Shocks and Frictions in US Business Cycles with Heterogeneous Agents*

Preliminary and Incomplete

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Abstract

Does market incompleteness change our view on the sources of business cycle fluctuations? Using a Bayesian likelihood approach, we estimate a Heterogeneous Agent New Keynesian (HANK) model in which aggregate demand and investment depend on aggregate changes in idiosyncratic income risk and portfolio liquidity, which are partly exogenous and partly respond to other aggregate shocks. We use the estimated model to compare the decomposition of U.S. GDP, consumption, and investment growth to various New Keynesian models without incomplete markets. We find that demand shocks explain a larger share of the business cycle, even the long run. Shocks to income risk and portfolio liquidity partly replace unobservable shocks to the risk premium.

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1 Introduction

A new generation of monetary business cycle models with heterogeneous agents (HANK, for short) has become popular. This new class of models implies new transmission channels of monetary\(^1\) and fiscal policy\(^2\), as well as new sources of business cycles.\(^3\) In this paper, we reexamine the analysis of Smets and Wouters (2007) in a medium-scale HANK model. Toward this end, we estimate a variety of New Keynesian models with various forms of heterogeneity using a full information Bayesian likelihood approach to assess whether these models change our view of the shocks and frictions in US business cycles.

HANK economies differ from economies with a representative household in that precautionary motives play an important role for the consumption/savings decision. The common assumptions are that individual income is subject to idiosyncratic risk and borrowing is constrained. In this environment, a household’s optimal savings and portfolio allocation depends on the level of income risk and the liquidity of her assets. Aggregate changes in income risk or liquidity are thus a new source of business cycle fluctuations relative to business cycle models with complete markets. These changes may come from aggregate shocks that directly affect income risk or liquidity and from the endogenous response of both to other aggregate shocks.\(^4\)

There is ample evidence that income risk and liquidity are both counter-cyclical. Storesletten et al. (2001) estimate that for the U.S. the variance of persistent income shocks to disposable household income almost doubles in recessions. Similarly, Guvenen et al. (2014) find a sizable increase in the left skewness of the income distribution in recessions. Various measures of liquidity are counter-cyclical as well. Hedlund (2016) documents a sharp increase in the time to sell a house in the U.S. during the Great Recession. Credit spreads rise in recessions as well; see Gilchrist and Zakrajšek (2012).

Following Bayer et al. (2019), we model idiosyncratic income risk as an autoregressive process with stochastic volatility, and portfolio liquidity as random participation in the capital market. In our model, households have access to two types of assets to smooth consumption. They can either hold liquid nominal bonds or invest in illiquid physical...
capital. Households trade capital with a time-varying probability, which follows an autoregressive process. Nominal rigidities make the economy demand-driven in the short-run as in the standard New Keynesian model.

The stochastic dynamics of the model is driven by seven standard aggregate shocks: total factor productivity, risk premium, monetary policy, government spending, taxes, and price- and wage-mark-up shocks; as well as two HANK-specific aggregate shocks: idiosyncratic income risk and portfolio liquidity. We assume that income risk and portfolio liquidity are a linear function of the state of the economy. This allows us to separate the importance of endogenous propagation of other shocks via income risk and liquidity relative to the importance of direct shocks to income risk and liquidity.

We treat income risk to be observable, and use the estimates of income risk for the U.S. provided by Bayer et al. (2019). The probability to adjust the portfolio, by contrast, is a partially observed state of model. We assume this state to be correlated with liquidity measures used in the literature. The other observables are GDP, consumption, investment, government spending and debt, the fed funds rate, inflation, wages, hours worked, and TFP.

We estimate various versions of this model to document how the sources of the business cycle change through the lens of HANK models. We compare the decomposition of GDP, consumption, and investment growth obtained from a New Keynesian model with (i) a representative agent (RANK), (ii) two agent types (savers and spenders, TANK), (iii) a representative agent with bonds in utility (BUNK), (iv) heterogeneous agents with one asset (HANK,1), and (v) heterogeneous agents with two-assets (HANK,2).

With these estimated models in hand, we ask two questions: 1) How do the estimated frictions differ across these models? 2) How do the variance decompositions of short- and long-run fluctuations in GDP, consumption, and investment differ? For briefness, we only compare the RANK to the HANK model with liquid and illiquid assets here. We find that frictions are substantially smaller in the HANK model. Average price stickiness is 8.5 quarters in HANK and 11 quarters in RANK. The investment adjustment cost are 3.5 times larger in RANK. The cost of capital utilization is 20% higher in RANK. At the same time, the standard deviation of shocks is larger in RANK – in particular shocks to the risk premium are 25% larger.

This is reflected in the variance decompositions. While demand shocks (monetary, fiscal, income uncertainty, portfolio liquidity, and risk premium) become more important in HANK, shocks to risk premium explains less in HANK than in RANK. Overall, demand shocks explain 35% more of short-run output fluctuations in HANK than RANK (27% vs 20%) and 400% more in the long-run (8% vs 2%). The composition of supply
shocks changes as well. In HANK, markup shocks become less important at all horizons relative to TFP shocks.

The remainder of this paper is organized as follows: Section 2 describes our model economy, its sources of fluctuations and its frictions. Section 3 provides numerical details on the numerical solution method and estimation technique we apply. Section 4 provides details on the parameters we calibrate to match steady state targets and our main estimation results for all other parameters. Section 5 discusses what these estimates and the model structures of the various model variants we estimate imply for the transmission of shocks and their relative importance for economic fluctuations. Section 6 concludes. An appendix follows.

2 Model

We model an economy composed of a firm sector, a household sector and a government sector. The firm sector comprises (a) perfectly competitive intermediate goods producers who rent out labor services and capital; (b) final goods producers that face monopolistic competition, producing differentiated final goods out of homogeneous intermediate inputs; (c) producers of capital goods that turn consumption goods into capital subject to adjustment costs; (d) labor packers that produce labor services combining differentiated labor from (e) unions that differentiate raw labor rented out from households. Price setting for the final goods as wage setting by unions is subject to a pricing friction à la Rotemberg (1982).

Households earn income from supplying (raw) labor and capital and from owning the firm sector, absorbing all its rents that stem from market power of unions and final-goods producers, and decreasing returns to scale in capital goods production.

The government sector runs both a fiscal authority and a monetary authority. The fiscal authority levies a time-constant labor income tax, issues government bonds, and adjusts expenditures to stabilize debt in the long run and aggregate demand in the short run. The monetary authority sets the nominal interest rate on government bonds according to a Taylor rule.

2.1 Households

The household sector is subdivided into two types of agents: workers and entrepreneurs. The transition between both types is stochastic. Both rent out physical capital, but only workers supply labor. The efficiency of a worker’s labor evolves randomly exposing
worker-households to labor-income risk. Entrepreneurs do not work, but earn all pure rents in our economy except for the rents of unions which are equally distributed across workers. All households self-insure against the income risks they face by saving in a liquid nominal asset (bonds) and a less liquid physical asset (capital). Trading illiquid capital is subject to random participation in the capital market.

To be specific, there is a continuum of ex-ante identical households of measure one, indexed by $i$. Households are infinitely lived, have time-separable preferences with time-discount factor $\beta$, and derive felicity from consumption $c_{it}$ and leisure. They obtain income from supplying labor, $n_{it}$, from renting out capital, $k_{it}$, and from interest on bonds, $b_{it}$, and potentially profit income or union transfers. A time-varying fraction of households, $\lambda_t$, is randomly selected to adjust their capital holdings in every period. $\lambda_t$ follows an autoregressive process with endogenous feedback to the interest rate on bonds $R^b_t$:

$$\hat{\lambda}_{t+1} = \rho_\lambda \hat{\lambda}_t + \Lambda_R \hat{R}^b_{t+1} + \epsilon_t^\lambda,$$

where $\hat{()}$ denotes log-deviations from steady state. Holdings of bonds have to be above an exogenous debt limit $\underline{B}$, and holdings of capital have to be non-negative.

A household’s labor income $w_{t} h_{it} n_{it}$ is composed of the aggregate wage rate on raw labor, $w_t$, the household’s hours worked, $n_{it}$, and its idiosyncratic labor productivity, $h_{it}$. We assume that productivity evolves according to a log-AR(1) process with time-varying volatility and a fixed probability of transition between the worker and the entrepreneur state:

$$\tilde{h}_{it} = \begin{cases} 
\exp \left( \rho_h \log \tilde{h}_{it-1} + \epsilon_h^h \right) & \text{with probability } 1 - \zeta \text{ if } h_{it-1} \neq 0, \\
1 & \text{with probability } \zeta \text{ if } h_{it-1} = 0, \\
0 & \text{else},
\end{cases}$$

with individual productivity $h_{it} = \tilde{h}_{it} \int \tilde{h}_{it} \, di$, such that $\tilde{h}_{it}$ is scaled by its cross-sectional average, $\int \tilde{h}_{it} \, di$, to make sure that average worker productivity is constant. The shocks $\epsilon_h^h$ to productivity are normally distributed with time-varying variance that follows an AR(1) process with endogenous feedback to aggregate labor supply $N_t$:

$$\sigma_{h,t}^2 = \sigma_h^2 \exp \hat{s}_t,$$

$$\hat{s}_{t+1} = \rho_s \hat{s}_t + \Sigma_N \hat{N}_t + \epsilon_t^s,$$

i.e., at time $t$ households observe a change in the variance of shocks that drive the next
period’s productivity. With probability $\zeta$ households become entrepreneurs ($h = 0$). With probability $\iota$ an entrepreneur returns to the labor force with median productivity. An entrepreneurial household obtains a fixed share of the pure rents (aside union rents), $\Pi^E_t$, in the economy (from monopolistic competition in the goods sector and the creation of capital). We assume that the claim to the pure rent cannot be traded as an asset. Union rents, $\Pi^U_t$ are distributed lump-sum across workers.

With respect to leisure and consumption, households have Greenwood-Hercowitz-Huffman (GHH) preferences and maximize the discounted sum of felicity:  
\[ E_0 \max_{\{c_{it}, n_{it}\}} \sum_{t=0}^{\infty} \beta^t u \left[ c_{it} - G(h_{it}, n_{it}) \right]. \]  
(5)

The maximization is subject to the budget constraints described further below. The felicity function $u$ exhibits a constant relative risk aversion (CRRA) with risk aversion parameter $\xi > 0$,  
\[ u(x_{it}) = \frac{1}{1 - \xi} x_{it}^{1-\xi}, \]
where $x_{it} = c_{it} - G(h_{it}, n_{it})$ is household $i$’s composite demand for goods consumption $c_{it}$ and leisure and $G$ measures the disutility from work. Goods consumption bundles varieties $j$ of differentiated goods according to a Dixit-Stiglitz aggregator:
\[ c_{it} = \left( \int c_{ijt}^{\frac{n-1}{n}} \, dj \right)^{\frac{n}{n-1}}. \]

Each of these differentiated goods is offered at price $p_{jt}$, so that for the aggregate price level, $P_t = \left( \int p_{jt}^{1-n} \, dj \right)^{\frac{1}{1-n}}$, the demand for each of the varieties is given by
\[ c_{ijt} = \left( \frac{p_{jt}}{P_t} \right)^{-\frac{n}{n-1}} c_{it}. \]

The disutility of work, $G(h_{it}, n_{it})$, determines a household’s labor supply given the aggregate wage rate, $w_t$, and a labor income tax, $\tau$, through the first-order condition:
\[ \frac{\partial G(h_{it}, n_{it})}{\partial n_{it}} = (1 - \tau) w_t h_{it}. \]  
(6)

Assuming that $G$ has a constant elasticity w.r.t. $n$, $\frac{\partial G(h_{it}, n_{it})}{\partial n_{it}} = (1 + \gamma) \frac{G(h_{it}, n_{it})}{n_{it}}$ with  
\[ 5 \text{The assumption of GHH preferences simplifies the numerical analysis substantially and allows us to estimate the model.} \]
\( \gamma > 0 \), we can simplify the expression for the composite consumption good \( x_{it} \) making use of the first-order condition (6):

\[
x_{it} = c_{it} - G(h_{it}, n_{it}) = c_{it} - \left(1 - \tau\right) w_t h_{it} n_{it} \frac{1}{1 + \gamma}.
\] (7)

When the Frisch elasticity of labor supply is constant, the disutility of labor is always a constant fraction of labor income. Therefore, in both the budget constraint of the household and its felicity function only after-tax income enters and neither hours worked nor productivity appears separately.

This implies that we can assume \( G(h_{it}, n_{it}) = h_{it}^{n_{1+\gamma}} \) without further loss of generality as long as we treat the empirical distribution of income as a calibration target. This functional form simplifies the household problem as \( h_{it} \) drops out from the first-order condition and all households supply the same number of hours \( n_{it} = N(w_t) \). Total effective labor input, \( \int n_{it} h_{it} di \), is hence also equal to \( N(w_t) \) because \( \int h_{it} di = 1 \). This means that we can read off productivity risk directly from the estimated income risk and treat both interchangeably. Correspondingly, we will – as a shorthand notation – call the risk households face regarding their productivity “income risk” and the shocks to \( h \) “income shocks,” accordingly.

The households optimize subject to their budget constraint:

\[
c_{it} + b_{it+1} + q_t k_{it+1} = b_{it} \frac{R(b_{it}, R^p_t, A_t)}{\pi_t} + (q_t + r_t) k_{it} + (1 - \tau) (h_{it} w_t N_t + \mathbb{1}_{h_{it} \neq 0} \Pi^U_t + \mathbb{1}_{h_{it} = 0} \Pi^F_t),
\]

\[
k_{it+1} \geq 0, b_{it+1} \geq B,
\]

where \( b_{it} \) is real bond holdings, \( B \) is an exogenous borrowing constraint, \( k_{it} \) is the amount of illiquid assets, \( q_t \) is the price of these assets, \( r_t \) is their dividend, \( \pi_t = \frac{P_t}{P_{t-1}} - 1 \) is realized inflation, and \( R \) is the nominal interest rate on bonds, which depends on the portfolio position of the household and the central bank’s interest rate \( R^p_t \), which is set one period before. All households that decide not to participate in the capital market (\( k_{it+1} = k_{it} \)) still obtain dividends and can adjust their bond holdings. Depreciated capital has to be replaced for maintenance, such that the dividend, \( r_t \), is the net return on capital.

We assume that there is a wasted intermediation cost, \( \mathcal{R} \), when households resort to unsecured borrowing and specify:

\[
R(b_{it}, R^p_t, A_t) = \begin{cases} 
R^p_t A_t & \text{if } b_{it} \geq 0 \\
R^p_t A_t + \mathcal{R} & \text{if } b_{it} < 0.
\end{cases}
\]
This assumption creates a mass of households with zero unsecured credit but with the possibility to borrow, though at a penalty rate. \( A_t \) is a spread between the policy rate and the rate at which households can save, a cost of intermediating government debt to households. It follows an AR(1) process in logs and fluctuates in response to shocks, \( \epsilon_A \).

Substituting the expression \( c_{it} = x_{it} + \frac{(1-\tau)w_th_{it}N_t}{1+\tau} \) for consumption, we obtain:

\[
x_{it} + b_{it+1} + q_t k_{it+1} = b_{it} \frac{R(b_{it}, R_{b,t}, A_t)}{\pi_t} + (q_t + r_t)k_{it} + (1-\tau) \left\{ \frac{\pi_t}{1+\tau} w_th_{it}N_t + \Pi_{h_{it}=0}^{F} \right\},
\]

\[k_{it+1} \geq 0, \quad b_{it+1} \geq B_t\tag{8}\]

Since a household’s saving decision will be some non-linear function of that household’s wealth and productivity, inflation, \( \pi_t \), and accordingly aggregate real bond holdings, \( B_{it+1} \), will be functions of the joint distribution, \( \Theta_t \), of \( (b, k, h) \) in \( t \). This makes \( \Theta \) a state variable of the household’s planning problem. This distribution evolves as a result of the economy’s reaction to aggregate shocks. We summarize all other aggregate state variables by \( S \) (income risk, liquidity, last period’s central bank rate and target markups).

Three functions thus characterize the household’s problem: The value function \( V_a \) for the case where the household adjusts its capital holdings, the value function \( V_n \) for the case in which it does not adjust, and the expected envelope value, \( EV \), over both:

\[
V_a(b, k; h; \Theta; S) = \max_{b', k'} u(x(b, b', k', k, h)) + \beta EV(b', k', h, \Theta', S')
\]

\[
V_n(b, k; h; \Theta; S) = \max_{b'} u(x(b, b', k, k, h)) + \beta EV(b', k, h, \Theta', S') \tag{9}
\]

\[
EV(b', k'; h; \Theta; S) = \lambda_{t+1} EV_a(b', k', h; \Theta, S) + (1 - \lambda_{t+1}) EV_n(b', k, h; \Theta, S)
\]

Expectations about the continuation value are taken with respect to all stochastic processes conditional on the current states.

2.2 Firm Sector

The firm sector consists of a sub-sector that aggregates labor and (labor packers and unions), a sub-sector that produces and sells consumption goods (intermediate goods producers and final goods producers), and a sub-sector that produces capital goods. When the profit maximization decisions in the firm sector require intertemporal decisions, we assume for tractability that they are delegated delegated to a mass-zero group of households (managers) that are risk neutral and compensated by a share in profits.
They do not participate in any asset market and have the same discount factor as all other households. Since managers are a mass-zero group in the economy, their consumption does not show up in any resource constraint and all, but the unions’, profits – net of price adjustment costs – go to the entrepreneur households (whose \( h = 0 \)). Union profits go lump sum to worker households.

2.2.1 Labor Packers and Unions

Worker households sell their labor services to a mass-one continuum of unions indexed by \( j \), who each offer a different variety of labor to labor packers who then provide labor services to intermediate goods producers. Labor packers produce final labor services according to the production function

\[
N_t = \left( \int n_{jt}^\alpha dt \right)^{\frac{\zeta_t}{\alpha-1}},
\]

out of labor varieties \( n_{jt} \). Cost minimization by labor packers implies that each variety of labor, each union \( j \), faces a downward sloping demand curve

\[
n_{jt} = \left( \frac{w_{jt}}{w_t} \right)^{-\zeta_t} N_t,
\]

where \( w_{jt} \) is the real wage set by union \( j \) and \( w_t^F \) is the wage at which labor packers sell labor services to final goods producers.

Since unions have market power, they pay the households a wage lower than the price at which they sell labor to labor packers. Given the wage \( w_t \) at which they buy labor from households and given the wage index \( w_t^F \), unions seek to maximize their discounted stream of profits. In doing so, they face costs of adjusting wages, \( N_t w_t^F \frac{\zeta_t}{2\kappa_w} \left( \log \frac{w_{jt}}{w_{jt-1}} \right)^2 \) quadratic in the log rate of wage change and proportional to the wage sum in the economy. They therefore maximize

\[
E_0 \sum_{t=0}^{\infty} \beta^t w_t^F N_t \left\{ \left( \frac{w_{jt}}{w_t^F} - \frac{w_t}{w_t^F} \right) \left( \frac{w_{jt}}{w_t^F} \right)^{-\zeta_t} - \frac{\zeta_t}{2\kappa_w} \left( \log \frac{w_{jt}}{w_{jt-1}} \right)^2 \right\},
\]

by adjusting \( w_{jt} \) every period; \( \tilde{\pi}^w \) is steady state wage inflation and the fact that it shows up in wage adjustment costs reflects indexation.

Since all unions are symmetric, we focus on a symmetric equilibrium and obtain the
wage Phillips curve from the corresponding first order condition

$$\log \left( \frac{\pi^w_t}{\pi^w} \right) = \beta E_t \left[ \log \left( \frac{\pi^w_{t+1}}{\pi^w} \right) + \frac{w^F_{t+1}}{w^F_t} \frac{N_{t+1}}{N_t} \right] + \kappa \left( \frac{w^F_t}{w^F_t} - \mu^w_t \right), \quad (12)$$

with $\pi^w_t := \frac{w_t}{w_{t-1}}$ being wage inflation and $\mu^w_t = \frac{c_t}{\pi_t}$ being the target mark-down of wages the unions pay to households, $w_t$, relative to the wages charged to firms, $w^F_t$. This target fluctuates in response to markup shocks, $\epsilon^\mu_t$, and follows an log AR(1) process.\(^6\)

### 2.2.2 Final Goods Producers

Similar to unions, final-goods producers differentiate a homogeneous intermediate good and set prices. They face a downward sloping demand curve the demand for good $j$,

$$y_{jt} = \left( \frac{p_{jt}}{P_t} \right)^{-\eta} Y_t,$$

for each good $j$ and as we do for unions, we assume price adjustment costs à la Rotemberg (1982). They buy the intermediate good at price $MC_t$.

Under this assumption, the firms’ managers maximize the present value of real profits given this costs of price adjustment, i.e., they maximize:

$$E_0 \sum_{t=0}^{\infty} \beta^t Y_t \left\{ \left( \frac{p_{jt}}{P_t} - MC_t \right) \left( \frac{p_{jt}}{P_t} \right)^{-\eta} - \frac{\eta}{2\kappa} \left( \log \frac{p_{jt}}{p^t_{jt-1} 1} \right)^2 \right\}, \quad (13)$$

with a time constant discount factor.

The corresponding first-order condition for price setting imply again a Phillips curve

$$\log \left( \frac{\pi^w_t}{\pi^w} \right) = \beta E_t \left[ \log \left( \frac{\pi^w_{t+1}}{\pi^w} \right) + \frac{\eta}{\eta+1} \frac{Y_{t+1}}{Y_t} \right] + \kappa \left( MC_t - \frac{1}{\mu^t} \right), \quad (14)$$

where $\pi^w_t$ is the gross inflation rate, $\pi^w_t := \frac{P_t}{P_{t-1}}$, $MC_t$ is the real marginal costs, $\pi^w_t$ steady state inflation and $\mu_t = \frac{\eta}{\eta+1}$ is the target markup. As for the unions, this target fluctuates in response to markup shocks, $\epsilon^\mu_t$, and follows an log AR(1) process. We choose the cost to vary with the target markup to create a Phillips curve with a constant steepness as under Calvo adjustment. The price adjustment then creates real costs $\frac{\eta}{\eta+1} Y_t \log(\pi^w_t/\bar{\pi}^w)^2$.

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\(^6\)Up to the first order approximation around the steady state, the Phillips curve is identical to $\log(\pi^w_t/\bar{\pi}^w) = \beta E_t \log(\pi^w_{t+1}/\bar{\pi}^w) + \kappa \left( \frac{w^F_t}{w^F_t} - \mu^w_t \right)$, the Phillips curve obtained under Calvo adjustment.
2.2.3 Intermediate Goods Producers

Intermediate goods are produced with a constant returns to scale production function:

$$Y_t = Z_t N_t^\alpha (u_t K_t)^{(1-\alpha)};$$

where $Z_t$ is total factor productivity and follows an autoregressive process in logs and $u_t K_t$ is the effective capital stock taking into account utilization $u_t$, i.e., the intensity with which the existing capital stock is used. Without loss of generality, capital utilization in steady state is normalized to 1. Using capital with an intensity higher than normal incurs maintenance costs (in units of the consumption good) beyond depreciation of $\delta(u_t) = \delta_1 (u_t - 1) + \delta_2/2 (u_t - 1)^2$ for every unit of physical capital, which, assuming $\delta_1, \delta_2 > 0$, is an increasing and convex function of utilization.

Let $MC_t$ be the relative price at which the intermediate good is sold to entrepreneurs. The intermediate-good producer maximizes profits,

$$MC_t Z_t Y_t - w^F_t N_t - (r_t + \delta_0 q_t + \delta(u_t)) K_t,$$

but it operates in perfectly competitive markets, such that the real wage and the user costs of capital are given by the marginal products of labor and effective capital:

$$w^F_t = \alpha MC_t Z_t ((u_t K_t)/N_t)^{1-\alpha},$$  \hspace{1cm} (15)

$$r_t + \delta_0 q_t = u_t (1-\alpha) MC_t Z_t (N_t/(u_t K_t))^\alpha - \delta(u_t),$$ \hspace{1cm} (16)

where $\delta_0$ is the depreciation rate of capital goods.

We choose maintenance costs (in consumption goods instead of capital goods) for utilization to disentangle the capacity utilization decision from investment, and hence to disentangle the estimates of the two frictions. We assume that utilization is decided by the owners of the capital goods, taking the aggregate supply of capital services as given. The optimality condition for utilization is given by

$$\delta_1 + \delta_2 (u_t - 1) = (1 - \alpha) MC_t Z_t (N_t/(u_t K_t))^\alpha,$$ \hspace{1cm} (17)

i.e., in capital owners increase utilization until the marginal maintenance costs equal the marginal product of capital services.
2.2.4 Capital Goods Producers

Capital goods producers operate a capital goods production function that turns $I_t$ units of the consumption good into $\left[1 - \frac{\phi}{2} \left(\log \frac{I_t}{I_{t-1}}\right)^2\right] I_t$ units of the capital good; i.e., they face quadratic adjustment costs on their output growth – investment adjustment costs. They are perfectly competitive and take the relative price of capital goods $q_t$ as given, i.e. they maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t I_t \left\{ q_t \left[1 - \frac{\phi}{2} \left(\log \frac{I_t}{I_{t-1}}\right)^2\right] - 1 \right\}.$$

(18)

Optimality of the capital goods production requires

$$q_t \left[1 - \frac{\phi}{2} \left(\log \frac{I_t}{I_{t-1}}\right)^2 - \phi \log \frac{I_t}{I_{t-1}}\right] - \beta E_t \left[q_{t+1} \phi \log \left(\frac{I_{t+1}}{I_t}\right) \frac{I_{t+1}}{I_t}\right] = 1,$$

(19)

and each capital goods producer will adjust its production until (19) is fulfilled.

Since all capital goods producers are symmetric, we obtain as the law of motion for aggregate capital

$$K_t - [1 - \delta_0] K_{t-1} = \left[1 - \frac{\phi}{2} \left(\log \frac{I_t}{I_{t-1}}\right)^2\right] I_t.$$

(20)

The functional form assumption implies that investment adjustment costs are minimized and equal to 0 in steady state.

2.3 Government

The government operates a monetary and a fiscal authority. The monetary authority controls the nominal interest rate on liquid assets, while the fiscal authority issues government bonds to finance deficits and adjusts expenditures to stabilize debt in the long run and output in the short run.

We assume that monetary policy sets the nominal interest rate on bonds following a Taylor (1993)-type rule with interest rate smoothing:

$$\frac{R_{t+1}^b}{R_t^b} = \left(\frac{R_{t+1}^b}{R_t^b}\right)^{\rho_R} \left(\frac{\pi_t}{\pi_t}\right)^{(1-\rho_R)\theta_x} \left(\frac{Y_t}{Y_{t-1}}\right)^{(1-\rho_R)\theta_y} e_t^R.$$

(21)

The coefficient $\bar{R}_t^b \geq 0$ determines the nominal interest rate in the steady state. The
coefficients $\theta_r, \theta_Y \geq 0$ governs the extent to which the central bank attempts to stabilize inflation and output around their steady-state values. $\rho_R \geq 0$ captures interest rate smoothing.

The government follows simple rules for government spending and taxes that react to government debt and output deviations from steady-state:

$$\frac{G_t}{G} = \left( \frac{G_{t-1}}{G} \right)^{\rho_G} \left( \frac{B_t}{B} \right)^{(1-\rho_G)\theta_G B} \left( \frac{Y_t}{Y} \right)^{(1-\rho_G)\theta_G Y} \epsilon^G_t. \quad (22)$$

$$\frac{\tau_t}{\tau} = \left( \frac{\tau_{t-1}}{\tau} \right)^{\rho_{\tau}} \left( \frac{B_t}{B} \right)^{(1-\rho_{\tau})\theta_{\tau} B} \left( \frac{Y_t}{Y} \right)^{(1-\rho_{\tau})\theta_{\tau} Y} \epsilon^\tau_t. \quad (23)$$

There are three shocks to government rules: monetary shocks, $\epsilon_R$, government spending shocks, $\epsilon_G$, and tax rate shocks, $\epsilon_\tau$. The government budget constraint then determines bond issuance $B_{t+1} = G_t - T_t + R^b_t/\pi_t$, where $T_t = \tau_t N_t w_t + \tau \Pi^g_t$.

### 2.4 Goods, Bonds, Capital, and Labor Market Clearing

The labor market clears at the competitive wage given in (15). The bond market clears whenever the following equation holds:

$$B_{t+1} = B^d(\Theta_t, S_t; q_t, \pi_t, w_t) := E[\lambda_t b^*_a + (1-\lambda_t) b^*_n], \quad (24)$$

where $b^*_a, b^*_n$ are functions of the states $(b, k, h; S_t)$, of current prices $q_t, \pi_t, w_t$, and of expectations of future prices. Expectations in the right-hand-side expression are taken w.r.t. the distribution $\Theta_t(b, k, h)$. Equilibrium requires the total net amount of bonds the household sector demands, $B^d$, to equal the supply of government bonds. In gross terms there are more liquid assets in circulation as some households borrow up to $B$.

Last, the market for capital has to clear:

$$K_{t+1} = K^d(\Theta_t, S_t; q_t, \pi_t, w_t) := E[\lambda_t k^* + (1-\lambda_t) k], \quad (25)$$

where the first equation stems from competition in the production of capital goods, and the second equation defines the aggregate supply of funds from households – both those that trade capital, $\lambda_t k^*$, and those that do not, $(1-\lambda_t) k$. Again $k^*$ is a function of the state variables $(\Theta_t, S_t)$, and current and expected future prices. The goods market then clears due to Walras’ law, whenever labor, bonds, and capital markets clear.
2.5 Recursive Equilibrium

A recursive equilibrium in our model is a set of policy functions \( \{x^*_a, x^*_n, b^*_a, b^*_n, k^*\} \), value functions \( \{V_a, V_n, EV\} \), pricing functions \( \{r, w, \pi, q, R^b\} \), aggregate capital and labor supply functions \( \{K, N\} \), distributions \( \Theta \) over individual asset holdings and productivity, and a perceived law of motion \( \Gamma \), such that

1. Given \( \{V_a, V_n\}, \Gamma, \) prices, and distributions, the policy functions \( \{x^*_a, x^*_n, b^*_a, b^*_n, k^*\} \) solve the households’ planning problem, and given the policy functions \( \{x^*_a, x^*_n, b^*_a, b^*_n, k^*\} \), prices and distributions, the value functions \( \{V_a, V_n\} \) are a solution to the Bellman equations (9).

2. The labor, the final goods, the bond, the capital and the intermediate good markets clear, and interest rates on bonds are set according to the central bank’s Taylor rule, i.e., (15), (14), (24), and (25) hold.

3. The actual and the perceived law of motion \( \Gamma \) coincide, i.e., \( \Theta' = \Gamma(\Theta, s') \).

2.6 Representative Agent Variants

We compare the incomplete markets, heterogeneous agent model above to representative agent model versions that feature complete markets. The first variant that we consider is a version with a single representative agent, a “RANK” model. In this model variant, the bonds market and the capital market clearing conditions are replaced with the following two aggregate Euler equation for bonds and capital respectively:

\[
u'(X_t) = E_t \left[ \frac{\beta u'(X_{t+1})}{R(R^b_{t+1}, A_{t+1})} \right]
\]

\[
u't(X_t) = E_t \left[ \frac{\beta u'(X_{t+1})}{r_{t+1} + qt_{t+1}} \right].
\]

Otherwise the model is the same.

Secondly, we consider a variant, where there are two types of households: saver and spender, in short “TANK” model. Savers make their intertemporal decisions according to the conditions above, while spenders use all their income (net of taxes) for consumption. We assume all profit income goes to savers. The idea is that this model picks up the fact that some households have higher marginal propensities to consume and aggregate shocks redistribute across households with different marginal consumption propensities.

Third, we use a variant of the representative agent model, where bond holdings provide additional utility, a bonds in the utility model, in short “BUNK”. Here the
The optimality condition is modified to

\[
 u'(X_t) = E_t \left[ \frac{\beta u'(X_{t+1})}{R(R_{t+1}, A_{t+1})} + \omega_1 B_{t+1}^{\omega_2} \right] 
\]

(28)

\[
 q_t u'(X_t) = E_t \left[ \frac{\beta u'(X_{t+1})}{r_{t+1} + q_{t+1}} \right]. 
\]

(29)

The idea here is that the incomplete markets model has a well behaved bonds demand function in steady state where the steady state interest rate is a function of the aggregate bond supply, such that households require a higher interest rate if bond holdings ought to be larger. The bonds in the utility formulation is thought to be a stand in for this.

3 Numerical Solution and Estimation Technique

We solve all model variants by perturbation methods, and choose a first order Taylor expansion around the steady state. For the model with household heterogeneity, we follow the method of Bayer and Luetticke (2018).

Details to be added ...

4 Calibration, Priors, and Estimated Parameters

We use a Bayesian approach as described in An and Schorfheide (2007) and Fernández-Villaverde (2010). Specifically, we use the Kalman filter to obtain the likelihood from the state-space representation of the model solution and a Nelder-Mead-type optimizer to find the maximize the posterior likelihood.\footnote{Random Walk Metropolis-Hastings is work in progress.} One period in the model refers to a quarter of a year. We estimate the model on U.S. data from 1983 to 2015 (post-Volcker disinflation). Tables 1 summarizes the externally chosen parameters and columns 2-4 of Table 2 list the prior distributions of the estimated parameters. Parameter estimates for the various models are then shown in the remaining columns of Table 2 and are discussed in the second part of this section.

4.1 Calibrated Parameters

For the household side, we set the discount factor such that the model with incomplete markets yields an annual return to capital of 4%. The relative risk aversion is set to a standard value of 2. The Frisch elasticity of 1 corresponds to estimates from the
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Households</strong></td>
<td></td>
<td></td>
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<tr>
<td>$\beta$</td>
<td>0.98</td>
<td>Discount factor</td>
<td>4% return on capital</td>
</tr>
<tr>
<td>$\xi$</td>
<td>2</td>
<td>Relative risk aversion</td>
<td>Standard value</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
<td>Inverse of Frisch elasticity</td>
<td>Chetty et al. (2011)</td>
</tr>
<tr>
<td>$\bar{R}$</td>
<td>11%</td>
<td>Interest wedge (annual)</td>
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<td>$\tau$</td>
<td>0.3</td>
<td>Tax rate</td>
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<tr>
<td>$\rho_h$</td>
<td>0.95</td>
<td>Persistence labor income</td>
<td>Standard value (annual)</td>
</tr>
<tr>
<td>$\sigma_h$</td>
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<td>STD labor income</td>
<td>Standard value (annual)</td>
</tr>
<tr>
<td><strong>Intermediate Goods</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.70</td>
<td>Share of labor</td>
<td>Income share of labor of 2/3</td>
</tr>
<tr>
<td>$\delta_0$</td>
<td>5.4%</td>
<td>Depreciation rate</td>
<td>NIPA: Fixed assets (annual)</td>
</tr>
<tr>
<td><strong>Final Goods</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>21</td>
<td>Elasticity of substitution</td>
<td>Markup 5%</td>
</tr>
</tbody>
</table>

literature; see Chetty et al. (2011). We take estimates for idiosyncratic income risk that are standard in the literature, $\rho_h = 0.95$ and $\sigma_h = 0.1$. The fraction of households in the entrepreneur state is chosen to match a wealth Gini coefficient of 0.78. Finally, households pay a proportional tax rate of 30% on their labor and profit income.

For the firm side, we target an income share of labor of 2/3, which implies a labor share, $\alpha$, of 0.7. The depreciation rate of 1.35% per quarter comes from NIPA. An elasticity of substitution between differentiated goods of 21 yields a markup of 5%. In the current version we abstract from wage stickiness and wage markups/unions.

### 4.2 Priors and Posteriors

Columns 2-4 of Table 2 presents the initial prior distributions. Where available, we use prior values that are standard in the literature (e.g. Smets and Wouters, 2007) and independent of the underlying data. The autoregressive parameters of the shock processes are assumed to follow a beta distribution with mean 0.5 and standard deviation 0.2. We assume the standard deviations of the shocks to follow inverse-gamma distributions with prior mean 0.1 percent and standard deviation 2. The only exceptions are the uncertainty and liquidity shocks, where we use a prior mean of 1.0, and the measurement errors, for which we assume a inverse-gamma prior with a lower prior mean.
of 0.05 percent. The employment and interest feedback parameters in the uncertainty and liquidity processes are assumed to follow Standard Normal priors. The feedback parameters in the government spending and tax rules (θ_{Yi} for i ∈ \{G, τ\}) are assumed to follow Gamma distribution, where the response parameters for G are multiplied by -1 to ensure countercyclical policies. For the inflation and output feedback parameters in the Taylor-rule, θ_π and θ_y, we impose normal distributions with prior means of 2 and 0.125, respectively, while the interest rate smoothing parameter ρ_R has the same prior distribution as the persistence parameters of the shock processes. We impose an inverse-gamma distribution with prior mean of 0.5 and standard deviation of 0.15 for δ_2/δ_1, the elasticity of marginal depreciation with respect to capacity utilization. For the Rotemberg price adjustment cost-parameter γ, we assume a Gamma prior with mean 0.09 and standard deviation 0.1. Finally, we stay close to the literature (e.g. Justiniano et al., 2010; Smets and Wouters, 2007) and impose a gamma prior with mean 5 for the parameter controlling investment adjustment costs φ.

### 4.3 Estimation Results

Table 2 shows that, relative to the RANK and TANK models, the HANK model requires less real and nominal frictions. This indicates stronger internal propagation in the HANK model. At the same time, monetary policy is less stabilizing in the HANK than in the RANK model, especially with respect to output. Fiscal policy behaves similarly across models, the one exception is the lower variance of tax shocks in the HANK model. The most notable difference between the estimated parameters of the shock processes is a lower persistence of markup shocks in HANK. There is some feedback from employment and interest rates to income volatility and liquidity but it’s estimated to be rather small. Measurement errors for investment and wages are rather larger, not so much for the other observables.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior distributions and posterior modes</th>
<th>Posterior mode</th>
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<tbody>
<tr>
<td></td>
<td>Distribution</td>
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<td>$\kappa$</td>
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<tr>
<td>$-\theta_{GB}$</td>
<td>Gamma</td>
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<tr>
<td>$-\theta_{GY}$</td>
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<td>$\theta_{rY}$</td>
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<td>$\sigma_s$</td>
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<td>$\Sigma_N$</td>
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<td>$\rho_\lambda$</td>
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<td>$\sigma_\lambda$</td>
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<tr>
<td>$\Lambda_R$</td>
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<td><strong>Measurement Errors</strong></td>
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<td>$\sigma_{me_Y}$</td>
<td>Inv.-Gamma</td>
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</tr>
<tr>
<td>$\sigma_{me_I}$</td>
<td>Inv.-Gamma</td>
<td>0.05</td>
</tr>
<tr>
<td>$\sigma_{me_N}$</td>
<td>Inv.-Gamma</td>
<td>0.05</td>
</tr>
<tr>
<td>$\sigma_{me_W}$</td>
<td>Inv.-Gamma</td>
<td>0.05</td>
</tr>
<tr>
<td>$\sigma_{me_B}$</td>
<td>Inv.-Gamma</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Notes:** The standard deviations of the shocks and measurement errors have been transformed into percentages by multiplying with 100.
5 Results

This section addresses the question whether HANK models imply a different view on the business cycle than New Keynesian models with representative households.

We first compare the variance decompositions of the U.S. business cycle from three estimated models, RANK, TANK, HANK.

To better understand these results, we discuss differences in the impulse responses to various shocks. We finally compare the estimated HANK models with one and two asset structure.

5.1 Variance Decompositions

We first group shocks into supply and demand shocks. Figure 1 reports the variance decompositions for the estimated RANK, TANK, and HANK model. In all three models, output, consumption, and investment are predominantly driven by supply shocks. When markets are complete, demand shocks only matter for short-run fluctuations (conditional variance decompositions after 4 quarters). They explain 20% of output fluctuations in the RANK model after 4 quarters and almost 60% in TANK. At longer horizons, however, demand shocks have very limited effects on output in both models. This is different with incomplete markets. The importance of demand shocks in the long-run is 8% – 4 times more than RANK and TANK. In the short-run it is 27% – in-between the numbers for the RANK and TANK model.

The short-run effects work mostly through hand-to-mouth households. The TANK model therefore captures this well. The long-run effects, however, work through asset-substitution. Households rebalance their portfolios with aggregate conditions and thereby affect the future capital stock.

Figure 2 decomposes the demand block into shocks to the risk premium ($\epsilon^A$), government spending ($\epsilon^G$), taxes ($\epsilon^T$), Taylor rule ($\epsilon^R$), income uncertainty ($\epsilon^\sigma$), and portfolio liquidity ($\epsilon^\lambda$). In the short-run, risk premium shocks are the most important demand shock in the RANK model, explaining 45% of output fluctuations coming from demand. This number drops to 40% in the HANK model. Monetary shocks become less important as well – especially for consumption. Instead, shocks to income uncertainty and portfolio liquidity explain more than 10% of output and consumption fluctuations.

Interestingly, risk premium shocks are more important for long-run fluctuations in HANK than in RANK. This comes from their interaction with portfolio choices.

Figure 3 decomposes supply shocks into TFP ($\epsilon^Z$) and markup ($\epsilon^\mu$) shocks. TFP shocks are more important in HANK than in RANK and TANK for output, consumption,
**Figure 1:** Variance Decompositions: Demand vs Supply

**Notes:** Variance decompositions into demand shocks (i.e., risk premium ($\epsilon^A$), government spending ($\epsilon^G$), taxes ($\epsilon^T$), Taylor rule ($\epsilon^R$), income uncertainty ($\epsilon^\sigma$), portfolio liquidity ($\epsilon^\lambda$)) and supply shocks (i.e., TFP ($\epsilon^Z$) and markup ($\epsilon^\mu$)). Conditional refers to 4 quarters.
Figure 2: Variance Decompositions: Demand shocks only

Notes: Variance decompositions into demand shocks (i.e., risk premium ($\epsilon^A$), government spending ($\epsilon^G$), taxes ($\epsilon^T$), Taylor rule ($\epsilon^R$), income uncertainty ($\epsilon^\sigma$), portfolio liquidity ($\epsilon^\lambda$)). Conditional refers to 4 quarters.
and investment. In particular, TFP explains only 20% of fluctuations in investment in RANK at 4 quarters, while it explains 80% in HANK. Markup shocks are significantly less important in HANK at both horizons.

5.2 Impulse Response Functions

Figure 4 shows the impulse responses to a risk premium shock for all three models with the same parameterization (top) and with the estimated parameters (bottom). Key for the smaller response of output is the re-estimation. When parameters are equal to the RANK economy, output falls more in HANK at all horizons. However, the estimated HANK model yields smaller and slightly less persistent risk premium shocks.

The same holds true for markup shocks; see Figure 5. The aggregate effects of markup shocks are smaller in HANK because these shocks are estimated to be smaller and less persistent. When both models are equally parameterized, markup shocks become more powerful through the larger internal propagation in HANK.

Figure 6 compares the impulse responses to monetary shocks. On impact, a monetary tightening makes output fall more in HANK relative to RANK because of a steeper fall in consumption. Investment, however, responds less. As a result, output is lower for longer in RANK. See Luetticke (2018) for a detailed discussion of the monetary transmission mechanism in HANK.

Finally, Figure 7 and 8 show the impulse responses to the two new shocks in HANK: income uncertainty and portfolio liquidity. Higher uncertainty or lower liquidity lead both to a drop in output of 0.2%. In response to the liquidity shock, consumption and investment fall, while the uncertainty shock depresses only consumption.
Figure 3: Variance Decompositions: Supply shocks only

Notes: Variance decompositions into supply shocks (i.e., TFP ($\epsilon^Z$) and markup ($\epsilon^\mu$)). Conditional refers to 4 quarters.
Figure 4: Impulse responses to a risk premium shock

Notes: Top: Impulse responses when all models have the same parameters (as in RANK). Bottom: Impulse responses with estimated parameters.
Figure 5: Impulse responses to a markup shock

Notes: Top: Impulse responses when all models have the same parameters (as in RANK). Bottom: Impulse responses with estimated parameters.
Figure 6: Impulse responses to a monetary shock

Notes: Top: Impulse responses when all models have the same parameters (as in RANK). Bottom: Impulse responses with estimated parameters.
Figure 7: Impulse responses to an income uncertainty shock

Notes:
Figure 8: Impulse responses to a liquidity shock

Notes:
5.3 Importance of liquidity

Figure 9, 10, and 11 plot the variance decompositions obtained from the HANK model with a representative portfolio alongside the results from before. The key difference between the HANK model with portfolio heterogeneity (HANK2) and the HANK model with representative portfolio (HANK1) lies in the variance decompositions of demand shocks, Figure 10. Shocks to income risk and portfolio liquidity have almost no contribution to the business cycle in the latter. Instead, shocks to the risk premium take their place.
Figure 9: Variance Decompositions: Demand vs Supply

**Notes:** Variance decompositions into demand shocks (i.e., risk premium ($\epsilon^A$), government spending ($\epsilon^G$), taxes ($\epsilon^T$), Taylor rule ($\epsilon^R$), income uncertainty ($\epsilon^\sigma$), portfolio liquidity ($\epsilon^\lambda$)) and supply shocks (i.e., TFP ($\epsilon^Z$) and markup ($\epsilon^\mu$)). Conditional refers to 4 quarters.
Figure 10: Variance Decompositions: Demand shocks only

Notes: Variance decompositions into demand shocks (i.e., risk premium ($\epsilon^A$), government spending ($\epsilon^G$), taxes ($\epsilon^T$), Taylor rule ($\epsilon^R$), income uncertainty ($\epsilon^\sigma$), portfolio liquidity ($\epsilon^\lambda$)). Conditional refers to 4 quarters.
Figure 11: Variance Decompositions: Supply shocks only

Notes: Variance decompositions into supply shocks (i.e., TFP ($\epsilon_Z$) and markup ($\epsilon_{\mu}$)). Conditional refers to 4 quarters.
6 Conclusion

More then 10 years after the influential publication of Smets and Wouters (2007), we reexamine their results through the lens of a state-of-the-art monetary business cycle model with heterogeneous households. We find that incorporating household heterogeneity reduces the importance of unobservable risk premium shocks while increasing the overall importance of demand shocks – in particular in the long run. In addition, household heterogeneity increases internal propagation such that frictions become less important.

References


