

Figure 1.10: Theoretical impulse response functions to a 1% increase in labor productivity in the non-durables sector. All panels show months on the horizontal axis. The vertical axis of the risk-free rate panel shows the deviation from the steady-state in annualized basis points, and the non-durables prices panel shows the percent deviation from trend prices. All other panels display percent deviation from the steady-state.

cycle (Green, 1997; Davis and Heathcote, 2005), and the model suggests that it is a natural response to productivity changes in the production of non-durable goods. This result is not due to the external habit as this lead-lag structure arises even when $\nu = 0$. Rather, it arises here because sticky prices in the non-durables sector cause firms to adjust their prices slowly in response to the productivity shock, leading to a delayed increase in demand for non-durables from consumers. However, as discussed in Fisher (1997), it is questionable whether this lead-lag feature extends to a model with investment in productive capital because an increase in productivity may cause households to delay investment in housing so that they can invest in productive capital. I leave this question as a topic for future research.

Figure 1.11 displays eight additional IRFs of housing market variables to a 1% increase in labor productivity in the non-durables sector. This group of IRFs provides the intuition for how a non-durable productivity shock is transmitted to the housing sector. As with an expansionary monetary policy shock, the positive non-durables productivity shock leads to a drop in the spread between the interest rate on mortgages and the rate on risk-free long-term bonds.[28] This causes a jump in the total surplus and the consumer surplus. The fraction of households that begin searching to be owner-occupiers rises, leading to an increase in house sales, the probability of selling a house and the rate of owner-occupied housing. Finally, as with a monetary policy shock, the rental price of housing must rise in order to incentivize residential investment firms to supply housing to the rental market, given the rise in house prices and in the house selling rate.

1.6 Empirical Methodology

In this section, I check the DSGE's qualitative results of a monetary policy shock. To estimate the empirical effects of monetary policy shocks, I use a factor-augmented vector autoregression (FAVAR). This methodology incorporates a large number of time series into one statistical model, allowing me to estimate the impact of monetary policy shocks on many features of housing markets. After estimating the FAVAR, I identify monetary policy shocks by using an external instrument, as introduced in Stock and Watson (2012) and Mertens

[28]As with Figure 1.9 above, Figure 1.11 displays this spread as the annualized basis points of the long-term mortgage rate less the annualized basis points of the long-term risk-free bond.

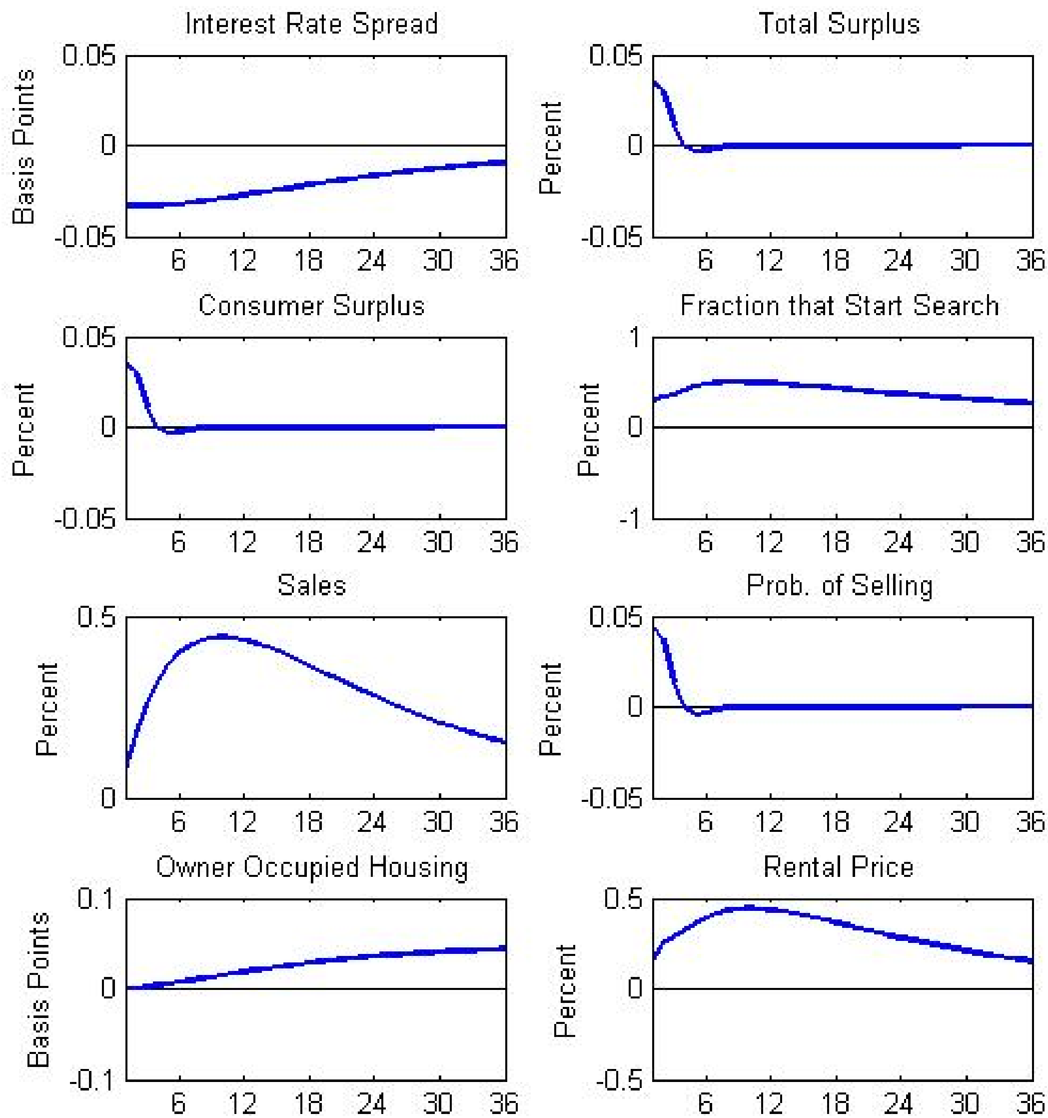

Figure 1.11: Theoretical impulse response functions to a 1% increase in labor productivity in the non-durables sector. All panels show months on the horizontal axis. The vertical axis of the interest rate spread panel shows the deviation from the steady-state in annualized basis points, and the owner-occupied housing panel shows the deviation from the steady-state in basis points. All other panels display percent deviation from the steady-state.

and Ravn (2013), which I construct by following Romer and Romer (2004).

1.6.1 The Factor-Augmented Vector Autoregression

A large number, n, of time series characterize the economy and are contained in the $n \times 1$ vector x_t. These time series are governed by

$$x_t = \Lambda' \begin{bmatrix} r_t \\ f_t \end{bmatrix} + e_t, \tag{1.48}$$

where r_t is a univariate policy interest rate, f_t is a $k-1 \times 1$ vector of unobserved macroeconomic factors, and Λ is an $k \times n$ matrix of factor loadings. The first term on the right-hand side of Equation (1.48) is the *common* component of all variables in x_t, and e_t is a $n \times 1$ vector *idiosyncratic* components that are specific to each variable in x_t.

Evolution of the common component is governed by

$$\begin{bmatrix} r_t \\ f_t \end{bmatrix} = \sum_{j=1}^{p} \Gamma_j \begin{bmatrix} r_{t-j} \\ f_{t-j} \end{bmatrix} + u_t, \tag{1.49}$$

where Γ_j is a $k \times k$ matrix for $j = 1, \ldots, p$, and u_t is a $k \times 1$ vector of reduced-form errors. Equation (1.49) is a vector autoregression in r_t and f_t. Because f_t is a vector of unobserved factors, I follow Bernanke, Boivin, and Eliasz (2005) and refer to Equation (1.49) a factor-augmented vector autoregression.

I follow Boivin, Giannoni, and Mihov (2009) and estimate Equations (1.48) and (1.49) using a two-step procedure. First, I estimate Λ and f_t in Equation (1.48) with principal components. Second, given f_t, I estimate Equation (1.49) with least squares. Appendix C of this chapter gives the details.

1.6.2 Identification of Policy Shocks

To identify the structural monetary policy shocks, I assume that the VAR errors, u_t, relate to a $k \times 1$ vector of structural shocks, v_t, according to

$$u_t = M v_t, \tag{1.50}$$

where M is $k \times k$ non-singular matrix. The structural shocks have the standard assumptions: $E(v_t) = 0$ and $E(v_t v_t') = I_K$. Let

$$v_t = \begin{bmatrix} v_{1,t} \\ v_{2,t} \end{bmatrix} \tag{1.51}$$

be the partition of the structural shocks into the 1×1 monetary policy shock, $v_{1,t}$, and the $k-1 \times 1$ vector of non-monetary policy shocks, $v_{2,t}$. With this partition of v_t, M can be written as

$$M = \begin{bmatrix} \underset{(1\times 1)}{\mu_{11}} & \underset{(1\times k-1)}{\mu_{12}} \\ \underset{(k-1\times 1)}{\mu_{21}} & \underset{(k-1\times k-1)}{\mu_{22}} \end{bmatrix},$$

where μ_{11} indicates how a structural monetary policy shock relates to the VAR error of r_t, and μ_{21} indicates how a structural monetary policy shock relates to the VAR errors of f_t. In order to identify μ_{11} and μ_{21}, I use an instrument, z_t, that is correlated with the structural monetary policy shocks but uncorrelated with the other structural shocks. Formally, I assume

$$\begin{aligned} E(z_t v_{1,t}) &= \phi \neq 0 \\ E(z_t v'_{2,t}) &= 0. \end{aligned} \tag{1.52}$$

These properties and the above partition of M yield

$$\begin{aligned} E(z_t u_{1,t}) &= \phi \mu_{11} \\ E(z_t u'_{2,t}) &= \phi \mu'_{21}, \end{aligned} \tag{1.53}$$

which can be estimated from data. The conditions in (1.53) can be rearranged to yield

$$\mu_{11}^{-1}\mu'_{21} = [E(z_t u_{1,t})]^{-1} E(z_t u'_{2,t}), \tag{1.54}$$

which is the instrumental variables estimate of $\mu_{11}^{-1}\mu'_{21}$, using z_t as an instrument for $u_{1,t}$. Once $\mu_{11}^{-1}\mu'_{21}$ has been estimated, this estimate along with the invertibility of M provides a sufficient number of restrictions to identify $[\mu_{11} \quad \mu'_{21}]'$ up to its direction. I assume that $\mu_{11} > 0$ so that positive monetary policy shock leads to an increase in r_t. Appendix D of this chapter provides the details.

1.6.3 Constructing the Monetary Policy Instrument

To construct my instrument for monetary policy shocks, I follow Romer and Romer (2004). The idea is to use the Federal Reserve's (Fed's) Greenbook forecasts, which are prepared for each Federal Open Market Committee (FOMC) meeting, in order to purge the changes in the target Federal Funds rate (FFR) of the state of the economy at the time that monetary policy decisions are being made. This will leave only the portion of the change in the target FFR that is attributable to monetary policy shocks and remove the portion that is attributable to other shocks in the economy, yielding a valid instrument for identifying monetary policy shocks.

Formally, I estimate the regression

$$\Delta \bar{r}_m = \gamma + \rho \bar{rb}_m + \sum_{i=-1}^{2} \beta_i w_{m,i} + \sum_{i=-1}^{2} \delta_i (w_{m,i} - w_{m-1,i}) + z_m, \tag{1.55}$$

where $\Delta \bar{r}_m$ is the change in the Fed's target FFR at FOMC meeting m, $\bar{rb}_m$ is the target FFR prior to meeting m, and $w_{m,i}$ is a vector of forecasts at meeting m with a forecast horizon of i quarters. That is, $w_{m,0}$ contains the forecasts for the quarter that the FOMC meeting is held, $w_{m,1}$ contains the forecasts for the quarter following the FOMC meeting, and so on. The term $w_{m,i} - w_{m-1,i}$ represents changes to the Fed's forecasts and accounts for the Fed's own forecasts errors. I include forecasts of inflation measured by the GDP deflator and GDP growth in $w_{m,i}$.

Because Greenbook forecasts are only available for FOMC meetings, which occur eight times per year and are irregularly spaced, Romer and Romer (2004) convert z_m to a monthly time series by assigning z_m to the month in which the FOMC meeting occurred, assigning a value of zero to months with no FOMC meeting. I follow this procedure and make one additional adjustment. After assigning z_m to the month of its meeting, I weight it by when the meeting occurred in the month. I do this because FOMC meetings occur at various times in each month. For example, the Fed made a 50 basis point cut on January 31, 2001 and on October 2, 2001. Because the January cut occurred at the very end of the month, it would not be able effect economic activity in the month of January. In contrast, it is reasonable to assume that the October cut could impact economic activity in the month October. The weighting scheme I use scales z_m by the days remaining in the month divided by the total days in that month. For example, I scale the October 2, 2001 meeting by $29/31 = 0.935$. For meetings that occur on the last day of the month, such as on January 31, 2001, I assign the full value of z_m to the following month.[29]

To estimate Equation (1.55), I use a sample of FOMC meetings that starts in January 1984 and ends in June 2008, yielding 196 observations. This sample reflects a period where the FFR was the Fed's primary policy tool. Prior to this sample, the Fed engaged in non-borrowed reserves targeting,[30] and after this sample the Fed rapidly expanded its balance sheet in an effort alleviate the effects of the financial crisis. Thus, January 1984 to June 2008 is a period where monetary policy is not contaminated by multiple policy instruments, and z_m accurately captures the surprise movements in monetary policy around FOMC meetings.

1.6.4 Data and Estimation Details for the FAVAR

To estimate the empirical model, I use a balanced panel of 212 monthly time series from 1984:1 to 2008:6, which gives 294 observations of each series. These series cover industrial production and capacity utilization (7 series), personal consumption expenditures (8 series), consumer price indices (16 series), producer price indices (6 series), price indices for personal consumption expenditures (8 series), personal income and its disposition (14 series), labor market quantities (23 variables), labor market prices (12 series), interest rates and interest rate spreads (22 series), stock and bond market indices (6 series), exchange rates

[29]There are 15 meetings in my sample that occur on the last day of their respective months.

[30]Coibion (2012) argues that including periods of non-borrowed reserves targeting in the Romer and Romer (2004) method may overstate the impact of monetary policy shocks.

(5 indices), monetary aggregates (9 series), consumer credit and commercial bank balance sheet aggregates (18 series), survey data (9 series), new residential construction (29 series), new residential sales (14 series), construction spending and price indices (5 series),[31] and the homeownership rate.[32] In order to estimate Equations (1.48) and (1.49), I transform all the series to induce stationarity, and then I normalize the series so that they have a mean of zero and a standard deviation of one.[33] Appendix E of this chapter provides a list of the data series and their transformations. To compute the IRFs, I re-scale all variables by their sample standard deviation.

To estimate Equations (1.48) and (1.49), I use monthly averages of the effective FFR as the policy interest rate, r_t. I set $k = 9$, using Bai and Ng's (2002) first information criterion.[34] I set the number of lags in Equation (1.49) to $p = 3$, which is consistent with the Akaike information criterion.[35] Estimates of all information criteria are presented in Appendix F of this chapter. Given this specification, the VAR errors, u_t, are available for 1984:4 to 2008:6, and the instrument, z_t, is available from 1984:1 to 2008:6. Thus, I use the overlapping sample, 1984:4 to 2008:6, to estimate the first column of M in Equation (1.50).

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[31] Construction spending is from the Census Bureau. Prior to 1993, I use the Census's legacy data format. To convert to real construction spending, I deflate the series using the Fisher price index of new single-family houses under construction. All results are robust to deflating with the Laspeyres price index of new single-family houses under construction.

[32] The homeownership rate is a quarterly series. I convert it to a monthly series with linear interpolation.

[33] Inducing stationarity prior to estimation is common in the literature. For example, see Bernanke, Boivin, and Eliasz (2005), Boivin, Giannoni, and Mihov (2009), Stock and Watson (2012).

[34] Bai and Ng's (2002) second criterion suggests $k = 8$, and their third criterion does not achieve minimum at less than $k = 15$. Thus, I choose $k = 9$ as an approximate middle ground of the criterion results.

[35] The Schwarz information criterion and the Hannan-Quinn criterion both suggest $p = 2$. However, I follow Kilian (2001) and use the larger lag order. Using $p = 2$ has only a small impact on the point estimates of the IRFs displayed below; however, it does reduce the size of the confidence intervals compared to those with $p = 3$.

I compute confidence intervals for the IRFs for each series using a wild bootstrap procedure as described in Mertens and Ravn (2013) with 2000 bootstrap replications. For each replication, I first draw 291 observations of η_t, where η_t is a random variable that takes the value 1 with probability 0.5 and the value -1 with probability 0.5. Second, I draw the initial condition block, $[r^b_{t-1}, f^{b'}_{t-1}]', ..., [r^b_{t-p}, f^{b'}_{t-p}]'$, randomly from the observed data by placing equal weight on each block, where the superscript b denotes bootstrapped data.[36] Third, I construct a series of bootstrap VAR shocks by $u^b_t = \hat{u}_t \eta_t$, where $\hat{u}_t$ are the estimated VAR errors from Equation (1.49). Fourth, I use the initial condition, the bootstrap VAR shocks, and the least squares estimates of Γ_j to recursively construct a bootstrap series r^b_t and f^b_t. Fifth, using r^b_t and f^b_t, I estimate $\hat{\Gamma}^b_j$ by least squares. Sixth, I define $z^b_t = z_t \eta_t$ to be the bootstrapped instrument and re-estimate the first column of the M matrix. Seventh, I construct the IRFs to a structural monetary policy shock. After all 2000 bootstrapped IRFs are generated, I compute 90% confidence intervals by sorting the IRFs and taking the 5th and 95th percentile IRF at each impulse horizon. Because the first column of M is re-estimated for each bootstrap replication, this procedure accounts for uncertainty in identifying monetary policy shocks. Further, it is robust against heteroskedasticity in the VAR shocks (Gonçalves and Kilian, 2004).

1.6.5 Results

Before presenting the empirical IRFs, I first compute the first-stage F-statistic for the instrumental variables regression in order to gauge the strength of the instrument. This is the F-statistic for the regression of $u_{1,t}$ on z_t, which is 38.5. This statistic is well above all of

[36] Given a sample size of 294 and $p = 3$, there are 292 such blocks. Thus, the probability of a block being drawn as the initial condition is 1/292.

the critical values reported in Stock and Yogo (2005) for one endogenous regressor and one instrument, suggesting that the instrumental variables estimator is not subject to the large bias that arises with weak instruments.

Figure 1.12 displays the IRFs of the effective FFR, the consumer price index (CPI) excluding shelter, personal consumption expenditure (PCE) of non-durables, real residential construction spending, new housing units under construction and median house prices to a monetary policy shock normalized to a 25 basis point reduction in the effective FFR. The solid lines display the point estimates of each IRF and the dotted lines display the 90% confidence intervals. The CPI excluding shelter increases without any "price puzzle" behavior following the shock. In addition, the PCE of non-durables increases following the shock. Qualitatively, the results are consistent with the DSGE's results presented in Figure 1.8. Quantitatively, the DSGE predicts a rise of non-shelter prices of 0.18% after 36 months, which is roughly double the 0.08% from the FAVAR. In addition, the DSGE's peak response in non-durable consumption is 0.08%, which is roughly half of the the FAVAR's peak response for PCE of non-durables of 0.15%.

With regard to housing variables, residential construction spending and the number of housing units under construction both rise following the shock with peak responses at 0.78%. These responses are roughly 5 times the response in non-durables PCE, which is consistent with the previous literature showing the housing sector to be very responsive to monetary shocks. Further, from 1984 to 2008, spending on non-durables consumption was only about 4.4 times the size of residential construction spending. This suggests that residential construction spending was more important for transmitting monetary policy shocks to aggregate

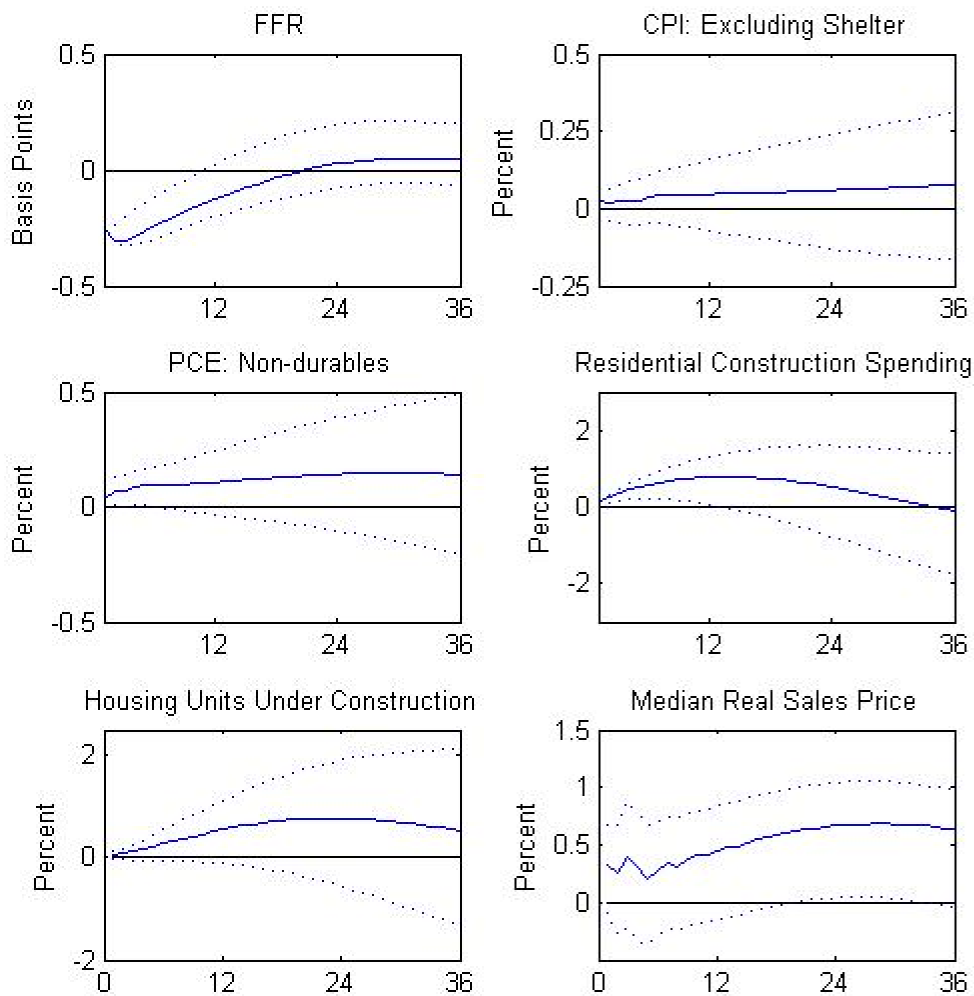

Figure 1.12: Impulse response functions to a monetary policy shock normalized to a 25 basis point reduction in the effective federal funds rate (FFR). Solid lines display the point estimates of the IRFs and dotted lines display the 90% confidence intervals. FFR is presented in basis points and all other variables are presented in percent.

economic activity prior to the zero lower bound period than non-durable consumption.[37] Compared to other recent large-scale time-series models, these responses are consistent with Bańbura, Giannone, and Reichlin (2010), who find that that housing unit starts rise less than 1%, but less than Luciani (2013), who finds that residential investment rises about 2%.[38] Finally, Figure 1.12 shows that the real median sales prices of new houses rise with a peak response of 0.68% at about two and a half years.[39]

Qualitatively, the increase in residential investment spending and in housing units under construction is consistent with the results of the DSGE in Figure 1.8. Quantitatively, the peak response in housing units under construction is the same for both the DSGE and FAVAR due to the calibration of the housing adjustment parameter, ι. However, the peak of residential investment spending is larger in the DSGE at 1.07% than in the FAVAR. This is due to a jump in wages in the DSGE model that drives up the cost of residential spending. While the DSGE provides a relatively good fit for the peak impact on residential spending compared to the FAVAR, it does not match the timing of the FAVAR well. In the DSGE, the peak impact comes in the first period while in the FAVAR is it comes at about one year for residential spending and about two years for number of units under construction. Including a more realistic production technology for houses with intermediate inputs, land and time-to-build may provide a better fit of the timing of housing construction and residential spending.

[37]This result is robust to earlier sample periods as well. Using data from 1965 to 1993, Bernanke and Gertler (1995) note that "residential investment drops sharply following a monetary tightening and accounts for a large part of the initial decline of final demand."

[38]Bańbura, Giannone, and Reichlin (2010) use a policy shock that leads to a 100 basis point rise in the FFR, and Luciani (2013) uses a policy shocks that leads to a 50 basis points rise in the FFR. I converted their results to be consistent with the 25 basis points drop presented in this paper.

[39]Consistent with the DSGE model, I compute real house prices to be the nominal median sales price of new houses prices of new houses divided by the consumer price index excluding shelter. I scale the series by 100 times the natural logarithm before including it in the FAVAR.

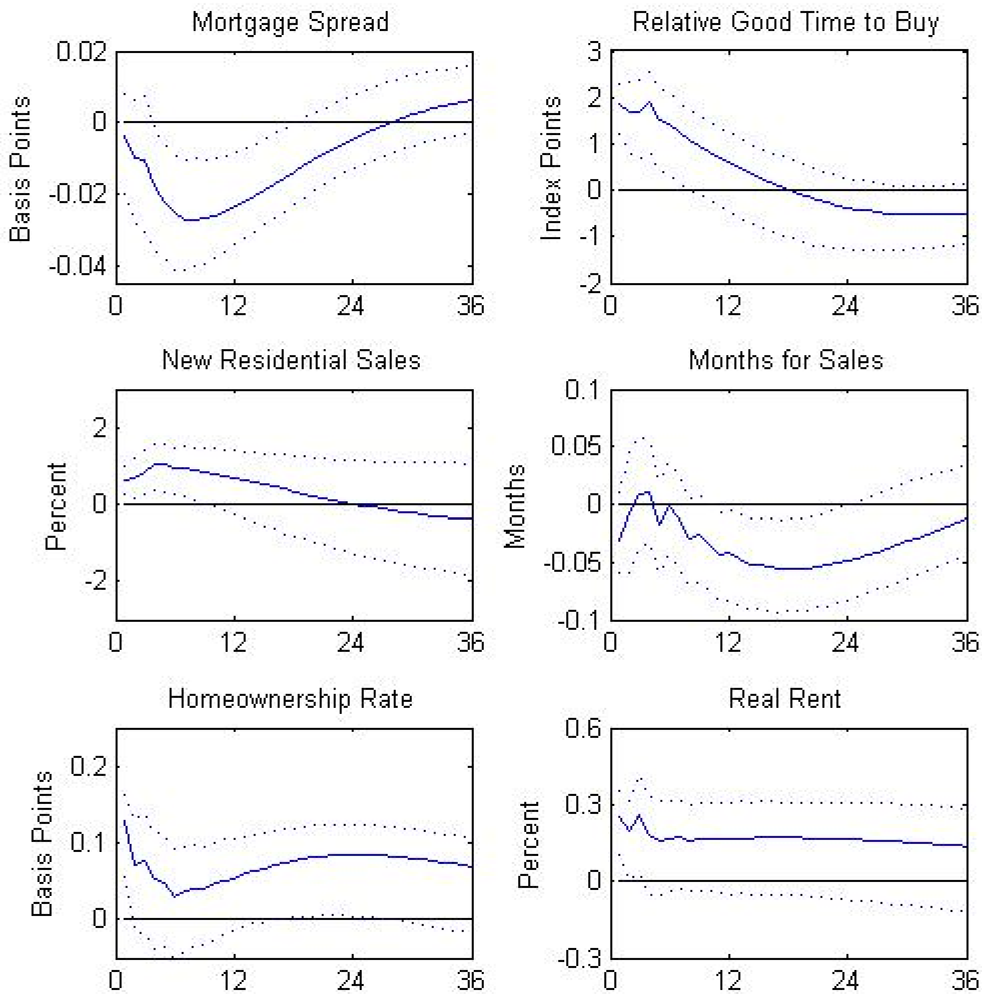

Figure 1.13: Impulse response functions to a monetary policy shock normalized to a 25 basis point reduction in the effective federal funds rate (FFR). Solid lines display the point estimates of the IRFs and dotted lines display the 90% confidence intervals.

To examine the transmission mechanism of monetary policy shocks to the housing market, Figure 1.13 shows the empirical IRFs of six additional housing market variables to a monetary policy shock normalized to a 25 basis point reduction in the effective FFR. Consistent with the mortgage market and the transmission of monetary shocks in the DSGE model, the first panel in Figure 1.13 shows that the spread between the 30-year mortgage and the 10-year Treasury bond falls after an expansionary monetary policy shock. In the DSGE model, this drop in this spread makes mortgage debt more attractive than risk-free debt and incentivizes households to begin searching for a house. As an empirical analog for this shift in the household value of searching, I use survey responses from the Thompson Reuters/University of Michigan Survey of Consumers. Specifically, I use responses from the survey question that asks "Generally speaking, do you think now is a good time or a bad time to buy a house?" These responses form an index that subtracts the number of consumers who respond "bad" from the number who respond "good" and adds 100.[40]. Following an expansionary monetary policy shock this index jumps, implying that consumers are more likely to consider it a good time to buy. This increase in consumer sentiment toward buying houses then leads to a jump in new residential sales, a decline in the number of months that newly completed houses stay on the market for sale and a rise in the homeownership rate. In addition, the real rental price jumps with a peak impact in the first three months following following the monetary policy shock.[41]

The DSGE's results presented in Figures 1.8 and 1.9 are consistent with the directions of

[40]Croce and Haurin (2009) find that this index is useful for forecasting turning points in the housing market.

[41]Consistent with the DSGE model, I compute real rental prices to be the consumer index price index of rent of primary residence divided by the consumer price index excluding shelter. I scale this series by 100 times the natural logarithm before including it in the FAVAR.

all of the empirical IRFs in Figures 1.12 and 1.13. This shows that the DSGE's intuition for how monetary policy shocks are transmitted to the housing sector can explain the empirical responses, including the responses for time on the market and the homeownership rate that do not appear in conventional macroeconomic models of housing. However, while the DSGE matches these qualitative features of these data, it under-predicts the size of several responses presented in Figure 1.13. In the DSGE model, the mortgage spread falls by half a basis point, sales rise 0.25% and owner-occupied housing peaks at less than 1 basis point above its steady-state. In the FAVAR, the mortgage spread falls by 3 basis points, sales rise by over 1% and the homeownership rate rises by about 10 basis points. One possible solution to this empirical discrepancy is to include frictions in addition to administrative costs into financial intermediation in the DSGE model. Gertler and Karadi (2014) show that credit costs can also cause a reduction in the mortgage spread following a monetary policy shock. This, in addition to the administrative costs, will likely generate a larger drop in the mortgage spread, incentivizing more house sales and larger rise in the homeownership rate in the DSGE model.

1.7 Conclusions

Residential construction has played an important role in U.S. business cycles and has been a focus of monetary policy makers. The purpose of this paper is to understand why housing construction has been so responsive to economic shocks. To achieve this purpose, I first constructed a two-sector DSGE model of the economy with both housing construction and the production of non-durable goods. Second, I estimated a FAVAR and identified the structural monetary policy shocks to show that the empirical IRFs of housing market variables are consistent with the theory in the DSGE model.

In the DSGE model, I use a searching, matching and bargaining framework to characterize the housing market. This captures the empirical reality that housing adjustments largely occur along extensive rather than intensive margins. Further, I assume that all houses are purchased with mortgage debt and that issuing a mortgage requires an administrative cost. This model yields four results. First, without searching and matching frictions, the quantity of new houses built does not respond to economic shocks, and it is constant at the rate of housing depreciation. This implies that search frictions transmit economic shocks to housing construction and that the large observed fluctuations in housing construction are due, in part, to the imperfect matching of buyers and sellers in the housing market. Second, the baseline calibration of the model yields large fluctuations in housing construction relative to non-durable consumption in response to monetary and non-durable productivity shocks. This suggests that an empirically plausible level of search frictions can yield the large movements in residential construction that are observed in the data. Third, monetary policy influences the spread between mortgages and risk-free long-term bonds. An expansionary monetary policy shock reduces this spread, incentivizing more renters to begin searching for a house and spurring housing construction. Fourth, production of non-durable consumption and of new housing co-move positively following a monetary shock, which is a result the new Keynesian DSGEs have struggled to match (Barsky, House, and Kimball, 2007).

To test the DSGE model's qualitative responses to monetary policy shocks, I estimate a FAVAR with numerous housing market variables and identify the structural monetary policy shocks using an external instrument, where the instrument follows Romer and Romer (2004). The empirical IRFs from the FAVAR are consistent with the DGSE model's qualitative results. Specifically, with regard to the second result of the DSGE model, the FAVAR shows that the response of residential spending to a monetary shock is larger than that of non-durable consumption. With regard to the third result of the DSGE model, the FAVAR shows that the spread between the 30-year mortgage rate and the 10-year Treasury bond falls following an expansionary monetary policy shock. With regard to the fourth result of the DSGE model, the FAVAR shows that consumption and residential construction spending co-move positively following a monetary shock. In addition, the IRFs from the FAVAR are qualitatively consistent with the DSGE model's responses for new residential sales, time on the market, the homeownership rate, house prices and rental market prices.

There are two important directions for future research. Because two stylized facts of the U.S. business cycle are that residential investment is more volatile than non-residential investment and that residential investment leads non-residential investment, the first direction is to incorporate productive capital into the model. This will allow me to test the model's ability to match these features and potentially provide insight on what generates them. The second direction for future research is to include financial frictions in addition to the administrative cost in the mortgage market, such as a credit channel discussed in Gertler and Karadi (2014) or limited access to the risk-free market as in Garriga, Kydland, and Sustek (2013). As discussed above, this will likely improve the model's fit with the empirical impulse response functions for the mortgage spread, housing sales and the homeownership rate. In addition, it will also allow for the inclusion of financial shocks and for the modelling of financial crises. Two features of the recent housing crisis were a large increase in the time it took to sell houses and a large drop in the homeownership rate. By including both of these variables, this model will be able to provide insight that standard housing models cannot.

Appendix A

In this appendix, I derive the conventional new Keynesian equations that characterize the production of non-durable consumption goods, the evolution of non-durable price inflation, and price dispersion. Final goods firms buy the intermediate goods $X_t(i)$ for $i \in [0,1]$ at price $P_t(i)$ and produce homogeneous final consumption goods according to Equation (1.27). They sell these final goods in a competitive market at price P_t. Every period, they choose X_t and $X_t(i)$ for $i \in [0,1]$ in order to maximize profits, which are given by $P_t X_t - \int_0^1 P_t(i) X_t(i) di$, subject to Equation (1.27). This yields the demand function for good i

$$X_t(i) = \left[\frac{P_t(i)}{P_t}\right]^{-\epsilon} X_t. \tag{A.1}$$

Then, plugging (A.1) back into Equation (1.27) and solving for P_t yields the price index

$$P_t = \left[\int_0^1 P_t(i)^{1-\epsilon} di\right]^{\frac{1}{1-\epsilon}} \tag{A.2}$$

Intermediate-goods firm i produces $X_t(i)$ according to Equation (1.30). Every period this firm faces a probability of $1-\alpha$ being able to re-optimize its price. With probability α, it keeps its price from the previous period. In period t, firm i has nominal profits of $P_t(i)X_t(i) - W_t N_{X,t}(i)$, which it pays back to households in the form of dividends. For firms that re-optimize, I denote the new price by $\tilde{P}_t(i)$. These firms choose $\tilde{P}_t(i)$ and sequences $\{X_{t+j}(i), N_{X,t+j}(i)\}_{j=0}^{\infty}$ to maximize

$$\sum_{j=0}^{\infty} (\beta\alpha)^j \mathbb{E}_t \frac{\tilde{P}_t(i) X_{t+j}(i) - W_{t+j} N_{X,t+j}(i)}{P_{t+j}(C_{t+j} - \nu C_{t+j-1})} \tag{A.3}$$

subject to demand in Equation (A.1) and production in Equation (1.30). The βs and the denominator in (A.1) arise because the firm discounts it profits by Lagrange multiplier on the households' budget. The optimal choice of $\tilde{P}_t(i)$ satisfies

$$\frac{\tilde{P}_t(i)}{P_t}\sum_{j=0}^{\infty}(\beta\alpha)^j\mathbb{E}_t\left[\left(\frac{P_{t+j}}{P_t}\right)^{\epsilon-1}\left(\frac{X_{t+j}}{C_{t+j}-\nu C_{t+j-1}}\right)\right] = \frac{\epsilon}{\epsilon-1}\sum_{j=0}^{\infty}(\beta\alpha)^j\mathbb{E}_t\left[\left(\frac{W_{t+j}}{A_{X,t+j}P_{t+j}}\right)\left(\frac{P_{t+j}}{P_t}\right)^{\epsilon}\left(\frac{X_{t+j}}{(C_{t+j}-\nu C_{t+j-1})}\right)\right]. \tag{A.4}$$

Define $Z_{1,t}$ to be the right-hand side of Equation (A.4). It can be written recursively as

$$Z_{1,t} = \frac{\epsilon}{\epsilon-1}\frac{W_t}{A_{X,t}P_t}\frac{X_t}{C_t-\nu C_{t-1}} + \beta\alpha\mathbb{E}_t(\Pi_{t+1}^{\epsilon}Z_{1,t+1}) \tag{A.5}$$

Next, define $Z_{2,t}$ to be the portion of the left-hand side of Equation (A.4) that excludes $\tilde{P}_t(i)/P_t$. Then, $Z_{2,t}$ can be written recursively as

$$Z_{2,t} = \frac{X_t}{C_t-\nu C_{t-1}} + \beta\alpha\mathbb{E}_t(\Pi_{t+1}^{\epsilon-1}Z_{2,t+1}). \tag{A.6}$$

Equations (A.4), (A.5) and (A.6) imply that the real, re-optimized price for firm i is

$$\frac{\tilde{P}_t(i)}{P_t} = \frac{Z_{1,t}}{Z_{2,t}}. \tag{A.7}$$

Because the only variable that depends on i in Equation (A.7) is $\tilde{P}_t(i)$, it is the case that all firms that re-optimize choose the same price, denoted by $\tilde{P}_t$. Using the Calvo (1983) assumption that a measure $1-\alpha$ of firms re-optimize to $\tilde{P}_t$ while a measure α of firms keep

$P_{t-1}(i)$, the price index in Equation (A.2) can be written as

$$P_t^{1-\epsilon} = (1-\alpha)\tilde{P}_t^{1-\epsilon} + \alpha \int_0^1 P_{t-1}(i)^{1-\epsilon} di,$$

which is equivalent to

$$1 = (1-\alpha)\left(\frac{\tilde{P}_t}{P_t}\right)^{1-\epsilon} + \alpha \Pi_t^{\epsilon-1}.$$

Then, plugging in Equation (A.7) and rearranging terms yields

$$\Pi_t = \left[\frac{1}{\alpha} - \frac{1-\alpha}{\alpha}\left(\frac{Z_{1,t}}{Z_{2,t}}\right)^{1-\epsilon}\right]^{\frac{1}{\epsilon-1}}. \tag{A.8}$$

Aggregating labor over each firm i yields

$$N_{X,t} = \int_0^1 N_{X,t}(i) di \tag{A.9}$$

Then, plugging in production in Equation (1.30) and demand in Equation (A.1) yields

$$A_t N_{X,t} = X_t P_t^{\epsilon} \int_0^1 P_t(i)^{-\epsilon} di. \tag{A.10}$$

Define price dispersion to be

$$D_t = P_t^{\epsilon} \int_0^1 P_t(i)^{-\epsilon} di. \tag{A.11}$$

Then, Equation (A.10) becomes

$$A_t N_{X,t} = D_t X_t. \tag{A.12}$$

Using the Calvo (1983) assumption that a measure $1-\alpha$ of firms re-optimize to $\tilde{P}_t$ while a measure α of firms keep $P_{t-1}(i)$, price dispersion can be re-written as

$$D_t = P_t^{\epsilon}(1-\alpha)\tilde{P}_t^{-\epsilon} + P_t^{\epsilon}\alpha \int_0^1 P_{t-1}(i)^{-\epsilon} di.$$

Then, Equations (A.7) and (A.10) give the evolution of price dispersion

$$D_t = (1-\alpha)\left(\frac{Z_{1,t}}{Z_{2,t}}\right)^{-\epsilon} + \alpha \Pi_t^{\epsilon} D_{t-1}. \tag{A.13}$$

Appendix B

This appendix summarizes the variables and equations in the searching equilibrium. It also establishes the uniqueness of the steady-state of this equilibrium.

B.1 Summarizing the Model

The model has 38 endogenous variables, τ_t, $H_{o,t}$, $H_{s,t}$, $H_{r,t}$, U_t, S_t, G_t, F_t, C_t, N_t, $R_{f,t}$, $R_{m,t}$, $R_{\eta,t}$, Q_t/P_t, W_t/P_t, $P_{r,t}/P_t$, I_t, $N_{I,t}$, $N_{X,t}$, X_t, Y_t, RS_t, J_t, $V_{\eta,t}$, $V_{o,t}$, $V_{s,t}$, $V_{r,t}$, CS_t, PS_t, TS_t, $Z_{1,t}$, $Z_{2,t}$, Π_t, η_t, $\chi_{s,t}$, $\gamma_{H,o,t}$, $A_{I,t}$, and $A_{X,t}$, and four exogenous shocks $\xi_{R,t}$, $\xi_{H,t}$, $\xi_{I,t}$, and $\xi_{X,t}$. The difference equations that characterize the equilibrium are

- Consumer optimization

$$\frac{1}{C_t - \nu C_{t-1}} = \beta R_{f,t} \mathbb{E}_t \left[\frac{1}{\Pi_{t+1}(C_{t+1} - \nu C_t)} \right] \tag{B.1}$$

$$\gamma_N (C_t - \nu C_{t-1}) = \frac{W_t}{P_t} \tag{B.2}$$

- Market tightness and housing match rates

$$\tau_t = \frac{H_{s,t-1} + \chi_{s,t} H_{r,t-1} + \chi_{s,t}[1 - (1-\delta)(1-\chi_r)] H_{o,t-1}}{(1-\delta)U_{t-1} + I_{t-1} + (1-\delta)\chi_r H_{o,t-1} - H_{s,t} - H_{r,t}} \tag{B.3}$$

$$F_t \tau_t = G_t \tag{B.4}$$

$$G_t = \zeta \left(1 - e^{-\tau_t}\right) \tag{B.5}$$

- Evolution of households states and housing stocks

$$1 = H_{o,t} + H_{s,t} + H_{r,t} \tag{B.6}$$

$$H_{s,t} = (1 - F_t)\{H_{s,t-1} + \chi_{s,t} H_{r,t-1} + \chi_{s,t}[1 - (1-\delta)(1-\chi_r)] H_{o,t-1}\} \tag{B.7}$$

$$H_{r,t} = (1-\chi_{s,t})[1-(1-\delta)(1-\chi_r)]H_{o,t-1} + (1-\chi_{s,t})H_{r,t-1} \tag{B.8}$$

$$U_t - H_{r,t} - H_{s,t} = (1-G_t)[(1-\delta)U_{t-1} + I_{t-1} + (1-\delta)\chi_r H_{o,t-1} - H_{s,t} - H_{r,t}] \tag{B.9}$$

$$S_t = F_t\{H_{s,t-1} + \chi_{s,t}H_{r,t-1} + \chi_{s,t}[1-(1-\delta)(1-\chi_r)]H_{o,t-1}\} \tag{B.10}$$

- Pricing of mortgage rates and long-term risk-free debt

$$\theta\frac{Q_t}{P_t} + \kappa_1 S_t = (R_{m,t} - 1 + \eta)\theta\frac{Q_t}{P_t}V_{\eta,t} \tag{B.11}$$

$$V_{\eta,t} = \frac{1}{R_{f,t}} + \beta(1-\eta)\mathbb{E}_t\left[\frac{C_t - \nu C_{t-1}}{\Pi_{t+1}(C_{t+1} - \nu C_t)}V_{\eta,t+1}\right] \tag{B.12}$$

$$(R_{\eta,t} - 1 + \eta)V_{\eta,t} = 1 \tag{B.13}$$

- Value of investment firms

$$\frac{W_t\bar{H}}{A_{I,t}P_t(C_t - \nu C_{t-1})} + \frac{\iota(I_t - I_{t-1})}{C_t - \nu C_{t-1}} = \beta\mathbb{E}_t J_{t+1} \tag{B.14}$$

$$J_t = G_t\frac{Q_t}{P_t(C_t - \nu C_{t-1})} + \beta(1-\delta)(1-G_t)\mathbb{E}_t J_{t+1} \tag{B.15}$$

$$J_t = \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta(1-\delta)\mathbb{E}_t J_{t+1} \tag{B.16}$$

- Value of housing for households

$$\begin{aligned} V_{o,t} = \gamma_{H,o,t} + \gamma_{H,r} &+ \beta(1-\delta)(1-\chi_r)V_{o,t+1} \\ &+ \beta[1-(1-\delta)(1-\chi_r)]V_{r,t+1} + \beta(1-\delta)\chi_r J_{t+1} \end{aligned} \tag{B.17}$$

$$\begin{aligned} V_{s,t} = -\kappa_2 + (1-F_t)&\left[\gamma_{H,r} - \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta\mathbb{E}_t V_{s,t+1}\right] \\ &+ F_t\left[V_{o,t} - \frac{(1-\theta)Q_t}{P_t(C_t - \nu C_{t-1})} - \frac{(R_{m,t} - 1 + \eta)\theta Q_t}{P_t(C_t - \nu C_{t-1})}V_{\eta,t}\right] \end{aligned} \tag{B.18}$$

$$V_{r,t} = \gamma_{H,r} - \frac{P_{r,t}}{P_t(C_t - \nu C_{t-1})} + \beta V_{r,t+1} \tag{B.19}$$

$$V_{r,t} = V_{s,t} \tag{B.20}$$

- Consumer, producer and total surplus

$$CS_t = V_{o,t} - V_{s,t} - \frac{(1-\theta)Q_t}{P_t(C_t - \nu C_{t-1})} - \frac{(R_{m,t} - 1 + \eta)\theta Q_t}{P_t(C_t - \nu C_{t-1})} V_{\eta,t} \tag{B.21}$$

$$PS_t = \frac{Q_t}{P_t(C_t - \nu C_{t-1})} - \beta(1-\delta)\mathbb{E}_t J_{t+1} \tag{B.22}$$

$$TS_t = CS_t + PS_t \tag{B.23}$$

- The bargaining solution for house prices

$$\omega PS_t = (1-\omega) CS_t \tag{B.24}$$

- Evolution of inflation

$$Z_{1,t} = \frac{\epsilon}{\epsilon - 1} \frac{W_t}{A_{X,t} P_t} \frac{X_t}{C_t - \nu C_{t-1}} + \beta \alpha \mathbb{E}_t(\Pi_{t+1}^{\epsilon} Z_{1,t+1}) \tag{B.25}$$

$$Z_{2,t} = \frac{X_t}{C_t - \nu C_{t-1}} + \beta \alpha \mathbb{E}_t(\Pi_{t+1}^{\epsilon - 1} Z_{2,t+1}). \tag{B.26}$$

$$\Pi_t = \left[\frac{1}{\alpha} - \frac{1-\alpha}{\alpha} \left(\frac{Z_{1,t}}{Z_{2,t}} \right)^{1-\epsilon} \right]^{\frac{1}{\epsilon - 1}}. \tag{B.27}$$

- Production

$$\bar{H} = A_{I,t} N_{I,t} \tag{B.28}$$

$$D_t X_t = A_{X,t} N_{X,t} \tag{B.29}$$

- Evolution of price dispersion

$$D_t = (1-\alpha) \left(\frac{Z_{1,t}}{Z_{2,t}} \right)^{-\epsilon} + \alpha \Pi_t^{\epsilon} D_{t-1} \tag{B.30}$$

- Output, residential spending and monetary policy

$$Y_t = C_t + \frac{P_{r,t}}{P_t} + RS_t + \kappa_1 S_t^2 \tag{B.31}$$

$$RS_t = \frac{W_t \bar{H}}{A_{I,t} P_t} I_t + \iota \frac{I_t - I_{t-1}}{I_{t-1}} I_t \tag{B.32}$$

$$\frac{R_{f,t}}{R_f} = \left(\frac{R_{f,t-1}}{R_f}\right)^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi}\right)^{\psi_\pi} \left(\frac{Y_t}{Y}\right)^{\psi_Y}\right]^{1-\rho_r} e^{\xi_{R,t}} \tag{B.33}$$

- Market clearing

$$X_t = C_t + \iota \frac{I_t - I_{t-1}}{I_{t-1}} I_t + \kappa_1 S_t^2 \tag{B.34}$$

$$N_t = N_{X,t} + N_{I,t} I_t \tag{B.35}$$

- Random variables

$$\ln(\gamma_{H,o,t}) = (1-\rho_H)\ln(\bar{\gamma}_{H,o}) + \rho_H \ln(\gamma_{H,o,t-1}) + \xi_{H,t} \tag{B.36}$$

$$\ln(A_{I,t}) = (1-\rho_I)\ln(\bar{A}_I) + \rho_I \ln(A_{I,t-1}) + \xi_{I,t} \tag{B.37}$$

$$\ln(A_{X,t}) = (1-\rho_A)\ln(\bar{A}_X) + \rho_X \ln(A_{X,t-1}) + \xi_{X,t} \tag{B.38}$$

B.2 Uniqueness of the Steady-State

This subsection establishes the uniqueness of the non-stochastic steady-state of the above 38 variables. However, it should be noted that I do not check for corner solutions when establishing uniqueness. That is, for the steady-state, I implicitly assume $H_o \in (0,1)$, $H_s \in (0,1)$, $H_r \in (0,1)$, $\chi_s \in (0,1)$, etc. Thus, this should be thought of as a proof of uniqueness of an interior solution. As noted above, the calibrated steady-state is interior and log-linearizations are used to solve the model. Thus, I only examine states of the economy within a neighborhood of the interior steady-state. A full examination of possible corner solutions is left for future research.

The proof establishing the uniqueness of the non-stochastic steady-state is straight forward. It shows that once the steady-state level of inflation is chosen, the remaining steady-state values can be computed by following an appropriate sequence of the model's equations. Steady-state variables are written without a time subscript.

First, the random variables in Equations (B.36), (B.37) and (B.38) yield non-stochastic steady-states of $\bar{\gamma}_{H,o}$, $\bar{A}_I$ and $\bar{A}_X$, respectively. Then, as is standard in new Keynesian models, the Taylor (1993) rule in Equation (B.33) reduces to $1 = 1$ in the non-stochastic steady-state. Thus, the level of steady-state inflation is exogenously chosen. The remaining steady-state values are computed as follows. The steady-state ratio of Z_1 and Z_2 is given by

$$\frac{Z_1}{Z_2} = \left(\frac{1 - \alpha \Pi^{\epsilon - 1}}{1 - \alpha} \right)^{\frac{1}{1-\epsilon}}$$

from Equation (B.27). Then, Equations (B.25) and (B.26) yield

$$[1 - \beta \alpha \Pi^{\epsilon}] Z_1 = \frac{\epsilon}{\epsilon - 1} \frac{W}{A_X P} \frac{X}{(1 - \nu) C}$$

and

$$[1 - \beta \alpha \Pi^{\epsilon - 1}] Z_2 = \frac{X}{(1 - \nu) C}.$$

This implies that the ratio of Z_1 and Z_2 is also given by

$$\frac{Z_1}{Z_2} = \frac{\epsilon}{\epsilon - 1} \frac{W}{\bar{A}_X P} \frac{1 - \beta \alpha \Pi^{\epsilon - 1}}{1 - \beta \alpha \Pi^{\epsilon}}.$$

Using this and the above ratio of Z_1 to Z_2, we can solve for the steady-state real wage as a function of steady-state inflation and model parameters

$$\frac{W}{P} = \bar{A}_X \frac{\epsilon - 1}{\epsilon} \left(\frac{1 - \beta\alpha\Pi^{\epsilon}}{1 - \beta\alpha\Pi^{\epsilon-1}} \right) \left(\frac{1 - \alpha\Pi^{\epsilon-1}}{1 - \alpha} \right)^{\frac{1}{1-\epsilon}}.$$

Next, given steady-state inflation, Equation (B.1) yields the risk-free interest rate

$$R_f = \frac{\beta}{\Pi}.$$

Given the steady-state real wage, steady-state real consumption is given by Equation (B.2)

$$C = \frac{1}{\gamma_N(1-\nu)} \frac{W}{P},$$

Equation (B.12) gives the steady-state of the value of mortgage payments

$$V_\eta = \frac{1}{R_f - 1 + \eta},$$

and Equation (B.13) yields the steady-state interest rate on long-term risk-free debt

$$R_\eta = R_f.$$

Then, Equation (B.14) gives the steady-state value of an investment firm

$$J = \frac{1}{\beta A_I (1-\nu) C} \frac{W}{P},$$

Equation (B.16) gives the steady-state real rental rate

$$\frac{P_r}{P} = [1 - \beta(1-\delta)](1-\nu)CJ,$$

Equation (B.19) gives the steady-state value of being a non-searching renter

$$V_r = \frac{1}{1-\beta}\left[\gamma_{H,r} - \frac{1}{(1-\nu)C}\frac{P_r}{P}\right],$$

Equation (B.20) gives the steady-state value of being a searching renter

$$V_s = V_r,$$

and Equation (B.17) gives the steady-state value of being an owner-occupier

$$V_o = \frac{1}{1-\beta(1-\delta)(1-\chi_r)}\{\bar{\gamma}_{H,o} + \beta[1-(1-\delta)(1-\chi_r)]V_r + \beta(1-\delta)\chi_r J\}.$$

Next, Equations (B.18), (B.19) and (B.20) yields

$$\kappa_2 = F_t\left[V_o - V_s - \frac{(1-\theta)Q}{P(1-\nu)C} - \frac{(R_m - 1 + \eta)\theta Q}{P(1-\nu)C}V_\eta\right]$$

and Equations (B.21), (B.22) and (B.24) yield

$$\omega\left[\frac{Q}{P(1-\nu)C} - \beta(1-\delta)J\right] = (1-\omega)\left[V_o - V_s - \frac{(1-\theta)Q}{P(1-\nu)C} - \frac{(R_m - 1 + \eta)\theta Q}{P(1-\nu)C}V_\eta\right].$$

Combined, these equations reduce to

$$\frac{Q}{P(1-\nu)C} = \frac{1-\omega}{\omega}\frac{\kappa_2}{F} + \beta(1-\delta)J.$$

Then, using Equation (B.15) to substitute out $Q/(P(1-\nu)C)$ and applying Equation (B.4) yields the steady-state labor market tightness

$$\tau = \frac{\omega}{1-\omega}\frac{1-\beta(1-\delta)}{\kappa_2}J.$$

Then, Equation (B.5) yields the steady-state probability of selling a house

$$G = \zeta(1-e^{-\tau}),$$

Equation (B.4) yields the steady-state probability of buying a house

$$F = \frac{G}{\tau},$$

Equation (B.15) yields the steady-state price of a house

$$\frac{Q}{P} = [1-\beta(1-\delta)(1-G)]\frac{J(1-\nu)C}{G},$$

Equation (B.22) yields the steady-state producer surplus

$$PS = \frac{Q}{P(1-\nu)C} - \beta(1-\delta)J,$$

Equation (B.24) yields the steady-state consumer surplus

$$CS = \frac{\omega}{1-\omega} PS,$$

Equation (B.23) yields the steady-state total surplus

$$TS = CS + PS,$$

Equation (B.21) yields the steady-state mortgage interest rate

$$R_m = (V_o - V_s - CS)\frac{(1-\nu)C}{\theta(Q/P)V_m} - \frac{1-\theta}{\theta V_\eta} + 1 - \eta$$

Equation (B.11) yields steady-state house sales

$$S = \frac{\theta}{\kappa_1}\frac{Q}{P}[(R_m - 1 + \eta)V_\eta - 1]$$

Equations (B.7) and (B.10) yield the steady-state measure of searching renters

$$H_s = \frac{1-F}{F} S,$$

Equations (B.8) and (B.10) yield the steady-state measure of owner-occupiers

$$H_o = \frac{S - FH_s}{F[1-(1-\delta)(1-\chi_r)]},$$

Equation (B.6) yields the steady-state measure of non-searching renters

$$H_r = 1 - H_o - H_s,$$

Equation (B.8) yields the fraction of non-searching renters that begin searching

$$\chi_s = \frac{[1-(1-\delta)(1-\chi_r)]H_o}{H_r + [1-(1-\delta)(1-\chi_r)]H_o},$$

Equations (B.3), (B.4), (B.9) and (B.10) yield the steady-state measure of houses that are not owner-occupied

$$U = \frac{1-G}{G}S + H_s + H_r,$$

Equation (B.9) yields steady-state investment

$$I = \frac{H_s + \chi_s H_r + \chi_s[1-(1-\delta)(1-\chi_r)]H_o}{\tau} - (1-\delta)(U + \chi_r H_o) + H_s + H_r,$$

Equation (B.34) yields steady-state non-durable goods production

$$X = C + \kappa_1 S^2,$$

Equation (B.32) yields steady-state residential construction spending

$$RS = \frac{W}{\bar{A}_I P} I,$$

Equation (B.31) yields steady-state GDP

$$Y = C + \frac{P_r}{P} + RS + \kappa_1 S^2,$$

Equations (B.25) and (B.26) yield the steady-states for the auxiliary pricing variables

$$Z_1 = \frac{1}{1 - \beta\alpha\Pi^{\epsilon}} \frac{\epsilon}{\epsilon - 1} \frac{\bar{A}_X W}{P} \frac{X}{(1-\nu)C}$$

$$Z_2 = \frac{1}{1 - \beta\alpha\Pi^{\epsilon-1}} \frac{X}{(1-\nu)C},$$

Equation (B.30) yields steady-state price dispersion

$$D = \frac{1-\alpha}{1-\alpha\Pi^{\epsilon}} \left(\frac{Z_1}{Z_2}\right)^{-\epsilon},$$

Equation (B.28) yields steady-state labor used for producing houses

$$N_I = \frac{\bar{H}}{\bar{A}_I},$$

Equation (B.29) yields steady-state labor used for producing non-durable goods

$$N_X = \frac{DX}{\bar{A}_X},$$

and Equation (B.34) yields total steady-state labor

$$N = N_X + N_I.$$

Appendix C

This appendix describes the estimation of the unobserved factors and their loadings following the procedure in Boivin, Giannoni, and Mihov (2009). Given T observations of x_t and r_t, define the following matrices:

$$\underset{(T\times n)}{X} = \begin{bmatrix} x_1' \\ \vdots \\ x_T' \end{bmatrix}, \quad \underset{(T\times k-1)}{F} = \begin{bmatrix} f_1' \\ \vdots \\ f_T' \end{bmatrix}, \quad \underset{(T\times 1)}{R} = \begin{bmatrix} r_1' \\ \vdots \\ r_T' \end{bmatrix}, \quad \underset{(T\times n)}{E} = \begin{bmatrix} e_1' \\ \vdots \\ e_T' \end{bmatrix}.$$

Then, Equation (1.48) can be written as

$$X = \begin{bmatrix} R & F \end{bmatrix} \Lambda + E.$$

Partition Λ so that $\Lambda = [\Lambda_R' \quad \Lambda_F']'$ and that the above equation is equivalent to

$$X = R\Lambda_R + F\Lambda_F + E. \tag{C.1}$$

The estimation procedure follows an iterative approach. To initialize the iteration, I estimate F, denoted by $\hat{F}^{(0)}$, to be $\sqrt{T}$ times the eigenvectors that correspond to the $k-1$ largest eigenvectors of XX'. Then, I estimate Λ_R and Λ_F, denoted by $\hat{\Lambda}_R^{(0)}$ and $\hat{\Lambda}_F^{(0)}$, from Equation (C.1) by least squares, taking $\hat{F}^{(0)}$ as given. Then, the initial estimated common component is given by $R\hat{\Lambda}_R^{(0)} + \hat{F}^{(0)}\hat{\Lambda}_F^{(0)}$.

Loop j of the iteration is given as follows

1. Compute $\tilde{X}^{(j)} = X - R\hat{\Lambda}_R^{(j-1)}$.

2. Estimate $\hat{F}^{(j)}$ to be $\sqrt{T}$ times the eigenvectors that correspond to the $k-1$ largest eigenvectors of $\tilde{X}^{(j)}\tilde{X}^{(j)\prime}$.

3. Estimate $\hat{\Lambda}_R^{(j)}$ and $\hat{\Lambda}_F^{(j)}$ from Equation (C.1) by least squares, taking $\hat{F}^{(j)}$ as given.

4. Compute the common component for loop j, $R\hat{\Lambda}_R^{(j)} + \hat{F}^{(j)}\hat{\Lambda}_F^{(j)}$, and check if it is sufficiently close to the common component for loop $j-1$. If it is, then stop the iteration. Otherwise, go back to step 1.

I use the sup norm to compute distances between the common components for each loop and a stopping distance of 1×10^{-8}. Given the baseline parameters, the program reaches this stopping distance at about 300 loops.

Appendix D

This appendix describes the identification of the first column of the matrix M, using an instrument, z_t. For ease of notation, re-write Equation (1.54) to be $\mu_{21} = \nu'\mu_{11}$, where $\nu = [E(z_t u_{1,t})]^{-1}E(z_t u'_{2,t})$ is $1 \times k-1$.[42] Then, define $E(u_{1,t}u'_{1,t}) = \sigma_{11}$, $E(u_{2,t}u'_{1,t}) = \sigma_{21}$, $E(u_{1,t}u'_{2,t}) = \sigma'_{21}$ and $E(u_{2,t}u'_{2,t}) = \sigma_{22}$. The system in (1.50) and $E(v_t v'_t) = I_K$ yields

$$\begin{bmatrix} \sigma_{11} & \sigma'_{21} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{bmatrix} \begin{bmatrix} \mu'_{11} & \mu'_{21} \\ \mu'_{12} & \mu'_{22} \end{bmatrix}$$

Because M is invertible and $\mu_{11} \neq 0$, it is the case that μ_{22} is invertible. Thus, the above system can be written as

$$\begin{bmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{bmatrix}^{-1} \begin{bmatrix} \sigma_{11} & \sigma'_{21} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \mu'_{11} & \mu'_{21} \\ \mu'_{12} & \mu'_{22} \end{bmatrix},$$

which is equivalent to

$$\begin{bmatrix} (\mu_{11} - \mu_{12}\mu_{22}^{-1}\mu_{21})^{-1} & -(\mu_{11} - \mu_{12}\mu_{22}^{-1}\mu_{21})^{-1}\mu_{12}\mu_{22}^{-1} \\ -(\mu_{22} - \mu_{21}\mu_{11}^{-1}\mu_{12})^{-1}\mu_{21}\mu_{11}^{-1} & (\mu_{22} - \mu_{21}\mu_{11}^{-1}\mu_{12})^{-1} \end{bmatrix} \begin{bmatrix} \sigma_{11} & \sigma'_{21} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \mu'_{11} & \mu'_{21} \\ \mu'_{12} & \mu'_{22} \end{bmatrix}$$

Using $\mu_{21} = \nu'\mu_{11}$, the above system can be written as

$$\sigma_{11} - \mu_{12}\mu_{22}^{-1}\sigma_{21} = (1 - \mu_{12}\mu_{22}^{-1}\nu')\mu_{11}\mu'_{11}, \tag{D.1}$$

$$\sigma_{21} - \theta'\sigma_{11} = (I_{K-1} - \nu'\mu_{12}\mu_{22}^{-1})\mu_{22}\mu'_{22}(\mu_{12}\mu_{22}^{-1})', \tag{D.2}$$

[42] Note that the letter ν is being used to denote a different variable here than in the DSGE model.

$$\sigma_{21}' - \mu_{12}\mu_{22}^{-1}\sigma_{22} = (1 - \mu_{12}\mu_{22}^{-1}\nu')\mu_{11}\mu_{11}'\nu, \tag{D.3}$$

and

$$\sigma_{22} - \nu'\sigma_{21}' = (I_{K-1} - \nu'\mu_{12}\mu_{22}^{-1})\mu_{22}\mu_{22}'. \tag{D.4}$$

on an equation-by-equation basis. Because σ_{11}, σ_{21}, σ_{22} and ν can all be estimated from data, Equations (D.1) through (D.4) is a system of four equations with three unknowns: $\mu_{11}\mu_{11}'$, $\mu_{12}\mu_{22}^{-1}$, and $\mu_{22}\mu_{22}'$. However, the number of equations in this system can be reduced by one. Using Equation (D.1) to substitute $(1-\mu_{12}\mu_{22}^{-1}\nu')\mu_{11}\mu_{11}'$ out of Equation (D.3) yields

$$\sigma_{21}' - \mu_{12}\mu_{22}^{-1}\sigma_{22} = (\sigma_{11} - \mu_{12}\mu_{22}^{-1}\sigma_{21})\nu. \tag{D.5}$$

Using Equation (D.4) to substitute $(I_{K-1} - \nu'\mu_{12}\mu_{22}^{-1})\mu_{22}\mu_{22}'$ out of Equation (D.2) yields

$$\sigma_{21} - \nu'\sigma_{11} = (\sigma_{22} - \theta'\sigma_{21}')(\mu_{12}\mu_{22}^{-1})', \tag{D.6}$$

Both Equation (D.5) and (D.6) yield

$$\mu_{12}\mu_{22}^{-1} = (\sigma_{21}' - \sigma_{11}\nu)(\sigma_{22} - \sigma_{21}\nu)^{-1} \tag{D.7}$$

Thus, it is possible for the three unknowns, $\mu_{11}\mu_{11}'$, $\mu_{12}\mu_{22}^{-1}$ and $\mu_{22}\mu_{22}'$, to solve Equations (D.1) though (D.4) simultaneously. Taking $\mu_{12}\mu_{22}^{-1}$ as estimable from Equation (D.7), Equations (D.1) and (D.4) then yield

$$\mu_{11}\mu_{11}' = (1 - \mu_{12}\mu_{22}^{-1}\nu')^{-1}(\sigma_{11} - \mu_{12}\mu_{22}^{-1}\sigma_{21}) \tag{D.8}$$

and

$$\mu_{22}\mu_{22}' = (I_{K-1} - \nu'\mu_{12}\mu_{22}^{-1})^{-1}(\sigma_{22} - \nu'\sigma_{21}'). \tag{D.9}$$

Because μ_{11} is 1×1, Equation (D.8) implies

$$\mu_{11} = \pm\sqrt{(1 - \mu_{12}\mu_{22}^{-1}\nu')^{-1}(\sigma_{11} - \mu_{12}\mu_{22}^{-1}\sigma_{21})} \tag{D.10}$$

so that μ_{11} is identified up to a sign restriction. This implies that $\mu_{21} = \nu'\mu_{11}$ is also identified up to a sign restriction, yielding the first column of M. I assume that $\mu_{11} > 0$ so that a positive monetary policy shock leads to an increase in the policy interest rate.

To estimate μ_{11} and μ_{21}, define

$$\underset{(T \times L)}{Z} = \begin{bmatrix} z_1' \\ \vdots \\ z_T' \end{bmatrix}, \quad \underset{(T \times 1)}{U_1} = \begin{bmatrix} u_{1,1}' \\ \vdots \\ u_{1,T}' \end{bmatrix}, \quad \underset{(T \times K-1)}{U_2} = \begin{bmatrix} u_{2,1}' \\ \vdots \\ u_{2,T}' \end{bmatrix}$$

given T observations of z_t and the VAR regression errors u_t. Then,

$$\hat{\nu} = (Z'U_1)^{-1}Z'U_2.$$

Then, $\hat{\sigma}_{11} = T^{-1}U_1'U_1$, $\hat{\sigma}_{21} = T^{-1}U_2'U_1$ and $\hat{\sigma}_{22} = T^{-1}U_2'U_2$. Plugging these Equations (D.7) and (D.10) yields $\hat{\mu}_{11}$, and then $\hat{\mu}_{21} = \hat{\nu}'\mu_{11}$.

Appendix E

This appendix presents the data for the factor-augmented vector autoregression. It gives the data series names and the method for transforming the data to stationarity. All series are seasonally adjusted prior to the stationarity transformation.

Index	Data Series Name	Transformation
	Industrial Production and Capacity Utilization	
1	Capacity Utiliztion: Total Industry	none
2	Capacity Utiliztion: Durable Manufacturing	none
3	Capacity Utiliztion: Nondurable Manufacturing	none
4	Industrial Production Index	$\Delta \ln \times 100$
5	Industrial Production Index: Consumer Goods	$\Delta \ln \times 100$
6	Industrial Production Index: Materials	$\Delta \ln \times 100$
7	Industrial Production Index: Business Equipment	$\Delta \ln \times 100$
	Personal Consumption Expenditures	
8	PCE	$\Delta \ln \times 100$
9	PCE: Goods	$\Delta \ln \times 100$
10	PCE: Goods: Durable goods	$\Delta \ln \times 100$
11	PCE: Goods: Nondurable goods	$\Delta \ln \times 100$
12	PCE: Services	$\Delta \ln \times 100$
13	PCE: Excluding food and energy	$\Delta \ln \times 100$
14	PCE: Food	$\Delta \ln \times 100$
15	PCE: Energy goods and services	$\Delta \ln \times 100$
	Cosnumer Price Index	
16	CPI for all urban consumers: All items	$\Delta \ln \times 100$
17	CPI for all urban consumers: Energy	$\Delta \ln \times 100$
18	CPI for all urban consumers: All items less food and energy	$\Delta \ln \times 100$
19	CPI for all urban consumers: All items less shelter	$\Delta \ln \times 100$
20	CPI for all urban consumers: Apparel	$\Delta \ln \times 100$
21	CPI for all urban consumers: Commodities	$\Delta \ln \times 100$
22	CPI for all urban consumers: Durables	$\Delta \ln \times 100$
23	CPI for all urban consumers: Food and Beverages	$\Delta \ln \times 100$
24	CPI for all urban consumers: Other goods and services	$\Delta \ln \times 100$
25	CPI for all urban consumers: Housing	$\Delta \ln \times 100$
26	CPI for all urban consumers: Medical care	$\Delta \ln \times 100$
27	CPI for all urban consumers: Nondurables	$\Delta \ln \times 100$
28	CPI for all urban consumers: Services	$\Delta \ln \times 100$
29	CPI for all urban consumers: Transportation	$\Delta \ln \times 100$
30	CPI for all urban consumers: Rent of primary residence	divide by CPI for all urban consumers: all items less shelter and then take $\ln \times 100$
31	CPI for all urban consumers: Owners' equivalent rent of primary residence	divide by CPI for all urban consumers: all items less shelter and then take $\ln \times 100$
	Producer Price Index	
32	PPI: Finished goods	$\Delta \ln \times 100$
33	PPI: Intermediate materials: Supplies & components	$\Delta \ln \times 100$
34	PPI: Intermediate foods & feeds	$\Delta \ln \times 100$
35	PPI: Intermediate energy goods	$\Delta \ln \times 100$
36	PPI: Crude materials for further processing	$\Delta \ln \times 100$
37	PPI: All commodities	$\Delta \ln \times 100$

Price Index for Personal Consumption Expenditures

38	Price index for PCE	$\Delta \ln \times 100$
39	Price index for PCE: Goods	$\Delta \ln \times 100$
40	Price index for PCE: Goods: Durable goods	$\Delta \ln \times 100$
41	Price index for PCE: Goods: Nondurable goods	$\Delta \ln \times 100$
42	Price index for PCE: Services	$\Delta \ln \times 100$
43	Price index for PCE: Excluding food and energy	$\Delta \ln \times 100$
44	Price index for PCE: Food	$\Delta \ln \times 100$
45	Price index for PCE: Energy goods and services	$\Delta \ln \times 100$

Personal Income and Its Disposition

46	Personal income	$\Delta \ln \times 100$
47	Compensation of employees	$\Delta \ln \times 100$
48	Wages and salaries	$\Delta \ln \times 100$
49	Wages and salaries: Private industries	$\Delta \ln \times 100$
50	Wages and salaries: Government	$\Delta \ln \times 100$
51	Supplements to wages and salaries	$\Delta \ln \times 100$
52	Employer contributions for employee and insurance funds	$\Delta \ln \times 100$
53	Employer contributions for government social insurance	$\Delta \ln \times 100$
54	Proprietors' income with inventory valuation and capital consumption adjustments	$\Delta \ln \times 100$
55	Rental income of persons with capital consumption adjustment	$\Delta \ln \times 100$
56	Personal income receipts on assets	$\Delta \ln \times 100$
57	Personal interest income	$\Delta \ln \times 100$
58	Personal dividend income	$\Delta \ln \times 100$
59	Personal current transfer receipts	$\Delta \ln \times 100$

Labor Market Quantities

60	Initial unemployment insurance claims	none
61	Civilian unemployment rate	none
62	Employment level: Part-time for economic reasons	none
63	Number unemployed for less than 5 weeks	none
64	Number for 5-14 weeks	none
65	Number unemployed for 15 weeks and over	none
66	Number unemployed for 27 weeks and over	none
67	Employees: Total nonfarm	$\Delta \ln \times 100$
68	Employees: Total private	$\Delta \ln \times 100$
69	Employees: mining and logging	$\Delta \ln \times 100$
70	Employees: Construction	$\Delta \ln \times 100$
71	Employees: Manufacturing	$\Delta \ln \times 100$
72	Employees: Durable goods	$\Delta \ln \times 100$
73	Employees: Nondurable goods	$\Delta \ln \times 100$
74	Employees: Trade, transformation and utilities	$\Delta \ln \times 100$
75	Employees: Information	$\Delta \ln \times 100$
76	Employees: Financial activities	$\Delta \ln \times 100$
77	Employees: Professional and business services	$\Delta \ln \times 100$
78	Employees: Education and business services	$\Delta \ln \times 100$
79	Employees: Leisure and hospitality	$\Delta \ln \times 100$
80	Employees: Other services	$\Delta \ln \times 100$
81	Employees: Government	$\Delta \ln \times 100$
82	Average weekly overtime hours of production and nonsupervisory employees: Manufacturing	none

Labor Market Prices

83	Average hourly earnings of production and nonsupervisory employees: Total private	$\Delta \ln \times 100$
84	Average hourly earnings of production and nonsupervisory employees: Mining and logging	$\Delta \ln \times 100$
85	Average hourly earnings of production and nonsupervisory employees: Construction	$\Delta \ln \times 100$
86	Average hourly earnings of production and nonsupervisory employees: Durable goods	$\Delta \ln \times 100$
87	Average hourly earnings of production and nonsupervisory employees: Nondurable goods	$\Delta \ln \times 100$

Labor Market Prices

88	Average hourly earnings of production and nonsupervisory employees: Trade, transportation and utilities	$\Delta \ln \times 100$
89	Average hourly earnings of production and nonsupervisory employees: Information	$\Delta \ln \times 100$
90	Average hourly earnings of production and nonsupervisory employees: Financial activities	$\Delta \ln \times 100$
91	Average hourly earnings of production and nonsupervisory employees: Professional and business services	$\Delta \ln \times 100$
92	Average hourly earnings of production and nonsupervisory employees: Education and health services	$\Delta \ln \times 100$
93	Average hourly earnings of production and nonsupervisory employees: Leisure and hospitality	$\Delta \ln \times 100$
94	Average hourly earnings of production and nonsupervisory employees: Other services	$\Delta \ln \times 100$

Interest Rates

95	Effective federal funds rate	none
96	3-month treasury bill: Secondary market rate	none
97	1-year treasury constant maturity rate	none
98	5-year treasury constant maturity rate	none
99	10-year treasury constant maturity rate	none
100	Moody's seasoned Aaa corporate bond yield	none
101	Moody's seasoned Baa corporate bond yield	none
102	30-year conventional mortgage rate	none
103	1-year adjustable rate mortgage average	none
104	90-day AA financial commercial paper interest rate	none
105	3-month eurodollar deposit rate (London)	none
106	Bond buyer GO 20-bond municipal bond index	none

Interest Rates

107	Spread 1-year treasury less 3-month treasury	none
108	Spread 5-year treasury less 1-year treasury	none
109	Spread 10-year treasury less 5-year treasury	none
110	Spread Moody's Aaa less 10-year treasury	none
111	Spread Moody's Baa less Moody's Aaa	none
112	Spread 30-year conventional mortgage less 10-year treasury	none
113	Spread 1-year adjustable rate mortgage average less 1-year treasury	none
114	Spread 90-day AA financial commercial paper interest rate less 3-months treasury	none
115	Spread 3-month eurodollar deposit rate (London) less 3-month treasury	none
116	Spread Bond buyer GO 20-bond municipal bond index less 10-year treasury	none

Asset Markets

117	S&P 500 index	$\Delta \ln \times 100$
118	S&P 500 dividend index	$\Delta \ln \times 100$
119	S&P 500 earnings index	$\Delta \ln \times 100$
120	NASDAQ composite index	$\Delta \ln \times 100$
121	Wilshire 5000 total market index	$\Delta \ln \times 100$
122	BofA Merrill Lynch US corp master total return index value	$\Delta \ln \times 100$

Exchange Rates

123	Japan/U.S. foreign exchange rate	Δ
124	U.S./U.K. foreign exchange rate	Δ
125	Canada/U.S. foreign exchange rate	Δ
126	U.S./Australia foreign exchange rate	Δ
127	Switzerland/U.S. foreign exchange rate	Δ

Monetary Aggregates

128	M1	$\Delta \ln \times 100$
129	M2	$\Delta \ln \times 100$
130	Total non-M1 M2	$\Delta \ln \times 100$
131	Currency	$\Delta \ln \times 100$
132	Demand deposits	$\Delta \ln \times 100$
133	Other checkable deposits - total	$\Delta \ln \times 100$
134	Small-denomination time deposits - total	$\Delta \ln \times 100$
135	Savings deposits - total	$\Delta \ln \times 100$
136	Retail money funds	$\Delta \ln \times 100$

Consumer Credit and Commercial Bank Balance Sheet Aggregates

137	Total consumer credit owned and securitized	$\Delta \ln \times 100$
138	Nonrevolving consumer credit owned securitized	$\Delta \ln \times 100$
139	Revolving consumer credit owned and securitized	$\Delta \ln \times 100$
140	Bank credit, all commercial banks	$\Delta \ln \times 100$
141	Securities in bank credit, all commercial banks	$\Delta \ln \times 100$
142	Treasury and agency securities, all commercial banks	$\Delta \ln \times 100$
143	Other securities, all commercial banks	$\Delta \ln \times 100$
144	Loans and leases in bank credit, all commercial banks	$\Delta \ln \times 100$
145	Commercial and industrial loans, all commercial banks	$\Delta \ln \times 100$
146	Real estate loans, all commercial banks	$\Delta \ln \times 100$
147	Consumer loans, all commercial banks	$\Delta \ln \times 100$
148	Interbank loans, all commercial banks	$\Delta \ln \times 100$
149	Deposits, all commercial banks	$\Delta \ln \times 100$
150	Large time deposits, all commercial banks	$\Delta \ln \times 100$
151	Residual (assets less liabilities), all commercial banks	$\Delta \ln \times 100$
152	Borrowings, all commercial banks	$\Delta \ln \times 100$
153	Total liabilities, all commercial banks	$\Delta \ln \times 100$
154	Other liabilities, all commercial banks	$\Delta \ln \times 100$

Survey Data

155	University of Michigan consumer sentiment	none
156	University of Michigan inflation expectations	none
157	University of Michigan survey of consumers: relative buying conditions for houses	none
158	ISM manufacturing: New order index	none
159	ISM manufacturing: Employment index	none
160	ISM manufacturing: Production index	none
161	ISM manufacturing: Inventories index	none
162	ISM manufacturing: Prices index	none
163	ISM manufacturing: Supplier deliveries index	none

New Residential Construction

164	New privately owned housing units authorized by building permits	$\Delta \ln \times 100$
165	New privately owned housing units authorized by building permits: In structures with on unit	$\Delta \ln \times 100$
166	New privately owned housing units authorized by building permits: In structures with 2 to 4 units	$\Delta \ln \times 100$
167	New privately owned housing units authorized by building permits: In structures with 5+ units	$\Delta \ln \times 100$
168	New privately owned housing units authorized by building permits: Total northeast	$\Delta \ln \times 100$
169	New privately owned housing units authorized by building permits: Total midwest	$\Delta \ln \times 100$
170	New privately owned housing units authorized by building permits: Total south	$\Delta \ln \times 100$
171	New privately owned housing units authorized by building permits: Total west	$\Delta \ln \times 100$
172	New privately owned housing units started	$\Delta \ln \times 100$
173	New privately owned housing units started: In structures with one unit	$\Delta \ln \times 100$
174	New privately owned housing units started: In structures with 5 or more units	$\Delta \ln \times 100$
175	New privately owned housing units started: Total northeast	$\Delta \ln \times 100$
176	New privately owned housing units started: Total midwest	$\Delta \ln \times 100$
177	New privately owned housing units started: Total south	$\Delta \ln \times 100$
178	New privately owned housing units started: Total west	$\Delta \ln \times 100$
179	New privately owned housing units under construction	$\Delta \ln \times 100$
180	New privately owned housing units under construction: In structures with one unit	$\Delta \ln \times 100$
181	New privately owned housing units under construction: In structures with 5 or more units	$\Delta \ln \times 100$
182	New privately owned housing units under construction: Total northeast	$\Delta \ln \times 100$
183	New privately owned housing units under construction: Total midwest	$\Delta \ln \times 100$
184	New privately owned housing units under construction: Total south	$\Delta \ln \times 100$
185	New privately owned housing units under construction: Total west	$\Delta \ln \times 100$
186	New privately owned housing units completed	$\Delta \ln \times 100$
187	New privately owned housing units completed: In structures with one unit	$\Delta \ln \times 100$
188	New privately owned housing units completed: In structures with 5 or more units	$\Delta \ln \times 100$
189	New privately owned housing units completed: Total northeast	$\Delta \ln \times 100$
190	New privately owned housing units completed: Total midwest	$\Delta \ln \times 100$
191	New privately owned housing units completed: Total south	$\Delta \ln \times 100$
192	New privately owned housing units completed: Total west	$\Delta \ln \times 100$

New Residential Sales

193	New single-family houses sold	$\Delta \ln \times 100$
194	New single-family houses sold in the Northeast	$\Delta \ln \times 100$
195	New single-family houses sold in the Midwest	$\Delta \ln \times 100$
196	New single-family houses sold in the South	$\Delta \ln \times 100$
197	New single-family houses sold in the West	$\Delta \ln \times 100$
198	New single-family houses for sale	$\Delta \ln \times 100$
199	New single-family houses for sale: Northeast	$\Delta \ln \times 100$
200	New single-family houses for sale: Midwest	$\Delta \ln \times 100$
201	New single-family houses for sale: South	$\Delta \ln \times 100$
202	New single-family houses for sale: West	$\Delta \ln \times 100$
203	Months' supply of new houses for sale at current sales rate	none
204	Median number of months new homes remain for sale since completion	none
205	Median sales price of new single-family houses	divide by CPI for all urban consumers: less shelter and then take $\ln \times 100$
206	Average sales price of new single-family houses	divide by CPI for all urban consumers: less shelter and then take $\ln \times 100$

Construction Spending and Price Indices

207	Price index of new single-family houses under construction: Laspeyres (fixed)	$\Delta \ln \times 100$
208	Price index of new single-family houses under construction: Fisher (deflator)	$\Delta \ln \times 100$
209	Residential construction spending including improvements	divide by price index of new single-family houses under construction (Fisher) and then take $\ln \times 100$
210	Residential construction spending: new single family	divide by price index of new single-family houses under construction (Fisher) and then take $\ln \times 100$
211	Residential construction spending: new multi-family	divide by price index of new single-family houses under construction (Fisher) and then take $\ln \times 100$

Homeownership Rate

212	Homeownership rate	none

Appendix F

This appendix displays the information criteria used to specify the empirical model in Section 1.6. First, I display estimates of the three information criteria provided in Bai and Ng (2002). Because all specifications of Equation (1.48) include r_t, the minimum number of factors I consider are $k = 2$. The minimized values are indicated with bold text.

k	IC1	IC2	IC3
2	-0.1215	-0.1126	-0.1491
3	-0.1724	-0.1592	-0.2138
4	-0.2193	-0.2017	-0.2745
5	-0.2405	-0.2185	-0.3095
6	-0.2531	-0.2267	-0.3359
7	-0.2589	-0.2281	-0.3555
8	-0.2658	**-0.2306**	-0.3762
9	**-0.2662**	-0.2265	-0.3904
10	-0.2661	-0.2220	-0.4041
11	-0.2634	-0.2150	-0.4152
12	-0.2611	-0.2083	-0.4267
13	-0.2581	-0.2008	-0.4375
14	-0.2529	-0.1912	-0.4461
15	-0.2485	-0.1825	**-0.4555**

Next, given $k = 9$, I display the Akaike information criterion (AIC), the Schwarz information criterion (SIC), and the Hannan-Quinn information criterion (HQC). The minimized values are indicated with bold text.

p	AIC	SIC	HQC
1	-14.602	-13.587	-14.195
2	-15.655	**-13.625**	**-14.842**
3	**-15.999**	-12.954	-14.780
4	-15.907	-11.841	-14.275
5	-15.807	-10.732	-13.775
6	-15.687	-9.598	-13.249

Chapter 2

Forecasting Residential Investment in the United States

2.1 Introduction

Residential investment was central to the 2002-2007 economic expansion and the 2008-2009 recession, and researchers and policy-makers have increased their focus on understanding and influencing it. Despite this focus, however, studies on residential investment forecasting are scarce. The objective of this paper is to fill this gap in the literature by making two contributions. First, I propose a forecasting model based on the stock-flow relationship of housing starts, housing completions and housing units under construction. Second, I compare the forecasting accuracy of this proposed model to several common time series models, the Survey of Professional Forecasters and the Federal Reserve's Greenbook.

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Forecasts of residential investment are important because residential investment has historically played a central role in U.S. business cycles — not just the most recent cycle. Green (1997) shows that residential investment Granger (1969) causes GDP, suggesting that good forecasts of residential investment can help forecast overall economic activity. Similarly, Leamer (2007) concludes that "[i]t is residential investment that contributes the most to weakness before recessions," implying that residential investment can help identify business cycle peaks. Further, while residential investment has averaged 4.7% of GDP since 1947, McCracken (2011) points out that it contributes significantly to economic recoveries. This fact has not been lost on policy makers. Following the 2009:Q2 trough, Bernanke (2009) and Kohn (2009) viewed residential investment as a potential source of economic growth. More recently, Bernanke (2012) and Yellen (2013) have noted that the weak contribution of residential investment has made the recent recovery unusual. Expectations of a stronger housing recovery in 2009 likely influenced the Federal Reserve's forecast of overall economic growth,[1] which would have influenced its policy decisions.

I build the forecasting model in this paper upon three features of residential investment and construction:

1. Single family residential investment drives the majority of the fluctuations in total residential investment.

2. Percent changes in single family residential investment reported by the Bureau of Economic Analysis (BEA) and one-unit structures under construction reported by the Census Bureau are highly correlated, and a linear, least squares regression fits the

[1]Feroli et al. (2012) show that from November 2009 to November 2011, the Federal Reserve made successive downward revisions to its forecasts of economic growth for 2010, 2011 and 2012.

relationship between these variables well.[2]

3. A stock-flow model, where starts are the flow of housing units into construction and completions are the flow of housing units out of construction, leads to a multicointegration relationship (Granger, 1986; Granger and Lee, 1989, 1990) among starts, completions and housing units under construction.

Multicointegration arises when construction, in both its *changes* and its *levels*, is a part of cointegrations with starts and completions. First, the stock-flow structure is

$$Construction_t - Construction_{t-1} = Starts_t - Completions_t.$$

If starts and completions are $I(1)$ and the change in construction is $I(0)$, then starts and completions are cointegrated with changes in construction acting as the stationary residual. Second, because changes in construction are $I(0)$, the level of construction will be $I(1)$. It is natural for completions to follow this level of construction over time because a house must be under construction before it can be completed, suggesting another cointegration relationship between the level of construction and completions.[3] Several other papers apply this stock-flow model and test for multicointegration when studying housing construction (Lee, 1992, 1996; Coulson, 1999; Engsted and Haldrup, 1999), but to my knowledge this is the first paper that uses it to forecast residential investment.

The error correction model (ECM) that corresponds to the multicointegration relationship among construction, starts and completions is the starting point of my forecasting

[2]Henceforth, I will use "residential investment" to refer to the quarterly data produced by the BEA and "construction" to refer to the monthly data produced by the Census.

[3]Under this multicointegration structure, the cointegration between completions and construction also implies a cointegration between starts and construction (Granger and Lee, 1989).

model, which proceeds in three steps. First, I estimate the ECM on monthly data from the Census's new residential construction report, and use it to forecast monthly one-unit structures started and completed. Second, I use these forecasts of starts and completions to produce monthly forecasts of one-unit structures under construction from the stock-flow nature of construction. Third, I take advantage of the first two features of residential investment and construction by using the quarterly average of the one-unit construction forecasts to forecast quarterly residential investment growth. In addition to accounting for multicointegration, this procedure provides a simple way of incorporating monthly Census data into residential investment forecasts. To ease discussion below, I will use "ECM" as a blanket term to refer to this three-step model.

I compare the forecast accuracy of the ECM to the Survey of Professional Forecasters (SPF), the Federal Reserve's Greenbook, a random walk (RW) model that predicts zero growth at all horizons, a univariate autoregression (AR) model, and two vector autoregression (VAR) models that include the same variables as the ECM. One VAR log-differences the variables prior to estimation, a DVAR, while the other has the variables in log-levels, an LVAR. I estimate all models on real-time data that would have been available to the SPF, and the comparisons yield the following results. First, the ECM produces lower root mean squared prediction errors (RMSPEs) than any of the other models or the SPF at five quarterly forecast horizons in the sample 1981:Q3 to 2013:Q2. Second, from 1981:Q3 to 2007:Q4, the Greenbook produces the lowest RMSPE for current quarter forecasts, but the ECM produces the lowest RMSPEs for all multi-step forecasts.[4] Third, relative to the VARs, the SPF and the Greenbook, the ECM's largest and most statistically significant RMSPE reductions come

[4]The Fed has only made Greenbook forecasts available through the 2007:Q4 vintage.

at multi-step forecast horizons. Fourth, the ECM performs best in the economically volatile 1981:Q3 to 1983:Q4 and 2006:Q1 to 2013:Q2 samples. Finally, the ECM's current quarter forecast gives a better indication of the 2002:Q1 to 2005:Q4 housing boom than the SPF or the Greenbook and of the 2006:Q1 to 2009:Q2 housing collapse than the SPF.

The effectiveness of the ECM has two important implications: one for forecasting in general and one for forecasting residential investment specifically. The general implication is that multicointegrated ECMs can be useful for forecasting variables that follow stock-flow relationships. Lee (1996) shows that multicointegrated systems follow from the solution to a general optimal control problem. In addition to housing construction, he applies this solution to inventory adjustment (where production and sales are the flows and inventory is the stock) and wealth effects (where disposable income and consumption are the flows and wealth is the stock), suggesting that inventory and wealth may be well forecasted by a multicointegrated ECM. Labor market variables also follow stock-flow relationships. Demiralp, Gantt, and Selover (2011) and Barnichon and Nekarda (2012) use stock-flow models to forecast unemployment levels and the unemployment rate, respectively. While Barnichon and Nekarda (2012) don't invoke multicointegration, their model is based on deviations of the unemployment rate from its conditional steady-state, using similar reasoning to an ECM.

The important implication for residential investment is that more effort should be put into forecasting one-unit construction. Currently, the SPF, the Livingston survey and the Federal Reserve's Greenbook all forecast total housing starts but not one-unit starts. However, focusing on one-unit construction is important to the ECM's performance because growth in construction of multi-unit structures is more volatile than that of one-unit structures, and as shown in the next section, single family residential investment tracks total residential investment much better than multifamily residential investment. Thus, construction of one-unit structures has less noise and a stronger signal for forecasting than total construction does.

The literature on forecasting residential investment is sparse. Baghestani (2011) is the most similar to this paper, and this paper makes several additional contributions. First, Baghestani (2011) only considers univariate forecasting models in addition to the SPF and Federal Reserve forecasts. This paper proposes a multivariate ECM and includes VARs in its forecast comparisons. Second, this paper collects and uses a real-time data set of one-unit starts, completions, construction, authorizations and houses authorized but not started, none of which are included in Baghestani (2011). Third, this paper highlights the value of using one-unit construction for forecasting residential investment over using total construction. Fourth, Baghestani (2011) only considers an evaluation period through 2004. This paper uses a larger sample that compares forecasting ability during the housing peak, the 2008-2009 recession, and the subsequent recovery.

The rest of the paper proceeds as follows. Section 2.2 discusses the three features of residential investment and construction that the ECM is built upon. Section 2.3 describes the ECM in detail, and Section 2.4 describes the other forecasting models. Section 2.5 discusses the data. Section 2.6 compares the performance of the models and the SPF, and Section 2.7 concludes.

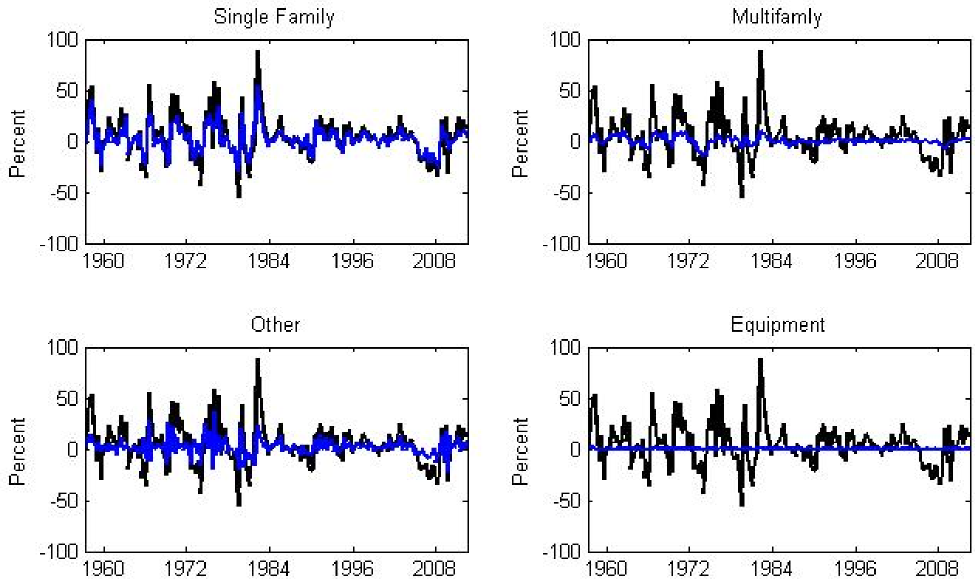

Figure 2.1: The black line in each panel is the annualized percent change in residential investment. The blue line in each panel displays the contribution of the respective category of residential investment.

2.2 Three Features of Residential Investment and Construction

The first feature of residential investment and construction is that single family residential investment drives the majority of the fluctuations in total residential investment. Figure 2.1 displays the annualized percent change in residential investment along with the contribution of each component of residential investment: single family, multifamily, other and equipment.[5] This figure shows that the contribution of single family residential investment most

[5]The sample in Figure 2.1 begins in the second quarter of 1958, which is the first period that the BEA provides separate data on all components of residential investment. Other residential investment includes manufactured homes, improvements, dormitories, net purchases of used structures, brokers' commissions on the sale of residential structures and adjoining land, and other ownership transfer costs.

Table 2.1: Correlation with Total Residential Investment and Variance Decomposition of Residential Investment

	Residential Investment	Single Family	Multi-family	Other	Equip
1958:Q2 to 2013:Q2:					
Correl with Total	1.00	0.91	0.59	0.71	0.47
Variance	371.4	148.9	16.0	62.2	0.1

closely matches the percent change of residential investment. To make this visual observation precise, Table 2.1 displays the correlation between the percent change in residential investment and the contribution of each component from 1958:Q2 to 2013:Q2. The contribution of single family structures has a correlation of 0.91, the highest amongst all components. Table 2.1 also includes a variance decomposition of the percent change in residential investment over the same sample period. It shows that the variance contributed by single family residential investment is nearly three times larger than any other component.

The influence of single family residential investment comes from its large size and variance relative to the other components. On average from 1958:Q1 to 2013:Q2, single family residential investment was 46% of total residential investment while investment in multifamily, other and equipment was 11%, 41% and 2%, respectively. Over the same period, the standard deviation of percent quarterly growth was 6.9 for single family residential investment and was 8.0, 4.7 and 3.8 for multifamily, other and equipment, respectively.[6] Thus, while multifamily residential investment is more volatile, the large size of single family residential investment gives it more influence.

The second feature of residential investment and construction is the high correlation

[6] These are the standard deviations of $(\ln(x_t)-\ln(x_{t-1}))\times 100$, where x_t is the variable of interest observed a quarterly frequency.

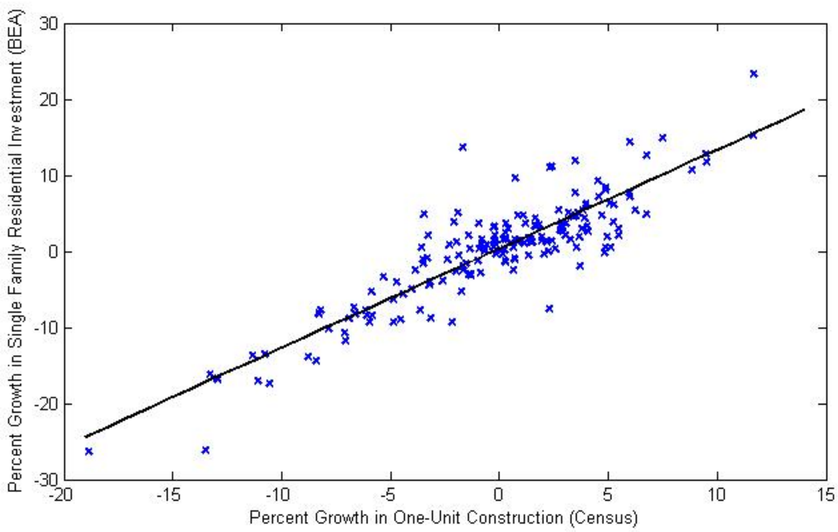

Figure 2.2: Scatterplot of the percent growth in one-unit construction from the Census Bureau and the percent growth in single family residential investment from the BEA with a linear, least squares regression line.

(0.88) between growth in single family residential investment reported by the BEA and growth in one-unit structures under construction reported by the Census Bureau. Figure 2.2 displays a scatter plot of these two variables from 1970:Q2 to 2013:Q2 with the corresponding linear, least-squares regression line. Because construction data from the Census is monthly and residential investment data from the BEA is quarterly, Figure 2.2 displays the quarterly average of one-unit construction. The linear regression provides a good approximation of the relationship of these two variables with $\bar{R} = 0.78$.

Unlike the first two features discussed in this section, which are empirical in nature, the third feature is structural. For the model, I assume that construction follows a stock-flow relationship, given by

$$c_t = s_t - f_t + c_{t-1}, \tag{2.1}$$

where c_t is one-unit construction, s_t is one-unit starts, and f_t is one-unit completions.[7] Here, starts are the flow of houses into construction and completions are the flow of houses out of construciton. This structure is consistent with the Census Bureau's definition of housing units "under construction," which is "housing units started, but not yet completed."[8] Rewriting the stock-flow relationship in Equation (2.1) yields

$$\Delta c_t = s_t - f_t, \tag{2.2}$$

where $\Delta x_t = x_t - x_{t-1}$ for any variable x_t. As discussed in the introduction, if s_t and f_t are I(1) and Δc_t is $I(0)$, then s_t and f_t are cointegrated. Further, if s_t and f_t are cointegrated with c_t, then the three variables are multicointegrated (Granger, 1986; Granger and Lee, 1989, 1990).

Lee (1992, 1996), Coulson (1999), and Engsted and Haldrup (1999) all apply this stock-flow model to housing construction and find empirical support for multicointegration. Further, Lee (1996) provides theoretical support by showing that the optimal control solution to a stock adjustment model yields the error correction representation of a multicointegrated system. This error correction representation is

$$\begin{aligned}\Delta \mathbf{x}_t = \beta_0 + \beta_1 \mathbf{z}_{t-1} + \beta_2 \Delta \mathbf{z}_{t-1} \\ + \beta_3 \Delta \mathbf{x}_{t-2} + \cdots + \beta_{2+p} \Delta \mathbf{x}_{t-1-p} + \varepsilon_t,\end{aligned} \tag{2.3}$$

where $\mathbf{x}_t = [s_t, f_t]'$ and $\mathbf{z}_t = [s_t, f_t, c_t]'$. Equations (2.2) and (2.3) give the joint dynamics of

[7]Each of these variables is monthly and produced by the Census. I use the notation f_t to be completions because c_t is used for construction, and completions can be similarly thought of as units finished.

[8]This definition is available at http://www.census.gov/construction/nrc/definitions/.

s_t, f_t and c_t that provide the basis of the forecasting model.

2.3 The Error Correction Forecasting Model

The forecasting model proceeds as follows. First, I forecast one-unit starts and completions. Second, I use the the stock-flow model of construction and the forecasts of one-unit starts and completions to forecast one-unit construction. Third, I use the first two features of residential investment and construction to forecast residential investment growth from the forecasts of one-unit construction.

2.3.1 Forecasting Starts and Completions

Empirically, it is the case that starts lead completions and construction, while construction and completions are roughly coincident. This suggests that the lags of starts and construction in Equation (2.3) should provide effective information for forecasting completions. Thus, I use the bottom row of Equation (2.3) to forecast completions:

$$\begin{aligned}\Delta f_t = \beta_{f,0} + \beta_{f,1}\mathbf{z}_{t-1} + \beta_{f,2}\Delta\mathbf{z}_{t-1} \\ + \beta_{f,3}\Delta\mathbf{x}_{t-2} + \cdots + \beta_{f,2+p}\Delta\mathbf{x}_{t-1-p} + \varepsilon_{f,t}.\end{aligned} \tag{2.4}$$

In contrast, because completions and construction lag starts, the lags of completions and construction in Equation (2.3), while necessary for maintaining the multicointegration relationship among the variables, may not be sufficient for producing good short-term forecasts of starts. Because of this, I add distributed lags of changes in one-unit structures authorized, Δa_t, and changes in one-unit structures authorized but not started, $\Delta a_{2,t}$, to the top row of Equation (2.3). As with construction, starts and completions, structures authorized and authorized but not started are monthly data series reported by the Census Bureau. They are measures of the number of buildings that have been authorized by permit for construction and are useful leading indicators because the Census uses building permit information as the basis for its survey of construction, which is the survey that the Census uses to measure starts. The econometric logic is as follows. The top row of Equation (2.3) is

$$\begin{aligned}\Delta s_t = \beta_{s,0} + \beta_{s,1}\mathbf{z}_{t-1} + \beta_{s,2}\Delta\mathbf{z}_{t-1} \\ + \beta_{s,3}\Delta\mathbf{x}_{t-2} + \cdots + \beta_{s,2+p}\Delta\mathbf{x}_{t-1-p} + \varepsilon_{s,t}.\end{aligned} \tag{2.5}$$

If the shock in this row can be written as

$$\begin{aligned}\varepsilon_{s,t} = \gamma_0\Delta a_t + \cdots + \gamma_q\Delta a_{t-q} \\ + \gamma_{2,0}\Delta a_{2,t} + \cdots + \gamma_{2,q}\Delta a_{2,t-q} + \eta_t,\end{aligned} \tag{2.6}$$

where the variance of η_t is less than that of $\varepsilon_{s,t}$, then the distributed lags of units authorized and units authorized but not started will improve the forecasts of starts. Thus, I use

$$\begin{aligned}\Delta s_t =& \beta_{s,0} + \beta_{s,1}\mathbf{z}_{t-1} + \beta_{s,2}\Delta\mathbf{z}_{t-1} \\ &+ \beta_{s,3}\Delta\mathbf{x}_{t-2} + \cdots + \beta_{s,2+p}\Delta\mathbf{x}_{t-1-p} \\ &+ \gamma_0\Delta a_t + \cdots + \gamma_q\Delta a_{t-q} + \gamma_{2,0}\Delta a_{2,t} + \cdots + \gamma_{2,q}\Delta a_{2,t-q} + \eta_t\end{aligned} \tag{2.7}$$

to forecast starts. To make this equation usable, I need the forecasts $a_{t|t-1}$ and $a_{2,t|t-1}$. To get these, I use AR(1) specifications for both a_t and $a_{2,t}$:

$$a_t = \delta_{1,0} + \delta_{1,1}a_{t-1} + \xi_{1,t} \tag{2.8}$$

and

$$a_{2,t} = \delta_{2,0} + \delta_{2,1} a_{2,t-1} + \xi_{2,t}. \tag{2.9}$$

2.3.2 Forecasting Construction

Given the forecasts of one-unit starts and completions, I use

$$c_{t|t-1} = s_{t|t-1} - f_{t|t-1} + c_{t-1}, \tag{2.10}$$

where the subscript $t|t-1$ denotes the forecast of period t on period $t-1$ information, to generate a forecast of one-unit construction. Because Equation (2.10) naturally lends itself to iterative forecasting, I construct the multi-step ahead forecasts iteratively. First, I use $a_{t|t-1}$ and $a_{2,t|t-1}$ from the initial forecast to generate the forecasts $a_{t+1|t-1}$ and $a_{2,t+1|t-1}$ using Equations (2.8) and (2.9). Second, I use $a_{t+1|t-1}$ and $a_{2,t+1|t-1}$ along with all one-step ahead forecasts to generate the forecast $s_{t+1|t-1}$ from Equation (2.7). Third, I use the forecasts $s_{t|t-1}$, $c_{t|t-1}$ and $f_{t|t-1}$ to generate $f_{t+1|t-1}$ from Equation (2.4). Fourth, given $s_{t+1|t-1}$ and $f_{t+1|t-1}$, I produce $c_{t+1|t-1}$ from

$$c_{t+1|t-1} = s_{t+1|t-1} - f_{t+1|t-1} + c_{t|t-1},$$

which is Equation (2.10) moved forward by one time period. This procedure can be repeated as many times as necessary to produce forecasts j-steps ahead.

2.3.3 Forecasting Residential Investment

Because residential investment is measured at a quarterly frequency but one-unit construction is measured at a monthly frequency, I relate residential investment to the quarterly average of construction as in Figure 2.2. This is the natural choice as quarterly residential investment puts equal weight on all months. I define

$$\bar{c}_{\tau|t-1} = \frac{c_{t+2|t-1} + c_{t+1|t-1} + c_{t|t-1}}{3}, \tag{2.11}$$

so that $\bar{c}_{\tau|t-1}$ is the one-step ahead forecast of average quarterly of construction. For notational purposes, I use τ to denote the current quarter and t to denote the first month of the current quarter.[9] For k-quarters ahead, I define

$$\bar{c}_{\tau+k|t-1} = \frac{c_{t+3k+2|t-1} + c_{t+3k+1|t-1} + c_{t+3k|t-1}}{3}. \tag{2.12}$$

As noted in Section 2.2, single family residential investment is highly correlated with total residential investment, and its contribution to total residential investment growth is large. Thus, instead of using a two-step approach where I use one-unit construction to forecast single family residential investment and then single family residential investment to forecast total residential investment, I use one-unit construction to forecast total residential investment directly. That is, I use

$$\Delta \ln(RI_{\tau+k|t-1}) = \theta_0 + \theta_1 \Delta \ln(\bar{c}_{\tau+k|t-1}) + \zeta_\tau, \tag{2.13}$$

[9] This implicitly assumes that the new residential construction data used in forecasts in quarter τ runs through the last month of the previous quarter. As discussed in Section 2.5, this is the appropriate timing for comparisons against the SPF.

where RI_τ is total residential investment in quarter τ.

2.4 Alternative Forecasting Models

In addition to the ECM described in Section 2.3, I consider four additional forecasting models. First, I consider a model that treats the natural log of residential investment as a random walk, which takes the form

$$\Delta \ln(RI_\tau) = \epsilon_\tau. \tag{2.14}$$

This model forecasts residential investment growth to be zero at all forecast horizons and will give an indication of how useful the more complex forecasting models are.

Second, I consider a univariate AR model of the form

$$\Delta \ln(RI_\tau) = \theta_0 + \theta_1 \Delta \ln(RI_{\tau-1}) + \cdots + \theta_p \Delta \ln(RI_{\tau-p}) + \epsilon_\tau. \tag{2.15}$$

I include this model because it often serves as a benchmark for macroeconomic forecasting comparisons. For example, Chauvet and Potter (2013) use an AR(2) model as a benchmark to forecast GDP growth.

The third and fourth models that I consider are VARs of the form

$$\Delta \mathbf{Y}_\tau = \alpha_0 + \alpha_1 \Delta \mathbf{Y}_{\tau-1} + \cdots + \alpha_p \Delta \mathbf{Y}_{\tau-p} + \epsilon_\tau, \tag{2.16}$$

and

$$\mathbf{Y}_\tau = \alpha_0 + \alpha_1 \mathbf{Y}_{\tau-1} + \cdots + \alpha_p \mathbf{Y}_{\tau-p} + \epsilon_\tau, \tag{2.17}$$

where $\mathbf{Y}_\tau = [\ln(RI_\tau), \ln(s_\tau), \ln(a_\tau), \ln(a_{2,\tau}), \ln(c_\tau), \ln(f_\tau)]'$. Equation (2.16) is a differenced vector autoregression (DVAR), and Equation (2.17) is a levels vector autoregression (LVAR). In the spirit of Hoffman and Rasche (1996), these models contain the same variables as the ECM;[10] however, they model the time series properties of the variables differently. If any of the variables are cointegrated, then the DVAR cannot account for the long-run equilibrium relationship and is misspecified. The LVAR can account for this relationship, but it does not explicitly impose the stock-flow structure from Equation (2.2). This creates a trade-off between the ECM and the LVAR model. If the stock-flow model is a good approximation of the true data generating process (DGP) of residential investment, then the ECM will have less estimation error. However, if it is a poor approximation, then the LVAR model will have more flexibility to estimate the true DGP.

To estimate the VARs, I convert s_t, a_t, $a_{2,t}$, c_t and f_t from monthly to quarterly frequencies by selecting the last month of the quarter as the quarterly observation. This choice produces slightly lower RMSPEs than averaging the monthly observations over each quarter. However, either choice imposes a restriction on the data prior to estimating the model. In contrast, the ECM in the previous section does not impose such restrictions. The first two steps of the ECM take full advantage of the monthly Census data, and it converts to a quarterly frequency only after making the forecasts of construction. Thus, comparing the VARs to the

[10]To be precise, it should be noted that the DVAR and LVAR include lags of residential investment while the ECM does not.

ECM indicates the value of a more flexible timing structure as well as explicitly imposing the stock-flow structure. The VARs also provide models in addition to the ECM that indicate the usefulness of including s_t, a_t, $a_{2,t}$, c_t and f_t when forecasting residential investment.

2.5 Data

To evaluate the predictive accuracy of the models in Sections 2.3 and 2.4, I compare their forecasts to the mean SPF forecasts and the Federal Reserve's Greenbook forecasts. I use the mean SPF forecast because it produces modestly smaller RMSPEs than the median. The SPF is published quarterly and produces forecasts for the current quarter, τ, and for each of the following four quarters. I will denote these forecasts by $\tau + k$ where $k = 0, 1, 2, 3, 4$ indicates the forecast horizon. The SPF's first residential investment forecast was in 1981:Q3, so I use forecast vintages from 1981:Q3 to 2013:Q2 for the forecast evaluation sample. This yields a sample size of $128 - k$ for each forecast horizon.

The SPF reports are maintained by the Federal Reserve Bank of Philadelphia and released in the middle of their respective quarters. For example, the 2013:Q1 SPF was released on February 15, 2013. This gives forecasters in the SPF access to the BEA's advance report of the national income and product accounts (NIPA) for the previous quarter and access to all of the Census Bureau's new construction reports for the previous quarter. For example, in the first quarter of each year, the SPF forecasters will have new construction reports through December of the previous year.

To make the model forecasts comparable to the SPF, I use real-time data with the same timing of information available to the SPF. That is, for any forecast quarter τ, I only use the residential investment and new construction report data through quarter $\tau - 1$.[11] The Federal Reserve Bank of Philadelphia maintains a real-time data set of residential investment, and the Federal Reserve Bank of St. Louis maintains a real-time data set of one-unit structures started. I collected real-time data for one unit structures authorized, one-unit structures authorized but not started, one-unit structures under construction and one-unit structures completed. Since April 2001, these data are available in the Census Bureau's new residential construction reports. Prior to April 2001, housing units authorized, authorized but not started, and started are from the Census Bureau's C20 reports, and units completed and under construction are from the Census Bureau's C22 reports.[12]

Unlike the SPF, Greenbook forecasts are not produced at a quarterly frequency. Rather, the Fed produces Greenbook eight times a year at roughly 6- to 7-week intervals. The Federal Reserve Bank of Philadelphia maintains a data set of Greenbook forecasts that roughly corresponds to the timing of SPF forecasts, and I use this data set for forecast comparisons. Further, the Fed only releases Greenbook forecasts with a 5-year lag, so the last available Greenbook vintage is in 2007. This yields a sample size of 106 for Greenbook comparisons. Finally, the Greenbook forecasts are presented at annualized rates. I divide by four to convert to quarterly forecasts.

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[11] The one exception is 1996:Q1. Due the federal government's shutdowns in late 1995 and early 1996, data from the Census Bureau were only available through November 1995, and data from the BEA were only available through 1995:Q3.

[12] Historically, the C22 reports were released about two weeks after the C20 report. However, all C22 reports from the previous quarter were available for the SPF.

2.6 Model Estimation and Forecast Evaluation

I estimate all of the models by least squares, using a recursive sample where the initial estimation period is fixed and observations are added as they become available for each forecast vintage. Because housing units under construction are first available in January 1970, my initial estimations of the ECM use a sample of January 1970 to June 1981. For consistency, I also estimate the models in Section 2.4 on samples that begin in 1970. For all models, I use the seasonally adjusted data from the Census Bureau that was available at the time of the forecast vintage.[13] For Equations (2.4) and (2.7), I include 18 monthly lags of Δs_t, Δf_t, Δa_t and $\Delta a_{2,t}$. The ECM works best with at least one year's worth of lags, and the results displayed below are quantitatively similar for between 15 and 21 monthly lags. I use two quarterly lags for the AR model and one quarterly lag for both VAR models. Forecast accuracy of the AR model is similar with between one and three lags and deteriorates with additional lags. The forecast accuracy of both VARs deteriorates with more than one lag.

I use squared prediction errors to compare the forecasts of the ECM to the other models, the SPF and the Greenbook, treating the BEA's most recent NIPA data as the true realization of residential investment. Define $e_{1,\tau+k}$ and $e_{2,\tau+k}$ to be the prediction errors of the ECM and a competing forecast made in quarter τ with forecast horizon k. Then, $d_{\tau+k} = e^2_{1,\tau+k} - e^2_{2,\tau+k}$ is the difference of their square errors. Because the ECM is non-nested with the AR model, DVAR model, LVAR model, SPF and Greenbook, I follow Diebold and Mariano (1995) and West (1996) (DMW) to compare the squared forecast errors. The null hypothesis is $E(d_{\tau+k}) = 0$, and the alternative hypothesis is $E(d_{\tau+k}) \neq 0$. The test statistic

[13] The Census Bureau does not seasonally adjust units authorized but not started. To seasonally adjust this series, I use the exponential smoothing function in RATS version 8 with a multiplicative seasonal for each data vintage.

is

$$S_k = \frac{\bar{d}_k}{[(P-k)^{-1}\hat{V}_k]^{1/2}}, \tag{2.18}$$

where P is the number of forecasts, $\bar{d}_k = (P-k)^{-1}\sum_{\tau=1}^{P-k} d_{\tau+k}$ and $\hat{V}_k = \hat{\gamma}_{k,0} + 2\sum_{j=1}^{k-1}\hat{\gamma}_{k,j}$ with $\hat{\gamma}_{k,j} = (P-k)^{-1}\sum_{\tau=1+j}^{P-k-j}(d_{\tau+k} - \bar{d}_k)(d_{\tau+k-j} - \bar{d}_k)$.[14]

Because the RW model is nested in the ECM,[15] I follow Clark and West (2006) and use an adjusted statistic to compare the difference in squared prediction errors between the ECM and RW model. For the adjusted test statistic, I first define $d_{t+k}^{adj} = (e_{1,\tau+k}^2 - \hat{y}_{1,\tau+k}^2) - e_{2,\tau+k}^2$, where $\hat{y}_{1,\tau+k}$ is the forecast from the ECM. Next, the null hypothesis is $E(d_{\tau+k}^{adj}) = 0$ and the alternative is now one-sided $E(d_{\tau+k}^{adj}) < 0$. Finally, I use the test statistic in Equation (2.18) where all calculations replace $d_{\tau+k}$ with $d_{\tau+k}^{adj}$. Clark and West (2007) show that for recursive estimation, this method yields critical values that are approximately standard normal.

Table 2.2 presents the results of the forecast evaluations over the entire evaluation sample. The first row displays the RMSPE of the ECM, and each subsequent pair of rows displays a comparison of the ECM to a competing forecast. The "Ratio" rows display the ratio of the ECM's RMSPE to the competing forecast's RMSPE, so that a number less than one indicates that ECM's RMSPE is smaller. The "DMW" rows display the corresponding Diebold and Mariano (1995) and West (1996) statistic from Equation (2.18), and "DMW-adj" for the RW model is a DMW statistic with the Clark and West (2006) adjustment. Overall, Table 2.2 shows that the ECM produced lower RMSPEs than all of the competing forecasts at all forecast horizons over the 1981:Q3 to 2013:Q2 sample. The ECM produces

[14] All results are robust to estimating $\hat{V}$ with Newey and West (1987) where lags are selected according to Newey and West (1994).

[15] Setting $\theta_0 = \theta_1 = 0$ in Equation (2.13) reduces the ECM to a random walk forecast as in Equation (2.14).

Table 2.2: Forecast Evaluation for τ in 1981:Q3 to 2013:Q2

	$\tau+0$	$\tau+1$	$\tau+2$	$\tau+3$	$\tau+4$
ECM	2.38	2.96	3.12	3.28	3.41
RW Ratio	0.58***	0.73***	0.79**	0.84**	0.87*
DMW-adj Statistic	-5.25	-3.08	-2.30	-2.05	-1.55
AR Ratio	0.70***	0.78*	0.81*	0.83*	0.86
DMW Statistic	-2.93	-1.94	-1.65	-1.70	-1.31
DVAR Ratio	0.91	0.80***	0.81*	0.83	0.86
DMW Statistic	-1.20	-3.54	-1.85	-1.54	-1.31
LVAR Ratio	0.76***	0.72***	0.71***	0.77***	0.83**
DMW Statistic	-3.67	-4.78	-3.79	-2.70	-1.96
SPF Ratio	0.94	0.90	0.87*	0.90*	0.92
DMW Statistic	-0.67	-1.28	-1.72	-1.70	-1.24

Notes: The first row displays the RMSPE of the ECM. Each subsequent pair of rows display the ratio of the ECM's RMSPE to that of a competing forecast, and the corresponding Diebold and Mariano (1995) and West (1996) (DMW) statistic from Equation (2.18). The competing forecasts are from the the random walk (RW) model, the univariate autoregression (AR) model, the differenced VAR (DVAR) model, the levels VAR (LVAR) model, and the Survey of Professional Forecasters (SPF). The RW model uses a one-sided test with an adjusted DMW statistic from Clark and West (2006). All other comparisons use two-sided tests. A ratio less than one indicates a smaller RMSPE for the ECM. (***),(**) and (*) indicate that RMSPEs are different at significance levels of 1%, 5% and 10%, respectively.

its largest and most statistically significant RMSPE reductions on the RW and AR forecasts in the current quarter. In contrast, it produces its largest and most statistically significant RMSPE reductions on the DVAR, LVAR and SPF forecasts at multi-step horizons.

The ECM's improvements over the DVAR and LVAR at multi-step horizons have two separate causes. First, the LVAR's forecasts have a large downward bias, while the ECM's do not. This bias is largest for $k = 1, 2$, leading to its especially poor performance at these horizons.[16] Second, the ECM's improvement upon the DVAR follows naturally from the timing of the error correction of starts and completions. When a shock hits the housing sector, starts respond more easily than completions because completions depend on the number of units currently under construction but starts do not. This generates a gap between starts and completions, leading to a change in construction via Equation (2.2). This change in construction leads to a change in completions, bringing completions back in line with starts and stabilizing construction. Census data show that construction of a single family house averages just over 6 months from start to completion, with slightly longer construction lengths around recessions. This suggests that the error correction process should average a little over two quarters. Because the DVAR does not account for this error correction process, it misspecifies the evolution of starts, completions and construction. Thus, the ECM's largest RMSPE improvements over the DVAR come at multi-step horizons, and especially at one- and two-quarter forecast horizons.

Table 2.2 also displays two other results of note about the conventional forecasting models. First, for near-term forecasts, the DVAR model improves upon the AR model, which improves the RW model. For the current-quarter forecast, the DVAR model reduces the RMSPE of the AR model by 23%, and the AR model reduces the RMSPE of the RW model by 17%. These results suggest that including a simple time-series structure and using the Census data help forecast residential investment. However, the second result of note in Table

[16]The mean prediction error (MPE) of LVAR is -1.5 percent or larger in magnitude at all forecast horizons, with MPEs of -1.97 percent and -1.95 percent at $k = 1$ and $k = 2$, respectively. These MPEs are statistically different from zero at a 1% level for $k = 0, 1, 2, 3$ and at a 5% level for $k = 4$. In contrast, the MPEs for the ECM are between -0.16 and -0.22 percent while the MPEs of the DVAR are between -0.15 and -0.4 percent. The MPEs of the ECM are not statistically distinct from zero at any forecast horizon, and only the current quarter MPE of the DVAR is statistically different from zero at conventional levels of significance ($p = 0.095$). MPEs from the RW, AR, SPF and Greenbook are not statistically distinct from zero at any forecast horizon.

Table 2.3: Forecast Evaluation for τ in 1981:Q3 to 2007:Q4

	$\tau+0$	$\tau+1$	$\tau+2$	$\tau+3$	$\tau+4$
ECM	2.24	2.63	2.77	3.03	3.22
SPF Ratio	0.94	0.85	0.84	0.91	0.94
DMW Statistic	-0.66	-1.49	-1.62	-1.26	-0.95
GB Ratio	1.09	0.97	0.92	0.94	0.92
DMW Statistic	1.16	-0.29	-1.01	-1.12	-1.04

Notes: The first row displays the RMSPE of the ECM. Each subsequent pair of rows display the ratio of the ECM's RMSPE to that of a competing forecast, and the corresponding Diebold and Mariano (1995) and West (1996) (DMW) statistic from Equation (2.18). A ratio less than one indicates a smaller RMSPE for the ECM. The competing forecasts are the Survey of Professional Forecasters (SPF) and the Greenbook (GB).

2.2 is that the benefits of including a time-series structure and using the Census data are short-lived. For forecast horizons $k = 2, 3, 4$, the AR and DVAR models yield RMSPEs that are essentially equivalent, and both of these models perform comparably to the RW model at horizons $k = 3, 4$.

Table 2.3 displays the comparisons of the ECM to the SPF and Greenbook forecasts. Due to the 5-year lag in the release of the Greenbook forecasts, Table 2.3 only includes forecasts with vintages that run through 2007. For the current-quarter forecast, the Greenbook has the lowest RMSPE; however, the null hypothesis of equal RMSPE between the Greenbook and the ECM cannot be rejected.[17] This nowcast advantage for the Greenbook has also been noted for GDP in previous research. Sims (2002a) and Faust and Wright (2009) argue that the Fed's effort to mirror the BEA's data construction process and use of subjective forecasts allows it to accurately measure the current state of the economy. For all other

[17] In contrast, the DMW statistic between the SPF and the Greenbook is 1.71, suggesting that the null hypothesis of equal RMSPE can be rejected at the 10% level for these two forecasts.

horizons, however, the ECM produces a lower RMSPE than the Fed, and this multi-step forecasting advantage for the ECM is consistent with the results in Table 2.2.

In addition to the results displayed in Tables 2.2 and 2.3, there are two other important results. First, the ECM produces its largest RMSPE improvements at the beginning and at the end of the evaluation sample, when the growth rate of residential investment is most volatile. Second, the ECM and the DVAR model capture the large increase in residential investment from 2002:Q1 to 2005:Q4 and the sharp decline in residential investment from 2006:Q1 to 2009:Q2 better than the SPF. I discuss these two results in turn.

2.6.1 Forecast Evaluation in the Beginning, Middle and End of the Evaluation Sample

Table 2.4 displays the RMSPEs of the ECM where the forecast vintage τ is in an early sample, 1981:Q3 to 1983:Q4, a middle sample, 1984:Q1 to 2005:Q4, or a late sample, 2006:Q1 to 2013:Q2.[18] In addition, it displays the ratio of the ECM's RMSPE to that of the other forecasts.[19] It shows that the EMC's RMSPE reductions predominantly occur in the early sample and in the late sample.

This result is important for three reasons. First, the middle sample is a period of relative economic tranquillity. In contrast, the early sample includes the Volker recession and its corresponding rapid recovery, and the late sample includes the housing collapse that began

[18]Even though τ falls into one of listed sample periods, I allow the multi-step ahead forecasts $\tau + k$ to fall into a later sample.

[19]Becuase Greenbook forecasts are not available through the end of 2013:Q2, I do not include them in the 2006:Q1 to 2013:Q2 sample.

Table 2.4: Forecast Comparison Across Evaluation Samples

	$\tau + 0$	$\tau + 1$	$\tau + 2$	$\tau + 3$	$\tau + 4$
1981:Q3 to 1983:Q4					
ECM	3.33	4.07	4.40	5.20	4.69
RW Ratio	0.38	0.48	0.57	0.70	0.63
AR Ratio	0.59	0.53	0.58	0.69	0.63
DVAR Ratio	0.83	0.59	0.59	0.70	0.60
LVAR Ratio	1.07	0.73	0.66	0.80	0.89
SPF Ratio	0.67	0.62	0.65	0.83	0.85
GB Ratio	0.95	0.72	0.78	0.90	0.77
1984:Q1 to 2005:Q4					
ECM	2.11	2.33	2.33	2.48	2.62
RW Ratio	0.86	0.95	0.93	0.97	1.00
AR Ratio	0.92	1.00	0.97	0.98	1.01
DVAR Ratio	0.85	0.86	0.95	0.98	1.01
LVAR Ratio	0.74	0.62	0.59	0.64	0.71
SPF Ratio	1.18	1.09	1.01	1.03	1.04
GB Ratio	1.15	1.14	1.01	1.02	1.06
2006:Q1 to 2013:Q2					
ECM	2.71	4.03	4.46	4.45	4.87
RW Ratio	0.51	0.75	0.83	0.83	0.91
AR Ratio	0.56	0.80	0.85	0.81	0.88
DVAR Ratio	1.13	0.87	0.86	0.84	0.89
LVAR Ratio	0.72	0.86	0.91	1.00	1.00
SPF Ratio	0.87	0.94	0.90	0.83	0.87

Notes: Each sample period shows the RMSPE for the ECM. In addition, the ratio of the EMC's RMSPE to that of the other forecasts are displayed. The alternative forecasts are from a random walk (RW) model, a univariate autoregression (AR) model, a differences VAR (DVAR), a levels VAR (LVAR), the Survey of Professional Forecasters (SPF), and the Federal Reserve's Greenbook (GB). Due to sample restrictions, Ratio GB is not computed for 2006:Q1 to 2013:Q2.

in 2006 and the Great Recession of 2008-2009. During the middle sample, the standard deviation of percent growth in quarterly residential investment was 2.4, while the corresponding standard deviations in the early and late samples were 9.2 and 4.8, respectively. These fluctuations in volatility are also evident in the size of the RMSPEs presented in Table 2.4, all of which are larger in the early and late samples than in the middle sample. Thus, the ECM does best in periods of high volatility when accurate forecasting is difficult.

Second, the shocks that generate the high volatility in the early and late samples are different. During the early sample, tight monetary policy and high interest rates were quickly followed by large interest rates drops, which led to a large recession followed by a rapid recovery. In contrast, the late sample has a financial crisis, historically low interest and mortgage rates, and large government support for mortgage-backed securities. Despite these different shocks, the ECM performs well in both periods while maintaining a parsimonious information set and simple, linear relationships.

Third, the fact that the ECM outperforms the SPF in the late sample indicates that the ECM contributes to the current state of professional residential investment forecasting.

To understand the ECM's success in the early and late samples, it is informative to compare the ECM's results with the DVAR. In the early and late samples, the DVAR performs well in the current quarter, but its forecasts immediately deteriorate in following quarters. In contrast, no such deterioration occurs in the middle sample. As discussed above, because houses take multiple quarters to build, the forecast improvements from modelling error correction should come at multi-step horizons. In the tranquil middle sample, shocks to starts and completions were relatively small, limiting the forecasting value of error correction. Conversely, the early and late sample had large shocks to starts and completions and error correction proves highly informative for multi-step forecasts.

In contrast to the DVAR, the LVAR performs well in the early and late samples relative to the middle sample. In the middle sample, the LVAR's forecast bias greatly diminishes its forecasting quality. However, despite its bias, the LVAR has more accurate forecasts than the DVAR for $k = 2, 3, 4$ in the early and late samples. Again, this indicates that the long-run relationships among cointegrated variables are important for multi-step forecasts of residential investment in the early and late samples.

Comparing the VAR models to the univariate models, there are two results of interest. First, the simple RW and AR models perform modestly better than the larger DVAR and LVAR models in the middle sample. The VAR models, as well as the ECM, use the Census's one-unit construction data. This data is more volatile than total residential investment and likely introduces excessive noise into the forecasts during this economically tranquil period. This noise fades at longer forecast horizons, and all of the forecasts other than the LVAR have similar accuracy at horizons $k = 3, 4$. Second, the DVAR and LVAR forecast well relative to the RW and AR models in the early and late samples, indicating that the one-unit construction data improves upon forecasts in volatile economic periods. These two results suggest that a tradeoff exists in using the Census's one-unit construction data. It improves forecasting accuracy when residential investment is volatile, but introduces excess noise when residential investment is tranquil.

2.6.2 Forecast Analysis After 2002

Because residential investment data is only available with a lag, an important role of any forecasting model is to estimate the current state of residential investment. From 2002:Q1 to 2005:Q4, both the SPF and Greenbook nowcasts systematically understated the growth rate of residential investment. During the 2006:Q1-2009:Q2 bust, the SPF systematically overstated it. In contrast, the ECM and DVAR models give a much better estimate of the housing boom and bust.

Average quarterly growth in residential investment was 1.94% from 2002:Q1 to 2005:Q4. For this sample, the average current-quarter forecasts for the SPF and Greenbook are 0.48% and 0.77%, respectively. In contrast, the ECM and DVAR models average 1.61% and 1.95%, respectively. For the 2006:Q1 to 2009:Q2 sample, average quarterly residential investment growth was -6.05%, but the average SPF nowcast was only -3.70%. In contrast, the ECM and DVAR model averaged -6.36% and -6.16%, respectively.[20] Because the common feature of the ECM and DVAR model is their use of the Census's one-unit construction data, these results suggest that focusing on one-unit construction would have helped professional forecasters better estimate the state of residential investment during the 2002-2005 housing boom and the 2006-2009 collapse.

2.7 Conclusion

This paper fills in the sparse literature on forecasting residential investment by making two contributions. First, it proposes a forecasting model of residential investment based on the multicointegration relationship among housing starts, completions and units under construction. Second, it compares forecasts from this proposed model to a random walk model, a univariate AR model, a differenced VAR model, a levels VAR model, the SPF and the Federal Reserve's Greenbook.

The model proposed in this paper is built upon on three features of residential investment

[20] Greenbook data is not yet available for the entire 2006:Q1 to 2009:Q2 sample.

and construction: single family residential investment drives the fluctuations in total residential investment, fluctuations in one-unit structures under construction correlate highly with single family residential investment, and starts, completions and units under construction follow a stock-flow relationship. The model proceeds in three steps. First, it forecasts one-unit structures started and completed with a multicointegration error correction model. Second, it uses these forecasts of starts and completions to forecast one-unit structures under construction. Third, it uses the forecasts of one unit construction to forecast total residential investment growth.

On an evaluation sample period of 1981:Q3 to 2013:Q2, the ECM produces smaller RMSPEs than the other models and the SPF at all forecast horizons, and relative to the VARs and the SPF, it generates the biggest RMSPE reductions at multi-step forecast horizons. On an evaluation sample period of 1981:Q3 to 2007:Q4, the Greenbook produces the most accurate nowcasts, but the ECM produces the most accurate multi-step forecasts. Two other results of note are that the ECM and VAR models perform best during the volatile economic periods of 1981:Q3 to 1983:Q4 and 2006:Q1 to 2011:Q4, and that the ECM and differences VAR give a much better measure of the state of the housing boom and bust from 2002:Q1 to 2009:Q2 than the SPF.

The ECM's accurate nowcasts in 2002-2009 and good overall performance in 2006-2013 demonstrate its contribution to the state of residential investment forecasting. Further, the success of the proposed model suggests that multicointegrated error correction models can be useful for forecasting. Future research should examine their effectiveness in forecasting other stock-flow variables, such as inventories, wealth and employment.

Chapter 3

Has the Impact of the Federal Funds Rate Increased?

3.1 Introduction

In the past decade, researchers have collected and studied a wealth of micro price data. As a result, economists have developed a number of stylized facts that describe micro pricing behavior (Nakamura and Steinsson, 2008; Klenow and Malin, 2010). This paper concentrates on the fact that goods exhibit greater price flexibility than services. Using United States CPI data from January 1988 to 2009, Klenow and Malin (2010) show that the mean and median price durations are smaller for both durable and nondurable goods than for services.[1] Specifically, the average posted price durations for durable goods, nondurable goods and services are 1.0, 1.9 and 3.1 quarters, respectively.

[1] The data source used by Klenow and Malin (2010) is the CPI Research Database, which is maintained by the U.S. Bureau of Labor Statistics. The database contains prices for all categories of goods and services other than shelter, which includes about 70% of consumer expenditure.

In addition to this nominal price heterogeneity across sectors, it is also the case that the sectoral composition of the United States has changed substantially over the past 50 years. Figure 3.1 displays three plots of the evolution of the goods sector and the services sector in the United States. Plot (a) displays the personal consumption expenditures (PCE) on goods and services relative to total PCE. From the first quarter of 1959 to the last quarter of 2010, goods have fallen from 54.7% of PCE to 33.4% of PCE, while services have risen from 45.2% to 66.6%. Plot (b) displays final sales of goods and services to total final sales. Similar to PCE, final sales on goods have fallen from 43.0% of total final sales to 27.8% of total final sales, while services have risen from 44.4% to 65.3%.[2] Finally, plot (c) displays the ratios of goods-producing employment and private service-providing employment to total private employment. The percentage of private employees producing goods has fallen from 42.4% to 16.5%, while percentage of private employees providing services has increased from 57.6% to 83.5%.

Combined, the increase in the relative size of the services sector from 1959 to 2010 and the fact that services are stickier than goods suggests that overall nominal prices in the United States have become stickier over the past 50 years. This general trend has been supported by the micro price literature. Nakamura and Steinsson (2008) show that both mean and median price durations increased from the 1988 to 1997 time interval to the 1998 to 2005 time interval.[3] This duration increase holds regardless of whether or not their data sample includes substitutions and sales. However, the Nakamura and Steinsson (2008)

[2]The ratios of finals goods to total final sales and the final sales of services to total final sales do not sum to one. This is because final sales of structures are also included in total final sales.

[3]As with Klenow and Malin (2010), the data source used by Nakamura and Steinsson (2008) is the CPI Research Database. It includes prices for all categories of goods and services other than shelter, which includes about 70% of consumer expenditure.

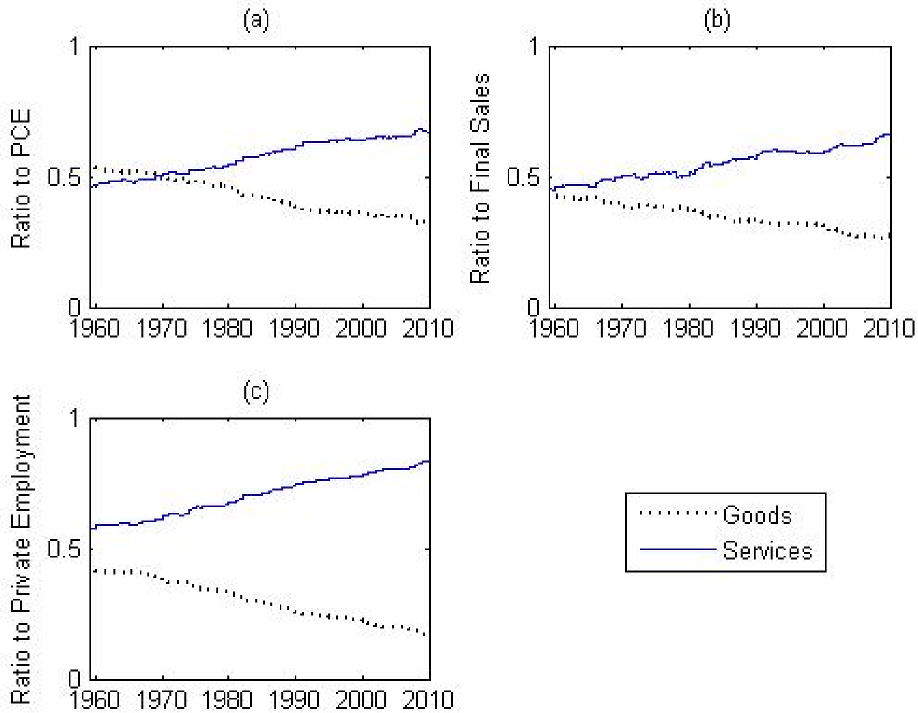

Figure 3.1: Plot (a) displays the personal consumption expenditures (PCE) on goods and services relative to total PCE. Plot (b) displays final sales of goods and services to total final sales. Plot (c) displays goods-producing employment and private service-providing employment to total private employment.

study does not include prices prior to 1988. In a more extensive study, Wulfsberg (2009) uses Norwegian data from 1975 to 2004 to show that both mean and median price durations increased from the 1975 to 1989 time period to the 1990 to 2004 time period.[4] Over this time period, Norway has experienced a relative increase in the services sector to the goods sector similar to that of the United States. In addition, over this time period, the macroeconomic inflationary environment in Norway was similar to that of the United States with high and volatile inflation from 1975 to 1985, ranging from 5% to 14%, and low and stable inflation

[4]The data source for Wulfsberg (2009) is Statistics Norway, whose database represents 73.9% of the Norwegian CPI on average.

from 1990 to 2004, ranging from 1% to 4%. This suggests that the macroeconomic pricing environments in the United States and Norway are comparable over these time periods.

In standard New Keynesian models, it is the nominal rigidities that allow changes in nominal interest rates to impact the real variables in the economy. Typically, the nominal rigidities in these models are assumed to be the same across all firms. Recently, economists have begun modelling economies with heterogeneous price rigidities (Aoki, 2001; Carvalho, 2006; Carvalho and Lee, 2011). However, these models have not examined what happens when the relative size of the sectors change. To examine how the increase in the relative size of the service sector impacts interest rate policy, I construct a New Keynesian model of the economy. This model follows Boivin and Giannoni (2006) so that labor is the only factor of production and consumer habit persistence and interest rate smoothing by the policy makers help match output and interest rate behavior observed in the data. In addition, I follow the timing structure of Boivin and Giannoni (2006) by assuming that consumers choose consumption and firms set prices one period in advance. This causes the structure of the economy be such that output and prices respond to interest rate shocks with a one period lag. This timing assumption allows interest policy shocks to be identified in an unrestricted vector autoregression (VAR) when the interest rate is placed last in the VAR ordering (Bernanke and Blinder, 1992).

My New Keynesian model deviates from Boivin and Giannoni (2006) in two ways. First, to address the difference in price adjustment behavior and the relative size of the goods sector versus the services sector, I allow firms to have different Calvo (1983) price change probabilities as developed in Carvalho (2006). Specifically, I split firms in the economy into two sectors and assume that the sectors have different price change probabilities and different expenditure shares implied by the utility function of the representative household. I then calibrate price changes and expenditure shares of each sector to match U.S. data on goods and services. Second, I do not allow firms to index their prices to inflation in periods where they do not re-optimize their prices. This is because, following an economic shock, indexation assumes that firms change their price every quarter, which contrasts with the results of Klenow and Malin (2010) discussed above. However, because inflation indexation is the feature that allows the model of Boivin and Giannoni (2006) to match empirical inflation behavior, my model does not characterize the impulse response of inflation to economic shocks well. For this reason, this paper's focus will be on the response of output to economic shocks.[5]

Within this framework, I show that when the relative size of service sector increases, a nominal interest rate shock has an increased impact on output. This model implies that output in recent time periods, when the relative size of services is large, should be more sensitive to interest rate shocks than in older time periods.

To test this implication, I estimate impulse response functions (IRFs) of output to Federal Funds rate shocks using both VAR and factor-augmented vector autoregression (FAVAR) methods on U.S. macroeconomic data in time periods 1959 to 1978 and 1983 to 2007. In contrast to theory, both the VAR and FAVAR estimations suggest that output is less sensitive to interest rate shocks in the recent time period, 1984 to 2007, than in the older time period, 1959 to 1978.

Finally, I examine interest rate policy changes, characterized by changes in the weights on a Taylor (1993) style interest rate rule, and show that policy changes consistent with Clarida,

[5]Larger size New Keynesian models are able to characterize the impulse responses of inflation without assuming indexation. However, these models include complications such as Calvo (1983) frictions in wages, capital adjustment costs and variable capacity utilization that distract from the focus of this paper. Christiano, Trabandt, and Walentin (2010) provide a thorough discussion.

Galí, and Gertler (2000) and Boivin and Giannoni (2006) can account for the dampened IRFs of output in the recent time period.

The rest of this chapter progresses as follows. Section 3.2 constructs a New Keynesian model of the economy, which implies that output in recent time periods should be more sensitive to interest rate shocks than in older time periods. Section 3.3 tests this implication with impulse response functions estimated with a VAR and FAVAR on United States economic data. Section 3.4 investigates the implications of changes in interest rate policy, and Section 3.5 concludes.

3.2 A Structural Model of the Economy

The economy is composed of a continuum of firms indexed by $i \in [0, 1]$. Each firm is a monopolist that produces a unique good and belongs to one of two sectors. Because the price change and expenditure share characteristics of these two sectors will be calibrated to match data on the goods and services sectors in the Unites States, I refer to these sectors as the goods sector (G) and the services sector (S). I denote the set of firms in each sector by $\mathcal{I}_k$ for $k \in \{G, S\}$, where $\mathcal{I}_G$ and $\mathcal{I}_S$ are measurable and have the property $\bigcup_{k\in\{G,S\}} \mathcal{I}_k = [0, 1]$. The measure of each set gives the mass of firms in each respective sector. I use n to denote the mass of firms in the goods sector and $1 - n$ to denote the mass of firms in the services sector.

All firms face nominal price rigidities. In a given period, each firm has a probability of changing its price as in Calvo (1983). As in Carvalho (2006), this probability is sector specific and given by α_k for $k \in \{G, S\}$. From the results in Klenow and Malin (2010), I assume that $\alpha_G \geq \alpha_S$ so that firms in the services sector change prices less frequently than firms in the goods sector.

The economy also has a representative household. This household provides labor to each firm to produce output and consumes a consumption bundle of goods and services. The household owns all of the firms, and any profits that the firms have at the end of the period are remitted back to the household in the form of dividends.

3.2.1 Households

The representative household has preferences given by

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(C_t - \tilde{\eta} C_{t-1})^{1-\sigma_C}}{1-\sigma_C} - \frac{\chi}{1+\sigma_H} \left(\int_0^1 H_t(i) di \right)^{1+\sigma_H} \right] \tag{3.1}$$

where $\beta \in (0,1)$ is the discount factor, C_t is the aggregate consumption bundle, $\sigma_C \in (0,1)$ drives the degree of relative risk aversion of current consumption,[6] $H_t(i)$ is the the amount of labor supplied to firm i, χ is the relative disutility of labor and σ_H is the inverse of the Frisch elasticity of labor supply. I assume that C_{-1} is given.

The parameter $\tilde{\eta} \in [0,1]$ governs the habit persistence of the household. Habit persistence is common in many large New Keynesian models (Christiano, Eichenbaum, and Evans, 2005; Smets and Wouters, 2007). Following Boivin and Giannoni (2006), I use habit persistence to help replicate the hump-shaped impulse response of output to interest rate shocks.

In each period, the household faces a budget constraint given by

$$P_t C_t + B_t = I_{t-1} B_{t-1} + \int_0^1 W_t(i) H_i(i) di + \int_0^1 D_i(i) di. \tag{3.2}$$

[6] Due to the habit persistence in this model, σ_C is not itself the degree of relative risk aversion. In the steady-state, when $C_t = C_{t+1} = \bar{C}$, then $-\frac{u_{11}}{u_1}\bar{C} = \frac{\sigma_C}{1-\tilde{\eta}}$, where $u(C_t, C_{t-1}) = \frac{(C_t - \tilde{C}_{t-1})^{1-\sigma_C}}{1-\sigma_C}$.

P_t is the price index of the consumption bundle. Even though there is no money in this model, I assume that P_t denotes nominal prices in currency units. Given this, $W_t(i)$ denotes the nominal wage rate paid by firm i, B_t denotes nominal bond holdings that accrue a gross nominal interest rate I_t and $D_t(i)$ is the nominal profit of firm i.

Following Carvalho (2006), I assume that household consumption is aggregated according to

$$C_t = \left[n^{\frac{1}{\phi}} C_{G,t}^{\frac{\phi-1}{\phi}} + (1-n)^{\frac{1}{\phi}} C_{S,t}^{\frac{\phi-1}{\phi}} \right]^{\frac{\phi}{\phi-1}}, \tag{3.3}$$

where $C_{G,t}$ and $C_{S,t}$ are the sectoral consumption bundles for the goods and services sectors, respectively. Here, $\phi > 1$ is the elasticity of substitution between the goods and services sectors.

Equation (3.3) implies that the price index P_t is given by

$$P_t = \left[n P_{G,t}^{1-\phi} + (1-n) P_{S,t}^{1-\phi} \right]^{\frac{1}{1-\phi}}, \tag{3.4}$$

where $P_{G,t}$ and $P_{S,t}$ are the sectoral price indexes for the respective sectoral consumption bundles. Additionally, Equation (3.3) implies that the demand functions for $C_{G,t}$ and $C_{S,t}$ are

$$\begin{aligned} C_{G,t} &= n \left(\frac{P_{G,t}}{P_t} \right)^{-\phi} C_t \\ C_{S,t} &= (1-n) \left(\frac{P_{S,t}}{P_t} \right)^{-\phi} C_t, \end{aligned} \tag{3.5}$$

given prices $P_{G,t}$, P_{St} and P_t, and given a level of total consumption C_t.

In each sector, consumption is aggregated according to

$$
\begin{aligned}
C_{G,t} &= \left[\left(\frac{1}{n}\right)^{\frac{1}{\phi}} \int_{\mathcal{I}_G} C_t(i)^{\frac{\phi-1}{\phi}} di\right]^{\frac{\phi}{\phi-1}} \\
C_{S,t} &= \left[\left(\frac{1}{1-n}\right)^{\frac{1}{\phi}} \int_{\mathcal{I}_S} C_t(i)^{\frac{\phi-1}{\phi}} di\right]^{\frac{\phi}{\phi-1}},
\end{aligned}
\tag{3.6}
$$

where $C_t(i)$ denotes the household's consumption of the output of firm i and $P_t(i)$ is the corresponding price. The equations in (3.6) imply that the sector price indexes are given by

$$
\begin{aligned}
P_{G,t} &= \left[\frac{1}{n} \int_{\mathcal{I}_G} P_t(i)^{1-\phi} di\right]^{\frac{1}{1-\phi}} \\
P_{S,t} &= \left[\frac{1}{1-n} \int_{\mathcal{I}_S} P_t(i)^{1-\phi} di\right]^{\frac{1}{1-\phi}}.
\end{aligned}
\tag{3.7}
$$

Additionally, the demand functions for $C_t(i)$ are

$$
\begin{aligned}
C_t(i) &= \frac{1}{n}\left(\frac{P_t(i)}{P_{G,t}}\right)^{-\phi} C_{G,t} \quad \text{for } i \in \mathcal{I}_G \\
C_t(i) &= \frac{1}{(1-n)}\left(\frac{P_t(i)}{P_{S,t}}\right)^{-\phi} C_{S,t} \quad \text{for } i \in \mathcal{I}_S,
\end{aligned}
\tag{3.8}
$$

given prices $P_t(i)$, $P_{G,t}$ and $P_{S,t}$, and given consumption levels $C_{G,t}$ and $C_{S,t}$.

The household takes all prices as given and maximizes utility in (3.1) subject to the budget constraints in Equation (3.2). In addition, I assume that the household chooses its consumption bundle one period in advance. This implies that the household chooses C_t based on information available in period $t-1$. This assumption is a weakening of Rotemberg and Woodford (1997) and Boivin and Giannoni (2006), which both assume that the household chooses consumption two periods in advance, and it will allow for identification of interest policy shocks in the empirical analysis in Section 3.3.

The first-order conditions with respect to C_t is

$$E_{t-1}\left[(C_t-\tilde{\eta}C_{t-1})^{-\sigma_C}-\beta\tilde{\eta}(C_{t+1}-\tilde{\eta}C_t)^{-\sigma_C}\right]=E_{t-1}[\Lambda_t P_t], \tag{3.9}$$

where I use $\beta^t\Lambda_t$ for the Lagrange multiplier for each period's budget constraint.

The first-order condition for the choice of B_t is given by

$$\Lambda_t=\beta I_t E_t\Lambda_{t+1}. \tag{3.10}$$

The first-order conditions for labor supplied to firms i and j are

$$\chi\left(\int_0^1 H_t(\tilde{i})d\tilde{i}\right)^{\sigma_H}=\Lambda_t W_t(i)$$
$$\chi\left(\int_0^1 H_t(\tilde{i})d\tilde{i}\right)^{\sigma_H}=\Lambda_t W_t(j).$$

These equations imply that $W_t(i)=W_t(j)$ so that the wage is the same across all firms. I denote the common wage as W_t. Then, the first-order conditions for labor reduce to

$$\chi\left(\int_0^1 H_t(i)di\right)^{\sigma_H}=\Lambda_t W_t. \tag{3.11}$$

Additionally, combining Equations (3.5) and (3.8) yields

$$C_t(i)=\left(\frac{P_t(i)}{P_t}\right)^{-\phi}C_t \tag{3.12}$$

for all i. Equation (3.12) is the demand curve for $C_t(i)$ given prices $P_t(i)$ and P_t and given a level of total consumption C_t.

3.2.2 Firms

Firm i in sector $k \in \{G, S\}$ hires labor and produces its variety of output according to the following linear technology:

$$Y_t(i) = Z_{k,t} N_t(i). \tag{3.13}$$

$Y_t(i)$ is the output of firm i, $N_t(i)$ is the corresponding labor input and $Z_{k,t}$ for $k \in \{G, S\}$ is a covariance stationary stochastic process representing sector specific technology shocks. All firms and the representative household are price takers in the labor market.

Firms choose their prices in order to maximize profits. As with the household's consumption decision, I assume that firms set their price one period in advance. Because not all firms can adjust their prices in a given period, I use $X_t(i)$ to denote the price choice of firms that are able to adjust. Therefore, firm i in sector $k \in \{G, S\}$ sets $X_t(i)$ by solving

$$\begin{aligned} &\max E_0 \sum_{t=0}^{\infty} Q_{0,t}(1-\alpha_k)^t [X_t(i) Y_t(i) - W_t N_t(i)] \\ &\text{s.t. } Y_t(i) = Z_{k,t} N_t(i) \quad \text{and} \quad Y_t(i) = \left(\frac{X_t(i)}{P_t}\right)^{-\phi} Y_t. \end{aligned} \tag{3.14}$$

The first constraint in the firm's problem in (3.14) reflects the technology constraint in Equation (3.13). The second constraint in (3.14) corresponds to the demand for the firm's output in Equation (3.12). The stochastic nominal discount factor between periods 0 and t used to price firms' profits, $Q_{0,t}$, is given by

$$Q_{0,t} = \beta^t \left(\frac{(C_{t+1} - \tilde{\eta} C_t)^{-\sigma_C} - \beta \tilde{\eta} (C_{t+2} - \tilde{\eta} C_{t+1})^{-\sigma_C}}{(C_0 - \tilde{\eta} C_{-1})^{-\sigma_C} - \beta \tilde{\eta} (C_1 - \tilde{\eta} C_0)^{-\sigma_C}} \right) \frac{P_0}{P_t}.$$

The first-order condition of (3.14) yields

$$X_t(i) = \frac{\phi}{\phi - 1} \frac{E_{t-1} \sum_{s=t}^{\infty} Q_{t,s}(1-\alpha_k)^{s-t} P_s^{\phi} Y_s W_s Z_{k,s}^{-1}}{E_{t-1} \sum_{s=t}^{\infty} Q_{t,s}(1-\alpha_k)^{s-t} P_s^{\phi} Y_s} \tag{3.15}$$

for firm i in sector $k \in \{G, S\}$.

The distribution of future wages conditional on time t information is the same for all firms that change prices in t. Therefore, they all charge the same nominal price $X_t(i)$. This implies that for each sector, the price index evolves according to

$$P_{k,t} = [\alpha_k X_{k,t}^{1-\phi} + (1-\alpha_k) P_{k,t-1}^{1-\phi}]^{\frac{1}{1-\phi}}. \tag{3.16}$$

3.2.3 Equilibrium

In the next subsection, I will log-linearize the above system of equations around the zero inflation, non-stochastic steady-state equilibrium in order to analyze this economy. First, I will define the zero inflation, non-stochastic steady-state equilibrium.

Gross inflation, Π_t, is defined as

$$\Pi_t = \frac{P_t}{P_{t-1}}.$$

A zero inflation, non-stochastic, steady-state equilibrium is a collection of price sequences $\{P_t, W_t\}_{t=0}^{\infty}$, $\{P_{k,t}\}_{t=0}^{\infty}$ for $k \in \{G, S\}$ and $\{P_t(i)\}_{t=0}^{\infty}$ for $i \in [0,1]$ and a collection of allocation sequences $\{C_t(i), Y_t(i), H_t(i), N_t(i), D_t(i)\}_{t=0}^{\infty}$ for $i \in [0,1]$, $\{C_{k,t}, Y_{k,t}\}_{\tau=0}^{\infty}$ for $k \in \{G, S\}$ and $\{C_t, Y_t\}_{t=0}^{\infty}$ such that the following conditions are satisfied:

(i) The household maximizes (3.1) subject to (3.2), taking the consumption composites in (3.3) and (3.6) and prices as given, yielding (3.4), (3.5) and (3.7) through (3.12);

(ii) The firm solves its problem in (3.14), taking technology in Equation (3.13) and wages as given, yielding (3.15) and (3.16);

(iii) The rate of inflation, Π_t, is equal to one for all periods, implying that P_t is constant for all periods;

(iv) The stochastic processes $Z_{G,t}$ and $Z_{S,t}$ are constant at their steady-state values for all periods;

(v) The allocations listed above are constant for all periods, and wages are constant for all periods;

(vi) Markets clear, implying $C_t = Y_t$, $C_{k,t} = Y_{k,t}$ for $k \in \{G, S\}$ and $C_t(i) = Y_t(i)$ for $i \in [0,1]$, $B_t = 0$, $H_t(i) = N_t(i)$ for $i \in [0,1]$ for all $t = 0, 1, 2, \ldots$.

I compute the steady-state equilibrium conditions in Appendix A of this chapter.

3.2.4 Log-linearization and the Generalized New Keynesian Phillips Curve

I log-linearize the optimizing behavior of the household and the firms, described in Subsections 3.2.1 and 3.2.2, around the zero inflation, non-stochastic, steady-state equilibrium defined in Subsection 3.2.3 and listed in Appendix A of this chapter. All log-linareizations use lower case variables to denote the log deviations from the steady-state. That is, for some variable A_t, I have $a_t = \ln A_t - \ln \bar{A}$, where $\bar{A}$ denotes the steady-state value of A_t. In Appendix B of this chapter, I list all of the log-linearizations for the optimizing behavior.

The log-linearized dynamics of aggregate and sectoral output and prices are given by

$$y_t = n y_{G,t} + (1-n) y_{S,t}, \tag{3.17}$$

$$p_t = np_{G,t} + (1-n)p_{S,t}, \tag{3.18}$$

$$y_{k,t} = y_t - \phi(p_{k,t} - p_t), \quad k \in \{G, S\}, \tag{3.19}$$

$$p_{k,t} = \alpha_k x_{k,t} + (1-\alpha_k)p_{k,t-1}, \quad k \in \{G, S\}, \tag{3.20}$$

$$\psi E_{t-1}(\lambda_t + p_t) = E_{t-1}(\beta\eta c_{t+1} - c_t + \eta c_{t-1}), \tag{3.21}$$

$$\lambda_t + i_t = E_t \lambda_{t+1} \tag{3.22}$$

$$\lambda_t + w_t = \sigma_H[c_t - nz_{G,t} - (1-n)z_{S,t}] \tag{3.23}$$

and

$$x_{k,t} = [1 - \beta(1-\alpha_k)]E_{t-1}\sum_{\tau=0}^{\infty}\beta^\tau(1-\alpha_k)^\tau(w_{t+\tau} - z_{k,t+\tau}) \tag{3.24}$$

for $i \in \mathcal{I}_k$ and $k \in \{G, S\}$. The parameters η and ψ are given by

$$\eta = \frac{\tilde{\eta}}{1 + \beta\tilde{\eta}^2},$$

$$\psi = \frac{(1-\tilde{\eta})(1-\beta\tilde{\eta})}{\sigma_C(1+\beta\tilde{\eta}^2)}.$$

I assume that a policy maker sets the nominal interest rate i according to a Taylor (1993) style interest rate rule. I assume that this rule takes the form

$$i_t = (1-\rho)(\delta_y y_t + \delta_\pi \pi_t) + \rho i_{t-1} + \nu_t, \tag{3.25}$$

where $\pi_t = p_t - p_{t-1}$. The policy maker can choose i_t down to an error of ν_t, which follows an AR(1) process given by

$$\nu_t = \rho_\nu \nu_{t-1} + \varepsilon_{i,t} \tag{3.26}$$

where $\varepsilon_{i,t}$ is a white noise shock.

In Appendix C of this chapter, I use Equations (3.19), (3.20), (3.21), (3.23) and (3.24) to produce the sectoral New Keynesian Phillips curves (SNKPC) and the generalized New Keynesian Phillips curve (GNKPC). For discussion purposes in this section, I will suppress $z_{G,t}$ and $z_{S,t}$.[7] Additionally, I let $\tilde{\eta} = 0$ so that there is no habit persistence. The SNKPC is given by

$$E_{t-1}\pi_{k,t} = \beta E_{t-1}\pi_{k,t+1} + \theta_k \left(\sigma_H + \sigma_C - \frac{1}{\phi}\right) E_{t-1}y_t + \frac{\theta_k}{\phi} E_{t-1}y_{k,t}, \tag{3.27}$$

where $\pi_{k,t} = p_{k,t} - p_{k,t-1}$ and

$$\theta_k = \frac{\alpha_k[1 - \beta(1 - \alpha_k)]}{1 - \alpha_k}, \tag{3.28}$$

for $k \in \{G, S\}$. Note that when $\tilde{\eta} = 0$, it is the case that $1/\psi = \sigma_C$.

Due to the fact that households and firms choose consumption and prices one period in advance, all variables in Equation (3.27) are determined in period $t - 1$. Additionally, because consumption and prices are chosen one period in advance, the interest rate shock ν_t will not effect output or prices in period t. Rather, interest rate shocks impact the current expectations of future prices and output. Therefore, it is the shock ν_{t-1} that drives the variables in Equation (3.27).

Using Equation (3.18) to aggregate the sectoral Phillips curves yields the generalized

[7]For the equilibrium in Appendix A of this chapter, I assume that the steady-state values $Z_{G,t}$ and $Z_{S,t}$ are equal. Therefore, the suppression of $z_{G,t}$ and $z_{S,t}$ represents both an equalization of technology across sectors and a restriction against technological deviations from the steady-state.

New Keynesian Phillips curve:

$$E_{t-1}\pi_t = \beta E_{t-1}\pi_{t+1} + [n\theta_G + (1-n)\theta_S]\left(\sigma_C + \sigma_H - \frac{1}{\phi}\right)E_{t-1}y_t + \frac{1}{\phi}E_{t-1}[n\theta_G y_{G,t} + (1-n)\theta_S y_{S,t}]. \tag{3.29}$$

As noted in Carvalho (2006), the last term on the right-hand side of Equation (3.29) is not present in the standard New Keynesian Phillips curve (NKPC) as found in Walsh (2003). This term captures the impact of price heterogeneity in the model. Because the prices of goods adjust more rapidly than the prices of services, the relative price of goods to services is not constant. Thus, following a shock, one sector will become cheap relative to the other sector. This causes demand for the cheap sector to rise relative to the expensive sector so that output differs across sectors.

When $\alpha_G = \alpha_S = \alpha$, then Equation (3.17) implies that Equation (3.29) reduces to

$$E_{t-1}\pi_t = \beta E_{t-1}\pi_{t+1} + \frac{\alpha[1-\beta(1-\alpha)]}{1-\alpha}(\sigma_C + \sigma_H)E_{t-1}y_t, \tag{3.30}$$

which is the standard NKPC. Hence, the traditional NKPC is a special case of the GNKPC, where prices and output are equal across all sectors.

Appendix C of this chapter contains the both the GNKPC and the corresponding standard NKPC, including habit formation and all shocks.

3.2.5 The Dynamics of Interest Shocks

Before solving the linearized model above, I put structure on the stochastic shocks $z_{G,t}$ and $z_{S,t}$. I assume that each of the shocks is an AR(1) process so that

$$z_{G,t} = \rho_G z_{G,t-1} + \varepsilon_{G,t}, \tag{3.31}$$

and

$$z_{S,t} = \rho_S z_{S,t-1} + \varepsilon_{S,t}. \tag{3.32}$$

I assume that each of the autoregressive parameters are in $[0, 1)$ and that $\varepsilon_{G,t}$ and $\varepsilon_{S,t}$ are each independent shocks with expectation zero. My solution procedure follows standard methods described in Sims (2002b).

In order to examine the dynamic impact of an interest rate shock, I first need to assign values to the parameters of the model. A complete summary of the parameters in the model can be found in Table 3.1. For quarterly periods, choosing $\beta = 0.99$ yields a steady-state real interest rate of 4%. In Christiano, Eichenbaum, and Evans (2005), the habit formation parameter is measured to be between 0.52 and 0.71. In contrast, Boivin and Giannoni (2006) estimate a value of 0.91. Because my model is more similar to that of Boivin and Giannoni (2006), I set $\tilde{\eta} = 0.85$. I choose $\sigma_C = 0.075$ so that in the steady-state $-\frac{u_{11}}{u_1}\bar{C} = 0.5$, and I choose $\sigma_H = 0.5$ to match Boivin and Giannoni (2006). Finally, $\phi = 11$ suggests a steady-state mark-up of 10%. Throughout the rest of paper, I assume that these parameters are constant across time.

For the policy weight on inflation, I choose $\delta_\pi = 1.5$, which is standard in the literature and is pulled from Carvalho (2006). For the policy weight on output and the degree of

Table 3.1: Summary of Parameters in the Model

Parameters	Description	Location
Utility parameters		
β	Household discount factor	Equation (3.1)
$\tilde{\eta}$	Household degree of habit formation	Equation (3.1)
σ_C	Household parameter governing risk aversion[a]	Equation (3.1)
σ_H	Inverse Frisch elasticity of labor supply	Equation (3.1)
χ	Relative disutility of labor	Equation (3.1)
ϕ	Elasticity of substitution between sectors and output types	Equations (3.3) and (3.6)
n	Relative utility share of goods in the consumption bundle	Equations (3.3) and (3.6)
Firm Parameters		
α_G	Probability of price change for goods firms	Equation (3.14)
α_S	Probability of price change for services firms	Equation (3.14)
Policy Parameters		
δ_y	Policy weight of output	Equation (3.25)
δ_π	Policy weight of inflation	Equation (3.25)
ρ	Degree of interest rate smoothing	Equation (3.25)
Stochastic Parameters		
ρ_ν	AR(1) coefficient on interest rate shocks	Equation (3.26)
ρ_G	AR(1) coefficient on goods technology shocks	Equation (3.31)
ρ_S	AR(1) coefficient on services technology shocks	Equation (3.32)

[a]Due to the habit persistence in this model, σ_C is not itself the degree of relative risk aversion. In the steady-state, when $C_t = C_{t+1} = \bar{C}$, then $-\frac{u_{11}}{u_1}\bar{C} = \frac{\sigma_C}{1-\tilde{\eta}}$, where $u(C_t, C_{t-1}) = \frac{(C_t - \tilde{C}_{t-1})^{1-\sigma_C}}{1-\sigma_C}$.

interest rate smoothing, I choose $\delta_y = 0.08$ and $\rho = 0.8$, which are pulled from Smets and Wouters (2007). For now, I assume that these parameters are constant over time. However, I will relax this assumption in Section 3.4.

Because the relative size of the goods and services sectors has varied over time, I allow n to change values. Additionally, because the composition of both the goods and services sectors have varied, I also allow α_G and α_S to change. Specifically, when choosing values for these parameters, I match two different time periods: 1959 to 1978 and 1983 to 2007. In Section 3.3, I discuss the choice of these two time periods. In short, they are the time periods most consistent with the model's assumption that the short term nominal interest rate is the primary policy tool.

Table 3.2: Model Parameter Values

Model 1 1959 to 1978		Model 2 1983 to 2007	
α_G	0.827	α_G	0.786
α_S	0.390	α_S	0.326
n	0.510	n	0.383

For ease of terminology, I refer to the parameters that correspond to the 1959 to 1978 time period as Model 1 and the parameters that correspond to the 1983 to 2007 time period as Model 2. The parameter values for Model 1 and Model 2 are listed in Table 3.2. In Model 1, I use $n = 0.510$. This represents the average ratio of goods sector PCE to total PCE less consumption of nonprofit institutions in the United States for 1959 to 1978. In Model 2, value of n is 0.383, which is the average ratio of goods sector PCE to total PCE less nonprofit consumption for 1983 to 2007.

Table 3.3: Durations and Weighted Durations for the 15 Industries in PCE

Goods Industries	Duration in Quarters[a]	Weights for 1959 to 1978[b]	Weighted Durations 1959 to 1978	Weights for 1983 to 2007[b]	Weighted Durations 1983 to 2007
Motor vehicles and parts	0.827	0.061	0.050	0.054	0.045
Furnishings and durable household equipment	1.547	0.046	0.070	0.032	0.049
Recreational goods and vehicles	1.917	0.026	0.050	0.032	0.061
Other durable goods	1.850	0.015	0.027	0.016	0.030
Food and beverages purchased for on premises consumption	1.070	0.165	0.176	0.093	0.100
Clothing and footwear	1.083	0.073	0.079	0.047	0.051
Gasoline and other energy goods	0.390	0.044	0.017	0.031	0.012
Other nondurable goods	1.803	0.082	0.147	0.077	0.140
Sum		0.510	0.0617	0.383	0.487
Average duration of goods			1.209		1.273

Services Industries	Duration in Quarters[a]	Weights for 1959 to 1978[b]	Weighted Durations 1959 to 1978	Weights for 1983 to 2007[b]	Weighted Durations 1983 to 2007
Housing and utilities	0.827	0.174	0.144	0.186	0.153
Health care	6.667	0.070	0.465	0.138	0.923
Transportation services	1.197	0.030	0.036	0.035	0.042
Recreation services	3.300	0.022	0.071	0.035	0.114
Food services and accommodations	2.120	0.064	0.136	0.065	0.138
Financial services and insurance	4.200	0.047	0.199	0.075	0.316
Other services	2.450	0.083	0.203	0.083	0.204
Sum		0.490	1.254	0.617	1.890
Average duration of services			2.562		3.063

[a]Source of durations is Carvalho and Lee (2011).

[b]Weights are computed as the average ratio of industry PCE to total PCE, excluding consumption by nonprofit institutions, over the corresponding time period. Data source is the Bureau of Economic Analysis.

The values of α_k for $k \in \{G, S\}$ are given by the inverse of the durations for each sector, which are computed in Table 3.3. The categories listed in Table 3.3 are the 15 major categories that compose total PCE. The duration in quarters column is obtained from Carvalho and Lee (2011). The weights for 1959 to 1978 and 1983 to 2011 are the average ratios of the PCE for each category to total PCE, excluding consumption of nonprofit institutions. I make the strong assumption that the duration of nominal prices is constant in each category across time. However, by allowing the relative sizes of each of the 15 categories to vary, the average duration of both the goods sector and the services sector increases. In the goods sector, the duration increase is driven by a relative size increase of recreational goods and vehicles and other durables goods, the two PCE categories with the highest duration.[8] In the services sector, the duration increase is driven by large increases in the health care and financial services and insurance PCE categories, the two PCE categories with the highest durations.

The average quarterly duration of the entire economy increases from 1.9 quarters to 2.4 quarters. This increase in duration of 0.5 quarters is likely a modest estimation of the actual change. Nakamura and Steinsson (2008) estimate that the average price duration increase from the 1988 to 1996 interval to the 1997 to 2005 interval is between 0.07 and 0.47 quarters in the United States. Over the a longer time period, Wulfsberg (2009) estimates that that the average price duration increase from the 1975 to 1989 interval to the 1990 to 2004 interval is 1.8 quarters in Norway.

Finally, I select $\rho_\nu = 0.55$, which represents a midpoint between Carvalho (2006) and Smets and Wouters (2007).

[8]Recreational goods and vehicles and other durable goods are the only goods sector PCE categories that increased in relative size between the two periods. All other categories fell.

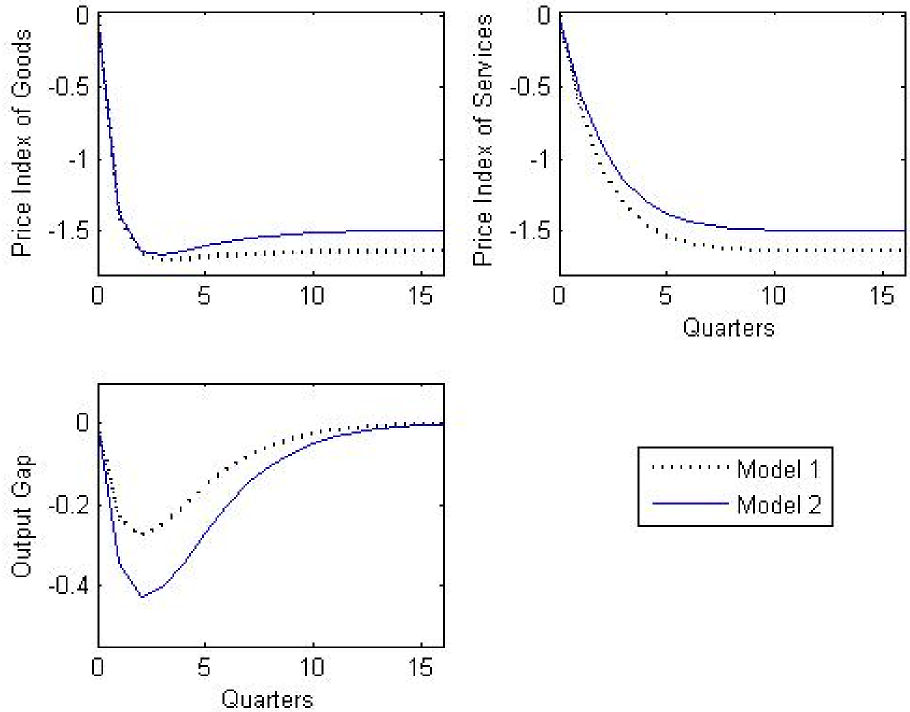

Figure 3.2: Theoretical impulse response functions of price indexes and output gap to a 0.25% interest rate shock. Model 1 contains parameter values for sectoral price change probabilities and relative sectoral size that are calibrated on 1959 to 1978 data. Model 2 contains parameter values for sectoral price change probabilities and relative sectoral size that are calibrated to 1983 to 2007 data. Model 2 represents an economy with greater nominal rigidities than Model 1.

The theoretical impulse response of prices, output and the real interest rate to an unanticipated 0.25% nominal interest rate shock are displayed in Figure 3.2. Not surprisingly, both the prices of goods and services fall faster under Model 1 than under Model 2. However, the behavior of both price indexes is similar under both models. In contrast, the impact of an unanticipated interest rate shock on output is substantially different between the two models. In Model 1, the output gap bottoms out at -0.279, and in Model 2, it bottoms out at -0.429. Thus, an interest rate shock has an impact that is about 54% larger in Model 2 than in Model 1. This result is driven by simultaneous changes in the relative size of the sectors, n, and the probability of price change in each sector, α_k. In Appendix D of this chapter, I separate the effects of changing n with those of changing α_k. Given the parameter values chosen above, the changes in α_k have a larger impact on the theoretical impulse response of output than the changes in n. However, both changes contribute a large portion of the total increase.

The result that output is more responsive under Model 2 than Model 1 is robust to a range of parameter changes. For $\tilde{\eta}$ in the range of 0.5 to 0.95, the response of output under Model 2 ranges from 45% to 60% larger under Model 2 than under Model 1.[9] Similarly, for σ_H in the range from 0.1 to 2.0, the response of output under Model 2 ranges from 50% to 60% larger under Model 2 than under Model 1. Also, for choices of σ_C that yield $-\frac{u_{11}}{u_1}\bar{C}$ from 0.1 to 1.0, the response of output under Model 2 ranges from 45% to 55% larger under Model 2 than under Model 1. Finally, for ρ_ν in the range 0.05 to 0.95, the response of output under Model 2 ranges from 50% to 55% larger under Model 2 than under Model 1. Section 3.4 contains a discussion of changing policy parameters. However, it is also the case that output is more responsive under Model 2 than Model 1 for policy changes.

These results are consistent with standard New Keynesian theory. In Model 2, nominal rigidities in both sectors have increased and the relative size of the stickier sector, services, has grown. Thus, Model 2 represents an economy with larger nominal rigidities than that under Model 1. Thus, on average, prices respond slower to a nominal interest rate shock under Model 2 than Model 1. This causes the present value of the future real interest rate to be higher under Model 2 than Model 1.

[9]Because changing $\tilde{\eta}$ changes $-\frac{u_{11}}{u_1}\bar{C}$, I adjust σ_C along with $\tilde{\eta}$ so that $-\frac{u_{11}}{u_1}\bar{C}$ is fixed at 0.5.

Because Model 2 is constructed from the 1983 to 2007 time period and Model 1 is constructed from the 1959 to 1978 time period, this model suggests that output in 1983 to 2007 should be more responsive to interest rate shocks than output in 1959 to 1978. This provides a testable implication, which is examined in Section 3.3.

3.3 Empirical Analysis

To test whether the impact of shocks to the Federal Funds rate have increased over time, I split U.S. economic data into two time periods, an early period and a late period. I then examine whether the impulse response functions (IRFs) of output to Federal Funds rate shocks, estimated using both a VAR and a FAVAR, are different across the time periods.

For the beginning of the early period, I use 1959. This is consistent with the VAR literature on monetary policy (Sims, 1992; Bernanke and Blinder, 1992; Boivin and Giannoni, 2006) and the FAVAR literature on monetary policy (Bernanke, Boivin, and Eliasz, 2005). For the end of the late period, I use 2007. This is because in the New Keynesian model in Section 3.2, the short term nominal interest rate is primary policy tool; however, in practice, the Federal Funds rate is not the primary policy tool after 2007. It hit the zero lower bound by the end of 2008 and became unavailable. Additionally, the Troubled Asset Relief Program and a 0.25% interest on reserves policy were both enacted in 2008, suggesting that policy makers were using tools in addition to the Federal Funds rate.

I choose 1978 as the end of the early period and 1983 as the beginning of the late period. This is because Bernanke and Mihov (1998) note that "1979-1982 was the only period in which the Fed indicated publicly that it was using a nonborrowed-reserves targeting procedure." This is inconsistent with the model in Section 3.2, which only uses a nominal interest

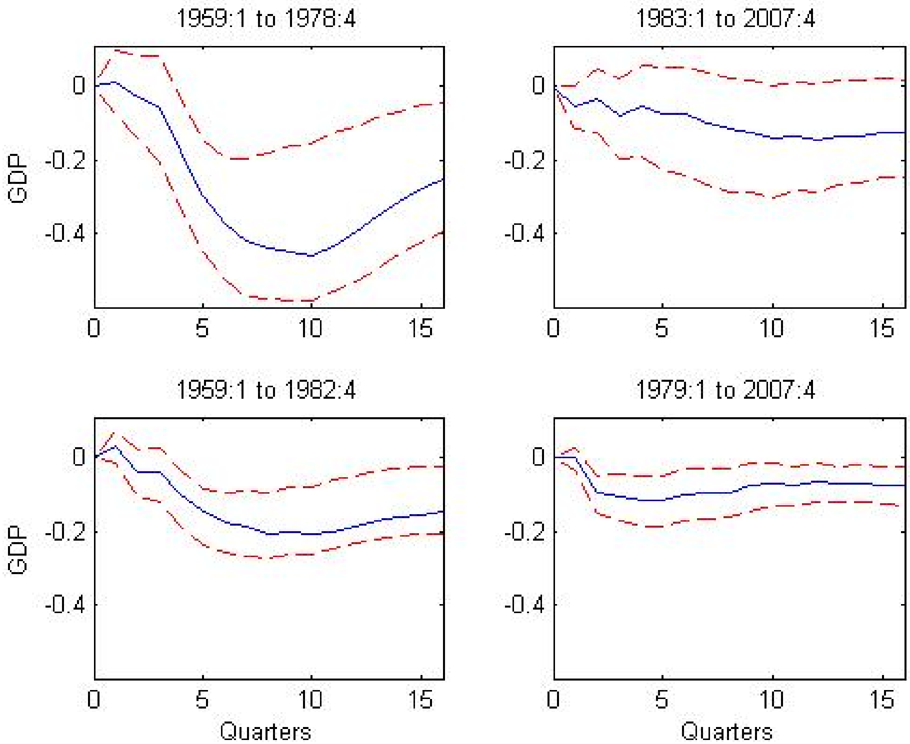

Figure 3.3: Impulse response functions of GDP to a 0.25% increase in the Federal Funds rate, estimated by a VAR on GDP, PCE price index for goods, PCE price index for services, the Federal Funds rate and the PPI commodities index for all commodities, where the Federal Funds rate is placed last in the VAR ordering. Dashed lines in each plot denote the 95% error bands computed from the bootstrap procedure of Kilian (1998).

rate policy tool. Additionally, 1979 to 1982 was the only period examined by Bernanke and Mihov (1998) that yielded a statistical model where the restrictions of nonborrowed-reserves are not rejected.

3.3.1 Vector Autoregressions

The New Keynesian model in Section 3.2 has the property that the current values of output and prices influence interest rate policy through the policy rule in Equation (3.25). However, due to the timing of consumption and price choices, the model assumes that current values of interest rates do not impact current output or prices. As noted in Bernanke and Blinder (1992), this theoretical structure allows for the identification of the impulse response functions of output due to interest rate shocks in an unrestricted VAR when the interest rate is placed last in the ordering.

Following the theory laid out in Section 3.2, I estimate a VAR on GDP, the PCE index of goods prices, the PCE index of services prices and the effective Federal Funds rate. In addition, as is common in macroeconomic VARs, I include a commodities price index to help mitigate endogeneity problems (Sims, 1992). The commodities price index that I use is the PPI Commodities index for all commodities. All data is quarterly, and I estimate the VAR using 5 lags.[10] Figure 3.3 displays the impulse response functions (IRFs) of output to a 0.25% increase in the Federal Funds rate for each of the listed time periods. The dashed lines denote the 95% error bands, constructed using the bootstrap procedure of Kilian (1998).

The estimated IRF of output to a Federal Funds rate shock is larger in the 1959 to 1978 time period than the 1983 to 2007 time period. This result contrasts with the implications of the New Keynesian model laid out in Section 3.2. However, it may not reject the entire model outright. One critical assumption in Section 3.2 is that the parameters of the interest policy rule in (3.25) are constant. Several studies (Clarida, Galí, and Gertler, 2000; Cogley and Sargent, 2005; Boivin and Giannoni, 2006) suggest that those parameters have changed over time. Specifically, those studies suggest that the weight on inflation increased after 1979. In Section 3.4, I consider the implications of relaxing a constant interest rate policy rule.

[10] Following Kilian (2001), I use the Aikake Information Criterion (AIC) to estimate the number of lags for this model. The AIC suggests that the model should have four lags. However, to keep it consistent with the FAVAR in the following subsection, I use five lags. The impact on the impulse response functions is minimial, and Kilian (2001) suggests that overfitting a VAR model is not particularly problematic.

For comparison purposes, I include both an early period and a late period with the 1979 to 1982 time window in Figure 3.3. This time period dampens the IRFs in both early and late time periods. However, it appears to have a larger effect on the early time period, whose IRF is less than half the size when 1979 to 1982 is included.

3.3.2 Factor-Augmented Vector Autoregression

As a robustness test for the results of the VAR above, I also estimate a factor-augmented vector autoregression or FAVAR developed in Bernanke, Boivin, and Eliasz (2005). Instead of estimating a VAR directly on output, prices and interest rates, as suggested by the theoretical model in Section 3.2, a FAVAR estimates a VAR on common factors within a large cross section of economic data.

FAVARs have two primary virtues for testing the robustness of small dimensional VARs. First, because they are estimated on large number time series, they capture the full range of data observed by the policy makers in practice. Thus, FAVARs are more likely to capture the full information set of policy makers and less likely to suffer from endogeneity problems. As evidence of this, both Bernanke, Boivin, and Eliasz (2005), and Boivin, Giannoni, and Mihov (2009) argue that FAVARs exhibit less of a price puzzle than a standard low-dimensional VAR. Second, FAVARs do not take a stand on which time series is the best measure of certain variables in a theoretical model. For example, it is not obvious that price indexes based on PCE provide a better theoretical measure than CPI price indexes, or vice versa. However, because FAVARs construct the factors from a large sample of time series, they use the most important variables common to all of the time series in the sample set.[11]

I use a data set of 174 time series obtained from Stock and Watson (2010) that ranges from 1959 to 2007. It is composed of both monthly and quarterly data, and I average the monthly data into quarterly data so that the data set is balanced. I denote the $N \times 1$ vector of data series by $\mathbf{X}_t$, where N is the count of the 174 time series. I assume that $\mathbf{X}_t$ is driven by a small number k of common factors, denoted by the $k \times 1$ vector $\mathbf{C}_t$. Following Bernanke, Boivin, and Eliasz (2005) and Boivin, Giannoni, and Mihov (2009), I assume that the Federal Funds rate is one of the common factors.

The data series and the common factors take the following structure

$$\mathbf{X}_t = \mathbf{\Psi}'\mathbf{C}_t + \epsilon_t \tag{3.33}$$

where $\mathbf{\Psi}$ is a $k \times N$ matrix of factor loadings and ϵ_t is an $N \times 1$ vector of idiosyncratic errors. As is common the FAVAR literature, I assume that the idiosyncratic errors are independent of the common factors. This allows us to think of the idiosyncratic errors as series specific shocks that are unique to each of the N time series in $\mathbf{X}_t$, whereas $\mathbf{C}_t$ contains the macroeconomic factors that are common to all N time series.

A complete description of the estimation procedure for $\mathbf{C}_t$ and $\mathbf{\Psi}$ is provided in Appendix E of this chapter. Once the common factors are estimated, I assume that they follow a VAR model, which takes the form

$$\mathbf{C}_t = \mathbf{\Gamma}(L)\mathbf{C}_{t-1} + v_t, \tag{3.34}$$

[11]In this study, I estimate the factors using the method of principal components. So, to be precise, the estimated factors represent a change of axes, where the new axes are selected sequentially so that each axis accounts for the largest possible variance amongst the data.

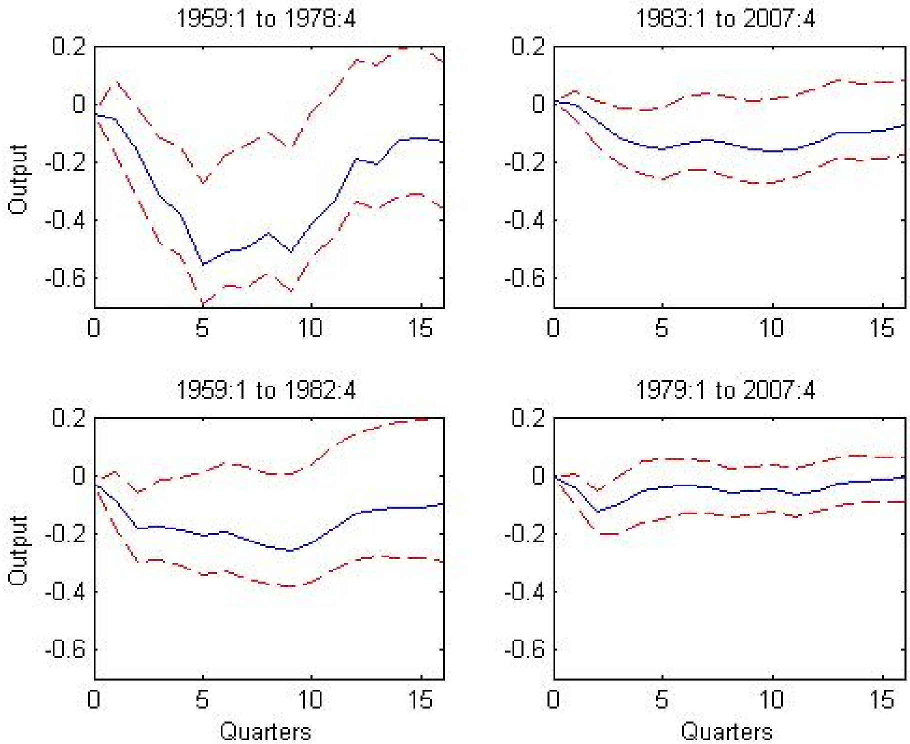

Figure 3.4: Impulse response functions of output to a 0.25% increase in the Federal Funds rate, estimated by a FAVAR with eight unobserved factors and the Federal Funds rate as common components, where the Federal Funds rate is placed last in the VAR ordering. Dashed lines in each plot denote the 95% error bands computed from the bootstrap procedure of Kilian (1998).

where $\Gamma(L)$ is a $k \times k$ lag matrix polynomial. I use five lags to estimate $\mathbf{\Gamma}(L)$ in Equation (3.34).[12] Given the estimated $\mathbf{\Gamma}(L)$, the impulse responses for each of the individual series evolve according to $\mathbf{\Psi}'\mathbf{\Gamma}(L)$.

I note here that identification of the impulse response function of output due to a Federal Funds rate shock is different in the FAVAR than in the VAR. In the FAVAR, I assume that

[12] As with the VAR estimation in the previous subsection, I use the AIC to choose the number of lags in the model. However, for the FAVAR, the AIC does not provide a limit on the number of lags to use. So I select five lags, which balances the AIC results in the VAR model with caution against underfitting the model.

a Federal Funds rate shock does not impact any of the other common factors in the same time period. This is consistent with the identifying assumption in the VAR in the previous subsection. However, because IRFs in the FAVAR also contain the matrix $\mathbf{\Psi}$, it is possible for the Federal Funds rate to contemporaneously impact output, prices and other variables. The size of the impact will depend on the estimated values in the last column $\mathbf{\Psi}'$. If the values in the last column of $\mathbf{\Psi}'$ are all zero, then the restriction that a Federal Funds rate shock cannot impact other common factors in the same period is the same as the restriction that a Federal Funds rate shock cannot impact output or prices in the same period. However, if the values in the last column of $\mathbf{\Psi}'$ are not all zero, then these two restrictions are not equivalent. In practice, this contemporaneous impact of Federal Funds rate shocks on output is very small, suggesting that the value in the last row of $\mathbf{\Psi}'$ corresponding to output is close to zero. Figure 3.4 shows that the initial impulse response of output to an Federal Funds rate shock deviates very little from zero.

The results of the of the FAVAR estimated IRFs of output to a Federal Funds rate shock are summarized in Figure 3.4. Despite the fact that the FAVAR is a substantially more complicated statistical model than the VAR, it yields very similar results with regard to the IRFs of output. As with the VAR estimation, the 1979 to 1982 time period has a muting effect on output in the FAVAR estimation. Also, the FAVAR estimation implies that output in the 1959 to 1978 time period is more sensitive to Federal Funds rate shocks than output in the 1983 to 2007 time period, which contrasts with the theory in Section 3.2.

3.4 A Model with a Changing Interest Rate Rule

The empirical results in Section 3.3 contradict the theoretical implication of the calibrated New Keynesian model in Sector 3.2. However, this contraction may not invalidate the use of the New Keynesian model presented in Section 3.2. One assumption made in Section 3.2 is that the parameters of the interest rate policy in Equation (3.25) stay constant over time. In contrast, several studies (Clarida, Galí, and Gertler, 2000; Cogley and Sargent, 2005; Boivin and Giannoni, 2006) suggest that monetary policy has become more responsive to inflation after 1979. In addition, Boivin and Giannoni (2006), using a one sector New Keynesian model, argues that this responsiveness has reduced the size of impulse responses of output to interest rate shocks.

To consider possible changes in interest rate policy, I relax the assumption that policy parameters remain constant across time. Specifically, I allow for two different parametrizations of δ_π, δ_y and ρ based on calibrated values that are standard in the literature. I refer to the two different parametrizations as Policy 1 and Policy 2, where Policy 1 coincides with the 1959 to 1978 time period and Policy 2 coincides with 1983 to 2007 time period. The parameter values for each policy are listed in Table 3.4.

Table 3.4: Policy Parameter Values

Policy 1 1959 to 1978		Policy 2 1983 to 2007	
δ_π	1.000	δ_π	2.000
δ_y	0.050	δ_y	0.100
ρ	0.800	ρ	0.700

Both Clarida, Galí, and Gertler (2000) and Boivin and Giannoni (2006) suggest that the

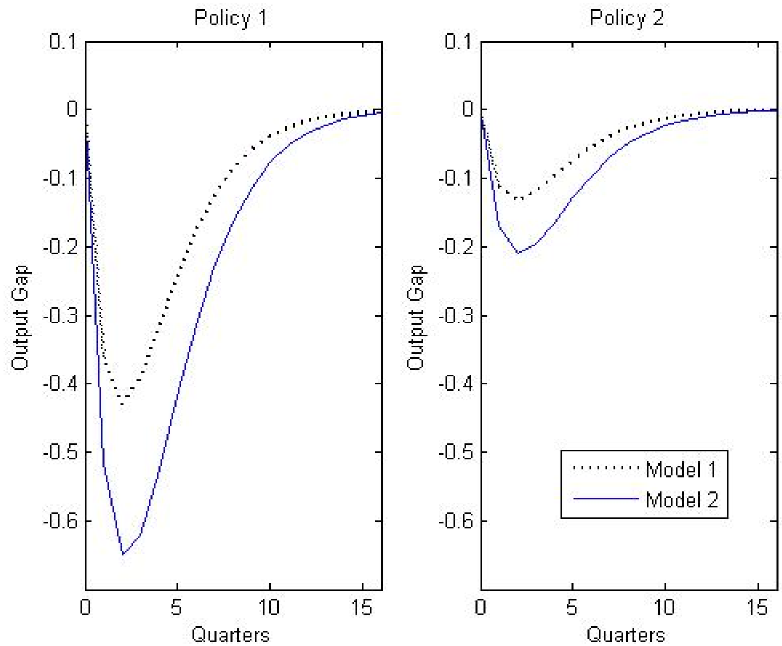

Figure 3.5: Theoretical impulse responses of output to a 0.25% interest rate shock. Model 1 contains parameter values for sectoral price change probabilities and relative sectoral size that are calibrated on 1959 to 1978 data. Model 2 contains parameter values for sectoral price change probabilities and relative sectoral size that are calibrated to 1983 to 2007 data. Model 2 represents an economy with greater nominal rigidities than Model 1. Policy 1 contains parameter values for interest rate policy calibrated on 1959 to 1978 data. Policy 2 contains parameter values for interest rate policy calibrated on 1983 to 2007 data. Policy 2 represents a policy that is more aggressive against inflation than Policy 1.

value of δ_π roughly doubled from before 1979 to after 1979. So, I use the value $\delta_\pi = 1.0$ for Policy 1 and $\delta_\pi = 2.0$ for Policy 2. In contrast, there is no clear indication of how δ_y changes between the two time periods. Clarida, Galí, and Gertler (2000) suggest that it increased by nearly four times whereas Boivin and Giannoni (2006) suggest that it was constant at zero for both time periods. I split the difference and assume that δ_y doubles from 0.05 in Policy 1 to 0.10 in Policy 2. Finally, I assume that ρ from 0.80 in Policy 1 to 0.70 in Policy 2. Again, this roughly splits the difference between the results in Clarida, Galí, and Gertler (2000) and Boivin and Giannoni (2006).

As in Section 3.2, I consider the two models of sector size and nominal rigidity that coincide with each time period of interest, listed in Table 3.2. For each model and each policy, the theoretical impulses of output to an unanticipated 0.25% interest rate shock are presented in Figure 3.5. Model 1 and Policy 1 coincide with the 1959 to 1978 time period. As shown in Figure 3.5, the impulse response of this model-policy combination is consistent with the estimated impulse responses of output in the VAR estimation displayed in Figure 3.3. It under shoots the impulse response of the FAVAR estimation; however, it falls within the 95% confidence band. Model 2 and Policy 2 coincide with the 1983 to 2007 time period. As shown in Figure 3.5, the impulse response of this model-policy combination bottoms out at a lower point than either the VAR or FAVAR estimations. However, it falls within the 95% confidence band for both estimations.

Figure 3.5 shows that if either policy was kept constant across time, then the observed impulse response of output should have increased from the early sample period to the late sample period. However, the shifting policy between the two periods overwhelms the effects of the relative increase of the services sector. This result is consistent with the empirical IRFs in Figures 3.3 and 3.4. Thus, for standard calibrated parameter values, the New Keynesian model in Section 3.2 can characterize the observed IRFs of output to interest rate shocks when policy parameters are allowed to change.

This result suggests that changes in interest rate policy are a plausible explanation for why the empirical results of Section 3.3 contradict the theoretical implications of Section 3.2. However, interest rate policy changes need not be the only explanation. It is also possible for changes in the utility parameters to impact the results of the model. Therefore, further analysis is needed to pin down the exact effects of policy changes.

3.5 Conclusion

Two stylized facts of the U.S. economy are that nominal prices in the services sector are stickier than those of the goods sector and that the relative size of the services sector has increased over the past 50 years. For parameter values calculated on PCE data, these two facts suggest that the average duration of prices in the United States has increased from 1.9 quarters to 2.4 quarters from 1959-1978 to 1983-2007. A two-sector New Keynesian model suggests that this increase in nominal rigidities leads to an increased impulse response impact on output from interest rate shocks. For parameter values consistent with the current DSGE literature, the New Keynesian model implies that the observed impulse response in output to an interest rate should be approximately 50% larger in 1983-2007 than in 1959-1978.

To test this implication, I estimate impulse response functions of United States GDP on Federal Funds rate shocks using both VAR and FAVAR methods. Both methods suggest that the impulse responses in output are larger in 1959-1978 than in 1983-2007, which contrasts with the theoretical implications. This muting of impulse responses may be due to changes in interest rate policy of the Federal Reserve that occurred between the two time periods. When parameter changes that are consistent with calibrations in the current literature are introduced into the New Keynesian model, the effects of these policy changes swamp the effects of increased nominal rigidities. Additionally, these policy changes produce theoretical impulse response functions of output that are consistent with the empirical impulse response functions using both the VAR and FAVAR methods.

This paper provides two avenues of future research. First, Section 3.4 indicates that simultaneous changes in sectoral nominal rigidities and relative sector size provide a plausible explanation for the behavior of output observed in the data. However, unlike price change frequency and relative sector size, which are directly observable from data, changes to the interest rate policy of the Federal Reserve have to be estimated from models. Because of this, the exact timing and size of policy changes is still an open question. Therefore, in order to determine if the empirical changes from the 1959 to 1978 period to the 1983 to 2007 period stem from changes in interest rate policy additional theoretical implications of changing interest rate policy need to be tested. These theoretical implications may be derived from larger New Keynesian models, such as the model in Christiano, Trabandt, and Walentin (2010), which allow for the examination of impulse responses of prices, inflation and real interest rates.

Second, as displayed in Figure 3.1, the change in relative sector size occurs as a smooth transition over time. In contrast, Section 3.2 models this change as a jump between steady-states. Modelling the change as a transition rather than a jump would provide additional realism to the theoretical model and its implications. However, because I use a solution technique that involves log-linearizing around a steady-state, modelling this transition will likely require non-linear solution methods or substantive changes in the assumptions of the model.

Appendix A

In this appendix, I solve for the zero inflation, non-stochastic, steady-state equilibrium. To do this, I first assume that the stochastic processes, $Z_{G,t}$ and $Z_{S,t}$, have a steady state value. Additionally, I assume that the steady state values for $Z_{G,t}$ and $Z_{S,t}$ are equivalent.

Firm i's first-order condition in Equation (3.15) reduces to

$$\bar{X}(i) = \frac{\phi}{\phi - 1}\frac{\bar{W}}{\bar{Z}}.$$

Because the right-hand side of this equation is constant, it will be the case that newly chosen prices will be the same as all past chosen prices. This implies that $\bar{X}(i) = \bar{P}(i)$.

The above shows that output is priced at a constant markup $\phi/(\phi - 1)$ over costs, which are technology adjusted wages. Equations (3.7) and (3.15) imply

$$\bar{X}_k = \bar{P}_k = \frac{\phi}{\phi - 1}\frac{\bar{W}}{\bar{Z}}$$

for $k \in \{G, S\}$. Additionally, Equation (3.4) implies

$$\bar{P} = \frac{\phi}{\phi - 1}\frac{\bar{W}}{\bar{Z}} \tag{\dagger}$$

so that $\bar{P}(i) = \bar{P}_k = \bar{P}$ for all $i \in [0, 1]$ and $k \in \{G, S\}$. Plugging these two equations into the equations in (3.5) and (3.8) yields

$$\bar{C}(i) = \frac{1}{n}\bar{C}_G \quad \text{for } i \in \mathcal{I}_G$$
$$\bar{C}(i) = \frac{1}{1-n}\bar{C}_S \quad \text{for } i \in \mathcal{I}_G$$
$$\bar{C}_G = n\bar{C}$$
$$\bar{C}_S = (1-n)\bar{C}$$
$$\bar{C}(i) = \bar{C} \quad \text{for } i \in [0,1]$$

By market clearing, technology in Equation (3.13) and the preceding list of equations, it is the case that

$$\bar{H}(i) = \bar{N}(i) = \frac{Y(i)}{\bar{Z}} = \frac{C(i)}{\bar{Z}} = \frac{\bar{C}}{\bar{Z}}.$$

Using this along with Equations (†), (3.9) and (3.11) yields

$$\bar{C} = \left[\frac{\phi-1}{\chi\phi}\frac{1-\beta\tilde{\eta}}{(1-\tilde{\eta})^{-\sigma_C}}\bar{Z}^{1+\sigma_H}\right]^{\frac{1}{\sigma_C+\sigma_H}}.$$

Finally, Equation (3.10) implies

$$\bar{I} = \beta^{-1}.$$

Appendix B

In this appendix, I log-linearize Equations (3.3) through (3.11), (3.13), (3.15) and (3.16) around the zero inflation, non-stochastic, steady-state equilibrium described in Appendix A of this chapter.

The log-linearization of consumption bundles and price indexes in Equations (3.3), (3.4), (3.5) and (3.6) are

$$c_t = nc_{G,t} + (1-n)c_{S,t}$$

$$p_t = np_{G,t} + (1-n)p_{S,t}$$

$$c_{G,t} = \frac{1}{n}\int_{\mathcal{I}_G} c_t(i)di$$

$$c_{S,t} = \frac{1}{1-n}\int_{\mathcal{I}_S} c_t(i)di$$

and

$$p_{G,t} = \frac{1}{n}\int_{\mathcal{I}_G} p_t(i)di$$

$$p_{S,t} = \frac{1}{1-n}\int_{\mathcal{I}_S} p_t(i)di$$

respectively.

The log-linearization of the household's demand functions in Equations (3.5) and (3.8) are

$$c_{k,t} - c_t = -\phi(p_{k,t} - p_t) \quad \text{for } k \in \{G, S\},$$

and

$$c_t(i) - c_{G,t} = -\phi[p_t(i) - p_{G,t}] \quad \text{for } i \in \mathcal{I}_G$$

$$c_t(i) - c_{S,t} = -\phi[p_t(i) - p_{S,t}] \quad \text{for } i \in \mathcal{I}_S.$$

Recalling that the household's total consumption bundle is chosen one period in advance so that c_t is known at time $t-1$, the log-linearization of the household's consumption choice in Equation (3.9) is

$$E_{t-1}(\lambda_t + p_t) = \frac{\sigma_c\tilde{\eta}}{(1-\beta\tilde{\eta})(1-\tilde{\eta})}c_{t-1} - \frac{\sigma_c(1+\beta\tilde{\eta}^2)}{(1-\beta\tilde{\eta})(1-\tilde{\eta})}c_t + \frac{\sigma_c\beta\tilde{\eta}}{(1-\beta\tilde{\eta})(1-\tilde{\eta})}E_{t-1}c_{t+1}.$$

The log-linearization of the household's choice of bond holdings in Equation (3.10) is

$$\lambda_t = i_t + E_t\lambda_{t+1}.$$

The log-linearization of the household's consumption-labor choice in Equation (3.11) is

$$\lambda_t + w_t = \sigma_H \int_0^1 h_t(i)di$$

The log-linearization of production in Equation (3.13) is

$$y_t(i) = z_{k,t} + n_t(i)$$

for $i \in \mathcal{I}_k$ and $k \in \{G, S\}$. This, along with market clearing and above log-linearizations, yields

$$\begin{aligned}\int_0^1 h_t(i) &= \int_{\mathcal{I}_G} n_t(i)di + \int_{\mathcal{I}_S} n_t(i)di = \int_{\mathcal{I}_G} (y_t(i) - z_{G,t})di + \int_{\mathcal{I}_S} (y_t(i) - z_{S,t})di \\ &= \int_{\mathcal{I}_G} c_t(i)di + \int_{\mathcal{I}_S} c_t(i)di - nz_{G,t} - (1-n)z_{S,t} \\ &= nc_{G,t} + (1-n)c_{S,t} - nz_{G,t} - (1-n)z_{S,t} = c_t - nz_{G,t} - (1-n)z_{S,t}.\end{aligned}$$

Therefore, we can rewrite the household's consumption-labor choice as

$$\lambda_t + w_t = \sigma_H[c_t - nz_{G,t} - (1-n)z_{S,t}].$$

The log-linearization of the firms' first-order condition in Equation (3.15) is

$$x_t(i) = [1 - \beta(1-\alpha_k)]E_{t-1} \sum_{j=0}^{\infty} \beta^j (1-\alpha_k)^j (w_{t+j} - z_{k,t+j})$$

for $i \in \mathcal{I}_k$ and $k \in \{G, S\}$. The log-linearization of the sectoral price evolution in Equation (3.16) is

$$p_{k,t} = \alpha_k x_{k,t} + (1-\alpha_k)p_{k,t-1}$$

for $k \in \{G, S\}$.

For the equations in Subsection 3.2.4, I use the market clearing condition $c_t = y_t$ to show all equations in terms of output instead of consumption.

Appendix C

In this appendix, I compute the generalized New Keynesian Phillips curve. For sector $k \in \{G, S\}$, Equation (3.24) can be written as

$$x_{k,t} = [1-\beta(1-\alpha_k)]E_{t-1}(w_t - z_{k,t}) + [1-\beta(1-\alpha_k)]E_{t-1}\sum_{\tau=1}^{\infty}\beta^{\tau}(1-\alpha_k)^{\tau}(w_{t+\tau} - z_{k,t+\tau})$$

which is equivalent to

$$\begin{aligned} x_{k,t} = {} & [1-\beta(1-\alpha_k)]E_{t-1}(w_t - z_{k,t}) \\ & + [1-\beta(1-\alpha_k)]\beta(1-\alpha_k)E_{t-1}\sum_{\tau=1}^{\infty}\beta^{\tau-1}(1-\alpha_k)^{\tau-1}(w_{t+\tau} - z_{k,t+\tau}) \\ = {} & [1-\beta(1-\alpha_k)]E_{t-1}(w_t - z_{k,t}) \\ & + \beta(1-\alpha_k)[1-\beta(1-\alpha_k)]E_{t-1}E_t\sum_{\tau=0}^{\infty}\beta^{\tau}(1-\alpha_k)^{\tau}(w_{t+1+\tau} - z_{k,t+1+\tau}). \end{aligned}$$

Notice that updating Equation (3.24) by one period yields

$$x_{k,t+1} = [1-\beta(1-\alpha_k)]E_t\sum_{\tau=0}^{\infty}\beta^{\tau}(1-\alpha_k)^{\tau}(w_{t+1+\tau} - z_{k,t+1+\tau}).$$

Substituting this into the equation above it yields

$$x_{k,t} = [1-\beta(1-\alpha_k)]E_{t-1}(w_t - z_{k,t}) + \beta(1-\alpha_k)E_{t-1}x_{k,t+1},$$

which defines $x_{k,t}$ recursively. Using Equation (3.20), this can be written as

$$\frac{p_{k,t} - (1-\alpha_k)p_{k,t-1}}{\alpha_k} = [1-\beta(1-\alpha_k)]E_{t-1}(w_t - z_{k,t}) + \beta(1-\alpha_k)E_{t-1}\frac{p_{k,t+1} - (1-\alpha_k)p_{k,t}}{\alpha_k},$$

which is equivalent to

$$\frac{p_{k,t} - \alpha_k E_{t-1} p_{k,t}}{1 - \alpha_k} = \theta_k E_{t-1}(w_t - z_{k,t} - p_{k,t}) + \beta E_{t-1}(p_{k,t+1} - p_{k,t}) + p_{k,t-1},$$

where

$$\theta_k = \frac{\alpha_k[1 - \beta(1 - \alpha_k)]}{1 - \alpha_k}$$

for $k \in \{G, S\}$. Because prices for period t are chosen in period $t-1$, it will be the case under rational expectations that $E_{t-1}p_{k,t} = p_{k,t}$. Defining $E_{t-1}\pi_{k,t+1} = E_{t-1}(p_{k,t+1} - p_{k,t})$, the previous two equations can be rewritten as

$$E_{t-1}\pi_{k,t} = \theta_k E_{t-1}(w_t - z_{k,t} - p_{k,t}) + \beta E_{t-1}\pi_{k,t+1}.$$

Next, using Equation (3.23) to substitute out w_t and applying market clearing so that $c_t = y_t$ yields

$$E_{t-1}\pi_{k,t} = \theta_k E_{t-1}\{\sigma_H y_t - \lambda_t - p_{k,t} - \sigma_H[n z_{G,t} + (1-n) z_{S,t}] - z_{k,t}\} + \beta E_{t-1}\pi_{k,t+1}.$$

Then, using Equation (3.21) to substitute out λ_t yields

$$\begin{aligned} E_{t-1}\pi_{k,t} = \beta E_{t-1}\pi_{k,t+1} + \theta_k E_{t-1}\Bigg\{ &-\frac{\beta\eta}{\psi} y_{t+1} + \left(\sigma_H + \frac{1}{\psi}\right) y_t - \frac{\eta}{\psi} y_{t-1} \\ &+ p_t - p_{k,t} - \sigma_H[n z_{G,t} + (1-n) z_{S,t}] - z_{k,t} \Bigg\}. \end{aligned}$$

Finally, substituting out $p_t - p_{k,t}$ with Equation (3.19) yields

$$E_{t-1}\pi_{k,t} = \beta E_{t-1}\pi_{k,t+1} + \theta_k E_{t-1}\Bigg\{-\frac{\beta\eta}{\psi}y_{t+1} + \left(\sigma_H + \frac{1}{\psi} - \frac{1}{\phi}\right)y_t - \frac{\eta}{\psi}y_{t-1} + \frac{1}{\phi}y_{k,t} - \sigma_H[nz_{G,t} + (1-n)z_{S,t}] - z_{k,t}\Bigg\},$$

which is the sectoral New Keynesian Phillips curve. Using Equation (3.18) to combine the sectoral New Keynesian Phillips curves for each sector yields

$$E_{t-1}\pi_t = \beta E_{t-1}\pi_{t+1} + [n\theta_G + (1-n)\theta_S]E_{t-1}\left[-\frac{\beta\eta}{\psi}y_{t+1} + \left(\sigma_H + \frac{1}{\psi} - \frac{1}{\phi}\right)y_t - \frac{\eta}{\psi}y_{t-1}\right] + \frac{1}{\phi}E_{t-1}[n\theta_G y_{G,t} + (1-n)\theta_S y_{S,t}] - E_{t-1}[n\theta_G z_{G,t} + (1-n)\theta_S z_{S,t}] - \sigma_H[n\theta_G + (1-n)\theta_S]E_{t-1}[nz_{G,t} + (1-n)z_{S,t}],$$

which is the generalized New Keynesian Phillips curve. When $\alpha_G = \alpha_S$ so that $\theta_G = \theta_S = \theta$, then applying Equation (3.17) yields

$$E_{t-1}\pi_t = \beta E_{t-1}\pi_{t+1} + \theta E_{t-1}\left[-\frac{\beta\eta}{\psi}y_{t+1} + \left(\sigma_H + \frac{1}{\psi}\right)y_t - \frac{\eta}{\psi}y_{t-1}\right] - \theta(1+\sigma_H)E_{t-1}[nz_{G,t} + (1-n)z_{S,t}],$$

which is the standard New Keynesian Phillips curve for a one sector economy.

Appendix D

In this appendix, I examine the theoretical effects of changing n and α_k separately from each other. Because the focus of the paper is on the impulse response of output to interest rate shocks, I limit the discussion to how n and α_k impact output.

To examine n and α_k separately, I consider four different specifications, listed in Table 3.2, where each specification has two different models. In the first specification, I fix $\alpha_G = 0.827$ and $\alpha_S = 0.390$, which correspond to their 1959 to 1978 values, an let n change from 0.510 to 0.383. In the second specification, I fix $\alpha_G = 0.786$ and $\alpha_S = 0.326$, which correspond to their 1983 to 2007 values, an let n change from 0.510 to 0.383. In the third specification, I fix $n = 0.510$, its 1959 to 1983 value, and let α_G and α_S switch from their 1959 to 1978 values to their 1983 to 2007 values. Finally, in the fourth specification, In the third specification, I fix $n = 0.383$, its 1959 to 1983 value, and let α_G and α_S switch from their 1959 to 1978 values to their 1983 to 2007 values. For parameters other than n, α_G and α_S, parameter values are taken as described in Subsection 3.2.5.

Table 3.5: Parameter Values

	Specification 1		Specification 2		Specification 3		Specification 4	
Parameters	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
α_G	0.827	0.827	0.786	0.786	0.827	0.786	0.827	0.786
α_S	0.390	0.390	0.326	0.326	0.390	0.326	0.390	0.326
n	0.510	0.383	0.510	0.383	0.510	0.510	0.383	0.383

Figure 3.6 displays the theoretical impulse responses of output to a 0.25% interest rate shock for each specification. In every specification, Model 2 displays a larger impulse response than Model 1. This is because is every specification, the nominal rigidities increase from Model 1 to Model 2 through either an increase in the relative size of the services sector or

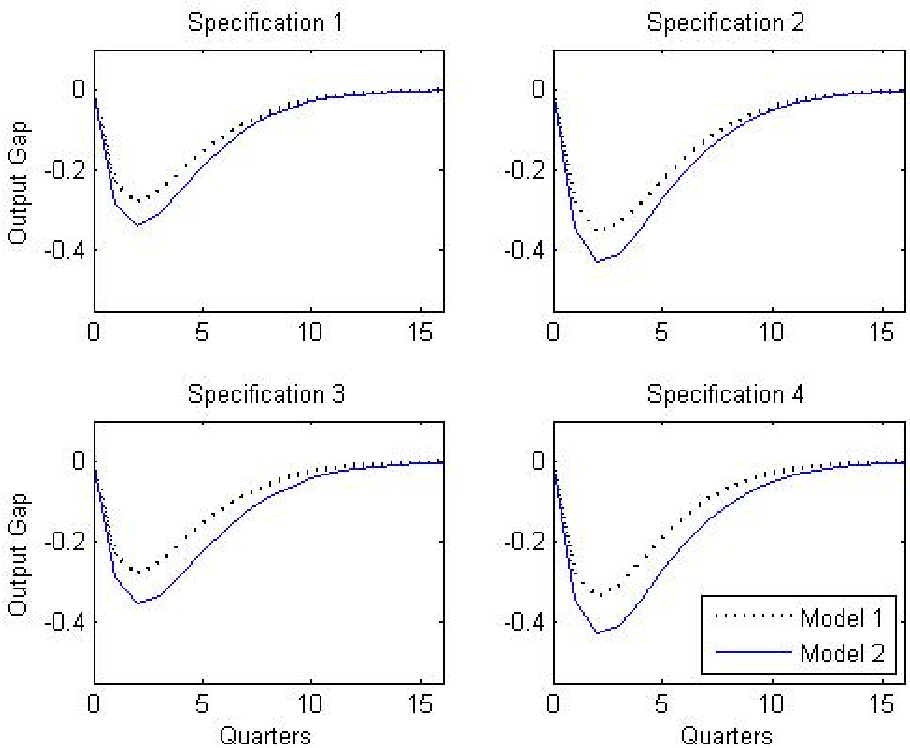

Figure 3.6: Theoretical impulse responses of output to a 0.25% interest rate shock. In Specification 1, the sectoral price change probabilities are calibrated to 1959 to 1978 data for both Model 1 and Model 2, but the relative sectoral sizes are calibrated to 1959 to 1978 data in Model 1 and to 1983 to 2007 data in Model 2. In Specification 2, the sectoral price change probabilities are calibrated to 1983 to 2007 data for both Model 1 and Model 2, but the relative sectoral sizes are calibrated to 1959 to 1978 data in Model 1 and to 1983 to 2007 data in Model 2. In Specification 3, the the relative sectoral sizes are calibrated to 1959 to 1978 data for both Model 1 and Model 2, but the sectoral price change probabilities are calibrated to 1959 to 1978 data in Model 1 and to 1983 to 2007 data in Model 2. In Specification 4, the the relative sectoral sizes are calibrated to 1983 to 2007 data for both Model 1 and Model 2, but the sectoral price change probabilities are calibrated to 1959 to 1978 data in Model 1 and to 1983 to 2007 data in Model 2. In all four specifications, Model 2 represents an economy with greater nominal rigidities than Model 1.

the increase in the stickiness in both sectors. Additionally, for a given model, Specification 2 has larger impulse responses than Specification 1. This is because in Specification 2, α_G and α_S have their 1983 to 2007 values and in Specification 1 they have their 1959 to 1983 values. Similarly, for a given model, Specification 4 has larger impulse responses than Specification 3. This is because in Specification 4, n has its 1983 to 2007 value and in Specification 3 it has its 1959 to 1983 value.

For both Specification 1 and Specification 2, the trough of the impulse response of Model 2 is about 21% larger in magnitude than the trough of the impulse response of Model 1. This implies that decreasing n from 0.510 to 0.383 while holding α_G and α_S constant increases the impulse response of output to an interest rate shock by about 21%.

For both Specification 3 and Specification 4, the trough of the impulse response of Model 2 is about 27% larger in magnitude than the trough of the impulse response of Model 1. This implies that switching α_G and α_S from their 1959 to 1978 values to their 1983 to 2007 values while holding n constant increases the impulse response of output to an interest rate shock by about 27%.

Examining both the changing n and the changing α_k in isolation indicates that, for the parameter values in Subsection 3.2.5, changing α_k has a larger impact than changing n. However, both changes contribute substantial increases to the total increase in the impulse response of output.

Finally, note that adding the isolated impulse response increases yields a total increase of 48%. However, for the models listed in Table 3.2, the increase of the impulse response in output from Model 1 to Model 2 is 54%. This indicates that, in addition to their isolated effects, n and α_k have an interaction effect that increases the impulse response of output.

Appendix E

In this appendix, I describe the procedure for estimating the FAVAR. First, for notation purposes, I define

$$\underset{(T\times N)}{\mathbf{X}} = \begin{bmatrix} \mathbf{X}_1' \\ \vdots \\ \mathbf{X}_T' \end{bmatrix}, \quad \underset{(T\times k)}{\mathbf{C}} = \begin{bmatrix} \mathbf{C}_1' \\ \vdots \\ \mathbf{C}_T' \end{bmatrix}, \quad \underset{(T\times N)}{\epsilon} = \begin{bmatrix} \epsilon_1' \\ \vdots \\ \epsilon_T' \end{bmatrix}.$$

Then, Equation (3.33) becomes

$$\mathbf{X} = \mathbf{C}\boldsymbol{\Psi} + \epsilon$$

Following Boivin, Giannoni, and Mihov (2009), I assume that the common factors are composed of $k-1$ unobservable factors and the Federal Funds rate so that

$$\mathbf{X} = \begin{bmatrix} \mathbf{F} & \mathbf{R} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Psi}_F \\ \boldsymbol{\Psi}_R \end{bmatrix} + \epsilon,$$

where $\mathbf{F}$ is the $T \times k-1$ matrix of unobserved factors, $\mathbf{R}$ is the $T \times 1$ matrix of Federal Funds rate data, $\boldsymbol{\Psi}_F$ is a $k-1 \times N$ matrix of loadings on $\mathbf{F}$ and $\boldsymbol{\Psi}_R$ is a $1 \times N$ matrix of loadings on $\mathbf{R}$.

In order to estimate $\mathbf{F}$, Ψ_F and Ψ_R, I follow Stock and Watson (2002) and minimize the following criterion

$$\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\epsilon_{it}^2 = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}(X_{it} - \Psi_{F,i}'F_t - \Psi_{R,i}R_t)^2,$$

where X_{it} is the realization of time series i in period t, $\Psi_{F,i}$ is the $k-1\times 1$ vector of loadings on the $k-1$ unobserved factors F_t in period t and $\Psi_{R,t}$ is the loading on the observation of the Federal Funds rate R_t in period t.

The solution to the minimization problem is as follows. First,

$$\hat{\mathbf{\Psi}}_R = (\mathbf{R}'\mathbf{R})^{-1}\mathbf{R}'\mathbf{X}.$$

Then, $\hat{\mathbf{\Psi}}_F$ is composed of the $k-1$ eigenvectors associated with the $k-1$ largest eigenvalues of $\hat{\Sigma}$ scaled by $\sqrt{N}$, where

$$\hat{\Sigma} = \frac{1}{T}(\mathbf{X} - \mathbf{R}\hat{\mathbf{\Psi}}_R)'(\mathbf{X} - \mathbf{R}\hat{\mathbf{\Psi}}_R)$$

is the estimated covariance matrix of $\mathbf{X} - \mathbf{R}\hat{\mathbf{\Psi}}_R$. Finally,

$$\hat{\mathbf{F}} = \frac{1}{N}(\mathbf{X} - \mathbf{R}\hat{\mathbf{\Psi}}_R)\hat{\mathbf{\Psi}}_F.$$

I estimate $\hat{\mathbf{\Psi}}_R$, $\hat{\Sigma}$ and $\hat{\mathbf{F}}$ using eight unobservable factors in addition to the Federal Funds rate. I choose this specification based on the second information criterion in Bai and Ng (2002). Of the three information criterion in Bai and Ng (2002), the second information criterion performs best in simulations.

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