Search-Based Endogenous Asset Liquidity and the Macroeconomy*

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Abstract

We develop a search-theory of asset liquidity which gives rise to endogenous financing constraints on investment in an otherwise standard dynamic general equilibrium model. Asset liquidity describes the ease of issuance and resaleability of private financial claims, which is the outcome of a costly search-and-matching process for such claims implemented by financial intermediaries. Limited liquidity of private claims creates a role for liquid assets, such as government bonds, to ease financing constraints. We show that endogenising liquidity is essential to generate positive co-movement between asset liquidity and asset prices. When the cost of channelling funds to entrepreneurs rises, investment and output fall while the hedging value of liquid assets increases, driving up liquidity premia. In the U.S., such intermediation cost shocks can account for about 37% of the variation in output, and more than 78% of the variation in liquidity premia.

Keywords: endogenous asset liquidity; asset search frictions; financing constraints
Classification: E22; E44; G11

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1 Introduction

The 2007-09 financial crisis is associated with a wide-spread liquidity freeze across many financial markets.[1] A deterioration of asset liquidity along with falling asset prices has since been recognised as a key propagation mechanism of financial distress to the real economy (Brunnermeier (2009)). Empirical evidence, however, points to variation in asset liquidity not only during financial crises, but also at business cycle frequency.[2] Are such fluctuations in asset liquidity an inherent and important characteristic of the business cycle?

This paper answers the above question affirmatively by showing that a macroeconomic model featuring endogenous variation in asset liquidity arising from costly financial intermediation is able to match salient, yet difficult-to-explain, business cycle features.

To this end, we introduce costly search fictions in the intermediation of privately issued financial assets into an otherwise standard real business cycle model. Financial assets are backed by physical capital and used to finance idiosyncratic investment opportunities. Search frictions limit the liquidity - or saleability - of these assets and give rise to endogenous financing constraints on firms' investment. These frictions also motivate investors' demand for highly liquid and safe assets to hedge liquidity risks. We model such assets as government bonds. Because of their special service, government bonds carry a liquidity premium, such that their price exceeds their fundamental value.[3]

Private financial assets in our framework capture both equity and debt securities.[4] Issuing and transacting such assets requires recourse to costly financial intermediation services in practice. Initial public offerings (IPOs), for instance, raised $488 billion in the U.S. in 2001, about one fourth of aggregate investment spending. The gross spread paid to under-

[1]Dick-Nielsen, Feldhütter, and Lando (2012) identify a structural break in the market liquidity of corporate bonds at the onset of the sub-prime crisis. Similarly, the liquidity of commercial paper declined dramatically as reported by Anderson and Gascon (2009), with money market mutual funds (the main investors in the market) shifting to highly liquid and secure government securities.

[2]Studies by Chordia, Roll, and Subrahmanyam (2001), Chordia, Sarkar, and Subrahmanyam (2005), and Naes, Skjeltorp, and Odegaard (2011) assert that market liquidity is pro-cyclical and highly correlated across asset classes such as bonds and stocks in the U.S..

[3]This definition follows Geromichalos, Licari, and Suárez-Lledó (2007) and Nosal and Rocheteau (2011).

[4]Formally, financial assets are modelled as equity stakes. However, since private claims do not carry default risks in our model, they stand for broader funding sources of investment including debt instruments.

writers (intermediaries for IPOs) is sizeable. Search for appropriate investors is crucial in this process. Underwriters typically seek to avoid placing a large number of shares with investors who are likely to flip them (i.e., wait until the price spikes upon the opening trade and then immediately dump the position). Instead, they prefer a balance of different types of investors, such as long-term, short-term, domestic and foreign. Between 1989 and 2007, the average spread of deals is around 10%, and more than 90% of the deals up to $250 million has about 7% spread. Seasonal public offerings (SEOs) have comparable volume as IPOs and face similar underwriting costs in order to find the most appropriate buyers. Corporate bonds issued to finance capital investment are also intermediated through underwriters. A typical public bond offering consists of multiple underwriters forming a selling syndicate. The gross spread can be as low as 1% to 2% of a deal, but the variation is much higher than the case of stocks.[5]

Search frictions affecting investment financing are well-suited to capture these features in a generic fashion.[6] By contrast, government debt is often issued in an auction format and its secondary market is liquid.

The introduction of endogenous asset liquidity has important implications for the dynamics of both financial and real variables in our model. Crucially, it allows asset prices and liquidity to move in the same direction. A persistent fall in asset liquidity, for instance, raises the costs of adjusting asset portfolios through the sale of financial assets. Therefore, asset demand falls, pushing down asset prices. At the same time, lower asset liquidity limits the amount of financial claims that can circulate. This tightens firms' financing constraints and exerts upward pressure on asset prices. In our model, the demand effect may dominate, such that asset prices and asset liquidity fall together. We first show that intermediation costs

[5]The figures quoted in this paragraph are based on Ritter and Welch (2002), Yasuda (2005), Abrahamson, Jenkinson, and Jones (2011), and Calomiris and Tsoutsoura (2010), along with our own calculations.

[6]While our framework mainly echoes features of market-based financial intermediation, search frictions have also been used to model credit intermediation by banks, both in the finance (see below references) and in the macroeconomic literature (De-Fiore and Uhlig (2011)). Hence, the intermediation process could also be regarded as bank-based, with banks offering costly screening and monitoring services and channeling funds in the form of loans from depositors to borrowers. In the interest of tractability, we refrain from modeling financial intermediaries' balance sheets more explicitly.

are necessary but not sufficient, and then we derive conditions for the positive price-liquidity relationship, which are linked to the dynamics of search costs.

The co-movement of asset prices and liquidity is a powerful amplification and propagation mechanism. A recessionary shock, which pushes both asset prices and liquidity down, tightens firms' financing constraints substantially as both lower liquidity and prices limit the ability to raise funds for investment. As a result, investment contracts sharply, amplifying also the impact of the recessionary shock on output. This mechanism allows shocks to the financial intermediation cost to generate volatile and pro-cyclical asset prices, which comove positively with asset liquidity as in the data. Due to the interaction of these financial dynamics with firms' financing constraints, even modest intermediation shocks trigger substantial variation in real variables. This feature makes them good candidates for explaining business cycle fluctuations alongside standard productivity shocks.

Asset price dynamics in our model contrast with existing studies of the business cycle implications of exogenous variation in asset liquidity. Popular general equilibrium models with liquidity frictions, such as Kiyotaki and Moore (2012) (henceforth KM) and Jermann and Quadrini (2012), introduce *exogenous* shocks to the liquidity of private financial assets. Adverse liquidity shocks tighten firms' financing constraints. But they do not reduce the demand for investment and financial claims to capital. Therefore, adverse exogenous liquidity shocks create excess demand on the asset market, which unambiguously pushes up asset prices at the same time as the economy slides into recession. The counterfactual response of asset prices to financial shocks in these frameworks has been extensively explored and documented by Shi (2015). Since the counter-cyclical asset price response dampens the sensitivity of financing constraints to financial shocks, very large liquidity shocks or additional frictions are needed to generate deep recessions in these frameworks (see, e.g., Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017)). Financial shocks, therefore, appear ill-suited in these models to explain regular business cycles, much in contrast to our framework.

We exploit the dynamic properties of our model to assess the empirical relevance of real versus financial shocks. In particular, we contrast aggregate productivity shocks with intermediation cost shocks. The latter capture the cost-effectiveness of producing financial services and directly affect intermediaries' profitability.

Both shocks generate procyclical asset liquidity and prices for a wide range of reasonable parameterisations of the model. But only adverse intermediation shocks induce portfolio rebalancing towards highly liquid government bonds, manifested in a higher liquidity premium. Negative productivity shocks, for instance, persistently decrease the return to capital, making investment into capital goods less profitable both today and in the future. While asset demand falls, investors have a weak incentive to hedge against future financing constraints associated with less liquid asset markets. This is reflected in a fall of the liquidity premium. By contrast, adverse intermediation shocks do not reduce the return to capital. Investors strongly value the hedging service provided by government bonds and rebalance their asset portfolios accordingly, resulting in a surging liquidity premium. Our model thus predicts that the dynamics of the liquidity premium can discriminate between financial and real shocks. Finally, more active portfolio rebalancing increases asset price volatility.

We then confront the model with U.S. financial and macroeconomic data. We measure the liquidity premium of government debt by the convenience yield associated with U.S. Treasuries.[7] The convenience yield tends to increase in recessions and correlates negatively with real output, while the value of physical capital contracts in recessions and correlates positively with real output. In addition, we explicitly model the provision of financial intermediation services in order to match the size of the U.S. financial sector. Specifically, intermediaries facilitate the flow of funds from investors to firms by matching supply of and demand for financial assets using capital and labour as inputs. They charge fees to the sellers and buyers of financial assets to cover their costs. We match average working hours related to U.S. financial intermediation and the unit cost of the intermediation.

An estimated version of the model using the sample period 1982Q1-2017Q2 suggests

[7] Specifically, we measure the convenience yield as the ratio of the yield on AAA-rated corporate bonds to that of Treasury bills following Krishnamurthy and Vissing-Jorgensen (2012) and Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017). Since both AAA-rated bonds and Treasury bills have negligible default risks, the yield spread of similar-maturity bonds reflects differences in liquidity.

that intermediation shocks explain the vast majority of variation in the convenience yield (78%). They also explain a sizeable share of fluctuations in output (37%) and capital value (38%). As financial intermediation is an intermediate input for investment, a unique feature arising from intermediate costs, intermediation shocks also affect the measured total factor productivity (TFP). Intermediation shocks and aggregate productivity shocks are almost equally important for TFP fluctuations.

Relation to the Literature. We complement the literature on financial/liquidity shocks as possible drivers of cyclical fluctuations in the spirit of KM and Shi (2015). Ajello (2016) studies exogenous shocks to intermediation costs instead of asset liquidity. Kurlat (2013) and Bigio (2015) extend KM with endogenous resaleability through adverse selection.[8] However, the latter papers ignore the role of liquid assets.

We add to the literature by linking endogenous asset liquidity to costly search. We also confront the model to the convenience yield carried by liquid government debt and the size of the financial sector.[9] We show that exogenous intermediation costs, which drive a wedge between the purchase and sale price of financial assets as in Ajello (2016), are necessary, but not sufficient to generate the positive co-movement between asset liquidity and prices. Instead, asset liquidity needs to endogenously affect intermediation costs in order to sufficiently change asset demand. Asset search frictions have this property.

Asset search in this paper draws on the pioneering work of Duffie, Gârleanu, and Pedersen (2005), Weill (2007), and Lagos and Rocheteau (2009), using search theory to model asset liquidity in over-the-counter (OTC) markets in a partial equilibrium setting.[10] This literature has also emphasised the ambiguous impact of trading frictions on asset prices. For instance, Gârleanu (2009) shows that trading frictions reduce asset demand and supply

[8] Eisfeldt (2004) and Guerrieri and Shimer (2014) are also notable examples, but these studies do not consider the feedback effects of liquidity fluctuations on production.

[9] Jaccard (2013) also allows financial intermediaries to produce liquidity services, but he does not study endogenous asset liquidity that are tied to investment financing constraints. We view the link between asset liquidity and financing constraints as crucial. Gazzani and Vicondoa (2016) provide evidence that liquidity shocks in secondary sovereign debt markets can have potent real effects on firms' financing constraints.

[10] An alternative approach to modelling asset liquidity focuses on information frictions, such as the adverse selection models in Eisfeldt (2004) and Guerrieri and Shimer (2014).

simultaneously, such that the turnover volume declines; as in our framework, the asset price response depends on which side of the market is affected more strongly. But the response in our paper is complicated by investment financing constraints.

Search frameworks have also been applied to a wide range of financial markets, including those for corporate bonds, private equity, and asset-backed securities.[11] Rocheteau and Weill (2011) provides an extensive survey on search theory and asset market liquidity. Meanwhile, Den Haan, Ramey, and Watson (2003), Wasmer and Weil (2004), Petrosky-Nadeau and Wasmer (2013), and Dong, Wang, and Wen (2016) have emphasised the role of search frictions in credit markets and their impact on aggregate dynamics.

Search-theoretic models of money, such as Shi (1995), Trejos and Wright (1995), Lagos and Wright (2005), Rocheteau and Wright (2005), and Guerrieri and Lorenzoni (2009) have further highlighted the importance of money for transaction purposes on anonymous search markets. The framework has been extended to analyse privately created liquid assets (Lagos and Rocheteau (2008)), trading delays with market makers (Lagos and Zhang (2016)), and bank-deposits (Williamson (2012)). Rocheteau (2011) shows that the trading restrictions from the money-search framework can be derived from tractable microfoundations exploiting the relative information-sensitivity of different financial assets. Lester, Postlewaite, and Wright (2012) feature asset liquidity and pricing with multiple types of assets with informational asymmetries. Assets are imperfect substitutes, similar to our setting.

Compared to these studies, we focus on the joint determination of asset liquidity (related to meeting rate) and asset prices, which is similar to the joint determination of market tightness and wage rates in labour search (e.g., Mortensen and Pissarides (1994) and Shimer (2005)). These assets are used to fund capital investment in a standard business cycle model, and they are subject to search frictions, similar to Geromichalos and Herrenbrueck (2016) and Mattesini and Nosal (2016); but asset liquidity interacts with investment financing constraints. Government debt, not subject to search frictions in the model, is used to relax the financing constraints. Finally, in our quantitative study, we focus on the size of the

[11] See, e.g., Wheaton (1990); Bao, Pan, and Wang (2011); Feldhutter (2011).

financial sector and the convenience yield of government bonds. These aspects distinguish our paper from Rocheteau and Rodriguez-Lopez (2014) and Branch, Petrosky-Nadeau, and Rocheteau (2016) who study the endogenous supply of liquid assets.

In a macroeconomic context, Yang (2014) and Cao and Shi (2014), also apply search theory to asset or capital markets. In the former study, aggregate productivity shocks can generate co-movement between asset liquidity and prices similar to our model. However, we show that productivity shocks generate a pro- rather than countercyclical convenience yield. The latter authors emphasize capital reallocation rather than financial intermediation.

Finally, while sharing similarities, this paper differs along important dimensions from our previous work (Cui and Radde (2016a)). First, the latter introduces directed search and intermediation chains on asset markets in contrast to the random search approach used here. The model exhibits equilibrium multiplicity even when both liquid and partially liquid assets circulate, thereby complicating its tractability. Second, the current paper offers both theoretical and empirical insights into the dynamic behaviour of asset liquidity and asset prices and the distinct role of financial shocks to explain the business cycle.

2 The Basic Framework

In this section, we describe a partial-equilibrium model featuring liquid government bonds and less liquid privately-issued financial assets. At this stage, we maintain the assumption of exogenous asset liquidity as in Shi (2015) and only model the price of privately-issued assets endogenously. We show that asset prices *can* positively co-move with asset liquidity once transactions of privately-issued claims become costly. The terms "asset liquidity" and "asset saleability" are interchangeable, but this paper will stick to asset liquidity.

2.1 The Environment

Consider a discrete time and infinite-horizon economy with four types of agents: a continuum of households with measure one, goods-producing firms, financial intermediaries, and a government. The consumption good is used as the numeraire throughout the paper. In the following, we only describe households and financial intermediaries.

At the beginning of each period $t = 0, 1, 2, \ldots$, all members of a representative household are identical. They equally divide the assets of the household. During a period, each member receives a status draw, becoming an entrepreneur with probability $\chi \in (0, 1)$ or a worker, otherwise. The type-draw is independent across members and over time. An entrepreneur has investment projects but no labour endowment, while a worker has a unit of labour endowment but no investment project. Both groups are temporarily separated until the end of the period. Such a large household structure facilitates aggregation with only ex-post heterogeneity among the household members. This structure has been used both in labour (see, e.g., Andolfatto (1996); Shimer (2010)) and macro-finance literature (Atkeson, Eisfeldt, and Weill (2015); Bianchi and Bigio (2014)) to reduce dimensionality.

Preferences

For simplicity, we use recursive notation, i.e., x_t is expressed as x, while x_{t+1} is expressed as x_+. At time t, let c^e be the consumption of an individual entrepreneur, and c^w and $\ell \in [0, 1]$ be an individual worker's consumption and hours of work, respectively. The household aggregates the utility of consumption and the dis-utility of labour supply from all its members according to

$$\chi u(c^e, \zeta) + (1 - \chi) U(c^w, \ell),$$

where $\zeta \in [0, 1]$ is a scaling parameter representing the entrepreneurs' efforts to implement investment projects. $u(.,.)$ is differentiable, strictly increasing, concave, and satisfies $\lim_{c \to 0} u_c(c, 0) \to \infty$. $U(.,.)$ is also strictly increasing and concave function of consumption and leisure, with $\lim_{c \to 0} U_c(c, 0) \to \infty$.

Timing and Technologies

Each period t is characterised by four stages.

The Representative Household's Decision Stage. Shocks to asset liquidity ϕ are realised. The types of household members are still unknown, so the household evenly divides its assets among all its members. The household holds a portfolio of government bonds (fully liquid assets b), physical capital (k), and private financial claims (s). Capital will be rented out to goods-producing firms to produce consumption goods at a later stage. Capital stock cannot be traded, but on every unit of capital, there is a private claim, which is either sold to other households or retained by this household. All claims on capital have the same liquidity ϕ and expected return.[12] They can be sold at the same (endogenous) price q. The households hold a diversified portfolio of private claims on the capital stock of the economy.

In the following, the asset market is referred to as the market for private claims, and the asset price is referred to as the price of such claims as well.

The household makes decisions for its members. Each entrepreneur is instructed to consume c^e, invest i, and hold a portfolio of private claims and liquid assets (s^e_+, b^e_+). Each worker is instructed to consume an amount c^w, supply labour ℓ, and hold an asset portfolio (s^w_+, b^w_+). After receiving these instructions, all members go to the market and remain separated until the end of period t.

The Production Stage. The type shock is realised and members follow their instructions. In this partial-equilibrium economy, competitive goods-producing firms rent capital stock at a fixed rate r and hire labour hours at a fixed rate w to produce *numeraire* consumption goods. After production, workers receives wage income, and owners of private claims receive the rental income from capital. Each unit of capital then depreciates at rate $\delta \in (0, 1)$ to $1 - \delta$. Every existing private claim is rescaled by a factor of $1 - \delta$.

The Consumption-Investment Stage. All members pay fixed lump-sum taxes τ, con-

[12] Private claims have a contingent payoff that varies with state of the economy and are, hence, akin to equity stakes. However, as our model does not feature bankruptcies of capital-producing firms, private claims do not carry default risk. Therefore, we think of them as capturing funding sources for investment more broadly, i.e. including debt instruments, such as corporate bonds and banking assets traded in inter-bank markets. We do not distinguish between these types of assets in order to preserve tractability.

sume, and adjust their asset portfolios; entrepreneurs invest. Workers use their savings to buy private claims and government bonds. A government bond that pays off one unit of consumption goods tomorrow is sold at a fixed price p_b. Entrepreneurs use their savings and seek further external funding to finance scaleable investment projects, which transform one unit of consumption goods into one unit of new capital.

The Pooling Stage. All members return to their respective households, again pooling their assets across all members.

Portfolio Adjustment Frictions

In the model, government bonds are assumed to be the only liquid assets, while privately-issued assets are not liquid.[13] Government bonds are typically issued through an auction process, and they are considered risk-free and are traded in highly liquid markets, in which the buy-sell spread of trading them is extremely narrow in practice. For example, Adrian, Fleming, and Vogt (2017) find that during the 1991-2017 sample period, the spreads are 0.8 basis points for the 2-year treasury note, 1.0 basis points for the 5-year note, and 2.0 basis points for the 10-year note.[14]

In practice, there are other types of assets which are also highly liquid, such as fiat money and short-term corporate debt. These assets are used for day-to-day transactions such as accounts payable, inventory, and meeting short-term liabilities. They are not explicitly modeled here, as we focus on assets that are used to fund physical investment, which takes some time to build. For the private economy as a whole, holding government bonds (especially long-term ones) to be liquidated for future investment purposes, or to be used as collateral to borrow funds in the future, seems reasonable.[15]

[13] We use short-term government bonds for tractability reasons. In the quantitative exercise, we target privately-issued assets and government bonds with similar maturities. Privately-issued assets stand for equity and debt issued to fund physical investment purposes. As shown in the reference in the introduction, there are significant costs of intermediating these assets and asset liquidity is limited. Asset liquidity will be determined by targeting a measure of the liquidity premium (see below quantitative analysis).

[14] Government bonds are also preferred assets for collateralised borrowing. The haircut, a reduction applied to the value of an asset, ranges from 0.5%-4%, while privately-issued assets can have haircuts of more than 25%, according to the U.S. Securities and Exchange Commission.

[15] A previous version of the paper (Cui and Radde (2016b)) used money instead of government bonds.

Government bonds are fully liquid and there is no cost of trading them. Household members cannot issue or short-sell them:

$$b_+^j \geq 0, \quad \forall j \in \{e, w\}. \tag{1}$$

Privately created financial assets, however, are only partially convertible into consumption goods in each period, and this conversion entails a cost. We assume that individuals' search for and matching with counterparties is more costly than delegating this process to specialised financial intermediaries. Financial intermediaries can, thus, facilitate the flow of funds from savers to entrepreneurs.

Not all private financial assets for sale can be successfully matched to buyers on account of search frictions, putting a lower bound on entrepreneurs' holdings of private assets. Let $f \in [0, 1]$ be the probability of a buy-side order being matched to a sell-side order; conversely, let $\phi \in [0, 1)$ be the probability of a sell-side order being matched to a buy-side order.

Entrepreneurs finance new capital by two sources, their initial funds and the proceeds from selling old claims and the issuance of new claims (against the new investment). To that end, entrepreneurs sell private claims to the rental income from their investment projects as well as sell retained claims to existing capital in exchange for consumption goods.

Note that this timing assumption creates a possible diversion problem. We assume that financial intermediaries spend resources to monitor the delivery of capital that backs the financial assets. As a result, for every unit of capital, there is exactly one unit of private claims such that the amount of assets *offered* for sale is bounded from above by entrepreneurs' ability to deliver capital.

The amount of private financial assets *retained* by entrepreneurs is, in turn, bounded from below: due to the limited liquidity of private financial assets, every member can sell at most ϕ fraction of, or must retain at least $(1 - \phi)$ fraction of, claims on each new investment

While the version with money shares many similarities with the current version, it complicates the set-up by introducing equilibrium multiplicity. Moreover, modelling government bonds allows us to use the convenience yield on Treasury securities as a key observable to identify financial shocks.

project i^j and previously accumulated claims $(1-\delta)s$ (adjusted for depreciation). Therefore, the holding of private claims is bounded below

$$s_+^j \geq (1-\phi)\left[i^j + (1-\delta)s\right], \quad \forall j \in \{e, w\}. \tag{2}$$

ϕ is thus interpreted as *asset liquidity* which financial frictions are tied to.

Finally, financial intermediaries charge transaction fees to cover costs related to e.g. screening and monitoring services. To model this, we let financial intermediaries pay κ units of consumption goods to process one buy order and to monitor the delivery of one sell order. Since not all orders are matched, financial intermediaries need to process f^{-1} buy orders and monitor ϕ^{-1} sell orders, for each unit of asset transacted. Transaction fees drive a wedge between the prices at which financial assets are purchased and sold. Specifically, let q^w denote the price offered to buyers, and q the price offered to sellers. Since the profit of each transaction accruing to an intermediary is the difference between the purchase and sale prices $q^w - q$, the following zero profit condition holds

$$q^w - q = \kappa\left(\frac{1}{f} + \frac{1}{\phi}\right). \tag{3}$$

In other words, the spread between the purchase and (re-)sale price of private assets covers the intermediation costs.

2.2 The Household's Problem

All members of the household are endowed with s units of claims to capital and b units of bonds.[16] The household makes consumption, savings, and investment plans (c^e, s_+^e, b_+^e, i) for each entrepreneur as well as consumption, savings, and labour supply plans (c^w, s_+^w, b_+^w, ℓ) for each worker. The household faces a resource constraint on each member.

An Entrepreneur's Constraints. After paying taxes, entrepreneurs finance new invest-

[16] All capital is simply rented out so that we do not need to keep track of capital.

ment ($i^e = i > 0$) and consumption ($c^e > 0$) with capital rental income rs as well as net receipts from trading government bonds $b - p_b b_+^e$ and selling private claims $q\left[i + (1-\delta)s - s_+^e\right]$:

$$c^e + i \leq rs + b - p_b b_+^e + q\left[i + (1-\delta)s - s_+^e\right] - \tau, \tag{4}$$

$$\text{where } s_+^e \geq (1-\phi)\left[i + (1-\delta)s\right] \text{ following (2).}$$

To understand the selling of private claims, notice that after capital depreciation, the entrepreneur owns $(1-\delta)s$ legacy claims; the entrepreneur's investment creates i units of new capital. The claims to old and new capital are either sold to other households or retained by the entrepreneur for the household. Since the entrepreneur holds s_+^e at the end of the period, $i + (1-\delta)s - s_+^e$ is the amount sold via financial intermediaries at a price q.

We focus on the equilibrium where the portfolio adjustment constraints (1) and (2) bind for entrepreneurs (e.g., $q > 1$, such that it is profitable to issue claims and invest). Being financing-constrained, entrepreneurs will seek to maximise their resources for investment projects by selling as many private claims as possible, such that $s_+^e = (1-\phi)\left[i + (1-\delta)s\right]$, while dis-saving all liquid assets, i.e. $b_+^e = 0$. In this case, the resource constraint (4) simplifies to

$$c^e + (1-\phi q)\, i \leq \left[r + (1-\delta)\phi q\right] s + b - \tau, \tag{5}$$

which we refer to as the *financing constraint*. The financing constraint can be interpreted in the following way: to invest in new capital stock, the entrepreneur's liquid net worth $\left[r + (1-\delta)\phi q\right] s + b$, net of consumption c^e and taxes τ, can be leveraged at $(1-\phi q)^{-1}$. Therefore, the financing constraint (5) effectively implies an upper bound on investment i.

A Worker's Constraints. A worker's resource constraint differs from that of an entrepreneur along two dimensions. First, a worker receives labour income $w\ell$. Second, the worker does not have investment projects (i.e., $i^w = 0$), but seeks to acquire $s_+^w - (1-\delta)s$ units of private claims for saving purposes. The expenditure on asset transactions amounts to $q^w\left[s_+^w - (1-\delta)s\right]$ where again $q^w > q$ is the price offered to buyers. The resource constraint is thus

$$c^w + q^w \left[s_+^w - (1-\delta)s\right] \leq w\ell + rs + b - p_b b_+^w - \tau. \tag{6}$$

Notice that workers should also respect the portfolio adjustment constraints (1) and (2). However, in equilibrium, these constraints will be slack as workers save in both private claims and government bonds.

The Household's Constraints. Let household-wide aggregates for consumption as well as current- and next-period holdings of private claims and government bonds be denoted as

$$z \equiv \chi z^e + (1-\chi) z^w \text{ for } z \in \{c, s, b, s_+, b_+\}. \tag{7}$$

We multiply financing constraint (5) by χ and workers' resource constraint (6) by $1-\chi$, adding them up by using (7); we then use $s_+ = \chi s_+^e + (1-\chi)s_+^w$, the binding adjustment constraints $s_+^e = (1-\phi)\left[i + (1-\delta)s\right]$ and $b_+^e = 0$, to obtain a household-wide resource constraint:

$$\begin{aligned} c + q^w s_+ + p_b b_+ \leq (1-\chi)w\ell + rs + b + \left[q^w - \chi\phi(q^w - q)\right](1-\delta)s \\ + \left[q^w - 1 - \phi(q^w - q)\right]\chi i - \tau. \end{aligned} \tag{8}$$

where, as explained before, the household-wide consumption is $c = \chi c^e + (1-\chi)c^w$.

The Household's Problem. Since entrepreneurs' portfolio adjustment constraints bind, i.e. $s_+^e = (1-\phi)\left[i + (1-\delta)s\right]$ and $b_+^e = 0$, the household's choice set is simplified to $\{\ell$, c^e, c^w, s_+, b_+, $i\}$. Let $v\left(s, b; \Gamma\right)$ be the value of a typical household with net private financial claims s, bond holdings b, given the aggregate state $\Gamma \equiv \phi$. Let β denote the household's discount factor and let $\mathbb{E}$ denote a mathematical expectation operator. We can write the value $v(s, b; \Gamma)$ recursively as

$$v(s, b; \Gamma) = \max_{\{\ell, c^e, c^w, s_+, b_+, i\}} \Big\{ \chi u\left(c^e, \zeta\right) + (1-\chi)\, U\left(c^w, \ell\right) + \beta \mathbb{E}_\Gamma \left[v(s_+, b_+; \Gamma_+)\right] \Big\}, \tag{9}$$

subject to (5), (8), and non-negativity constraints

$$i \geq 0, \quad c^e \geq 0, \quad c^w \geq 0, \quad s_+ \geq 0, \quad b_+ \geq 0, \text{ and } \ell \in [0,1].$$

Characterising the Problem. Let $U_c = U_c(c^w, \ell)$ and $U_\ell = U_l(c^w, \ell)$ denote the partial derivatives of U w.r.t. consumption and hours of work respetively, and let $u_c = u_c(c, \zeta)$. Let $\rho\chi U_c$ be the Lagrange multiplier of the financing constraint (5), where the rescaling χU_c simplifies the optimality conditions in the following. The optimal choice of (ℓ,c^e,i) then satisfies

$$U_\ell = wU_c, \tag{10}$$

$$u_c = (1+\rho)U_c, \tag{11}$$

$$q^w - 1 - \phi(q^w - q) \leq (1 - \phi q)\, \rho, \text{ and } i \geq 0, \tag{12}$$

where the last condition holds with complementary slackness. (10) is a standard labour supply condition. (11) captures the ratio of the marginal utilities of consumption between an entrepreneur and a worker. If $\rho > 0$, entrepreneurs are financing constrained and, therefore, have a higher marginal utility of consumption compared to workers. (12) is a key equation in the model and characterises the optimal choice of investment, relating its marginal benefit (left-hand side) to its marginal cost (right-hand side).

Consider first the cost-side. For one unit of investment, an entrepreneur can raise ϕq in external funds by selling financial claims to the newly produced capital, such that it only has to finance a fraction $(1 - \phi q)$ internally, which can be interpreted as a “down-payment” on investment. The cost is adjusted by ρ, which is the shadow price of an entrepreneur’s financing constraint in terms of the household’s consumption.

Second, the marginal benefit of investing reflects the net value of newly created capital to the household. Specifically, by investing one unit of consumption goods, an entrepreneur creates a claim at the cost of one. This saves workers from buying outside at q^w, which implies a net gain of $q^w - 1$. However, for the fraction ϕ that is issued to workers (not necessarily in the same household), the marginal gain is reduced by $q^w - q$ from intermediation costs. The household then invests a positive amount if the marginal cost does not exceed the marginal benefit, and decides not to invest ($i = 0$), otherwise.

Finally, we show the two Euler equations for the saving decision in bonds b_+ and private claims s_+:

$$1 = \mathbb{E}_\Gamma \left[\frac{\beta U_{c,+}}{U_c} \frac{1}{p_b} (1 + \chi \rho_+) \right], \tag{13}$$

$$1 = \mathbb{E}_\Gamma \left[\frac{\beta U_{c,+}}{U_c} \left[\frac{r_+ + (1-\delta) q_+^w}{q^w} + \frac{r_+ + (1-\delta)\phi_+ q_+}{q^w} \chi \rho_+ - \frac{(1-\delta)\chi\phi_+ \left(q_+^w - q_+\right)}{q^w} \right] \right], \tag{14}$$

where $\beta U_{c,+}/U_c$ is the stochastic discount factor of an unconstrained worker. In (13), $1/p_b$ is the basic market real return on government bonds. How this return is valued, from the point of view of the household, depends on whether the marginal purchase by a worker today winds up in the hands of a worker or an entrepreneur next period. If the bond is held by a financially unconstrained worker next period, its marginal utility amounts to the real return $1/p_b$. This happens with probability $1 - \chi$. If, however, the bond winds up in the hands of a financially constrained entrepreneur, the marginal utility of consumption of this household member is raised by a factor $1 + \rho_+$ as the additional liquid resources relax the financing constraint. This happens with probability χ. In (13), the expression capturing the future value of liquid assets can be compounded into $1/p_b + \chi\rho_+/p_b$, where the first term is the market real return on government bonds, while the second term reflects the bonds' additional effect on relaxing the financing constraint.

In (14), the return from holding private claims consists of three parts. The first and second parts are similar to the two parts in the payoff from holding bonds: a basic return $\left[r_+ + (1-\delta)q_+^w\right]/q^w$ and a premium associated with the fact that private claims also relax the financing constraint, but only up to the liquid fraction ϕ_+. The difference is that government bonds are fully liquid, and ϕ_+ appears only in this asset pricing equation for private claims. The third part is an adjustment to account for the fact that private claims are effectively sold at a discounted price q_+ below the purchase price q_+^w.

2.3 Asset Liquidity and Asset Price

Our goal is to study the co-movement between asset liquidity ϕ and asset price q. Having ϕ and q moving in the same direction is important for amplifying macroeconomic shocks, because financing investment externally will be much harder if both the liquid fraction and the asset price fall together. If ϕ and q move in opposite directions, macroeconomic shocks could be stabilised automatically.

Given the wage and rental rates $\{w, r\}$, the intermediation technology κ, the government bond price p_b, and tax (or transfers) τ, we can solve for the household's optimal choices, and, more importantly, determine the price of private claims as a function of asset liquidity ϕ. Since the interesting equilibrium is the one in which entrepreneurs' financing constraint binds, investment is profitable and, hence, non-negative ($i > 0$). The optimality condition for investment (12) then holds with equality.

Let us first consider the case in which intermediation is costless, i.e. $\kappa = 0$. The zero profit condition for intermediaries (3) then becomes $q^w = q$, such that equation (12) simplifies to

$$q - 1 = (1 - \phi q)\rho \Rightarrow q = 1 + \frac{1-\phi}{\phi + \rho^{-1}} > 1.$$

This condition immediately implies $\partial q / \partial \phi < 0$, and asset price and liquidity move in *opposite* directions. To further understand this result, notice that for any given shadow price of the financing constraint ρ, the marginal benefit of investing (i.e., $q - 1$) is strictly increasing in q, while the down-payment $(1 - \phi q)$ on investment is strictly decreasing in q. When liquidity shocks push down ϕ, the down-payment rises. Therefore, when the falling ϕ also tightens the financing constraint and raises the shadow price of the financing constraint ρ, the marginal cost of investment goes up for any price q. The equilibrium asset price q has to rise to equate the marginal benefit and cost of investment.[17]

In words, a fall in ϕ amounts to a negative supply shock in the asset market, creating

[17]Theoretically, ρ could fall with ϕ if the negative liquidity shock tightened the household's resource constraint (8) more than the financing constraint (5), lowering workers' consumption relative to entrepreneurs'. However, this is an unlikely outcome, as liquidity shocks directly reduce entrepreneurs' consumption.

excess demand for private financial claims. The asset price must rise to equilibrate supply and demand. That is why $\partial q/\partial\phi < 0$; the asset price q would generally *increase* in response to a negative liquidity shock, which resembles the result in Shi (2015).

By contrast, when financial intermediation is costly, i.e., $\kappa > 0$, the asset price and asset liquidity *can* move in the same direction. In this case, the price of buying exceeds that of selling assets. Both buyers and sellers will then need to consider the costs of asset transactions incurred today and in the future (should they become entrepreneurs and need to sell private claims). The impact of transaction costs on asset demand can push down the asset price when current or future asset liquidity ϕ falls.

To understand this effect, we again use equation (12), replacing q^w by using the zero profit condition (3):

$$q + \kappa\left(\frac{1}{\phi} + \frac{1}{f}\right) - 1 - \phi\kappa\left(\frac{1}{\phi} + \frac{1}{f}\right) = (1 - \phi q)\,\rho \Rightarrow q = \frac{1 + \rho - \kappa(1-\phi)(\phi^{-1} + f^{-1})}{1 + \phi\rho}.$$

First, a falling ϕ raises the intermediation cost per successful asset transaction, $\kappa\left(\frac{1}{\phi} + \frac{1}{f}\right)$, and the marginal gain from physical investment by entrepreneurs goes up. Second, with a falling ϕ, a smaller fraction of investment will be financed through the sale of private claims. The intermediation cost from selling private assets, $\phi\kappa(\phi^{-1} + f^{-1}) = \kappa(1 + \phi f^{-1})$, shrinks, also raising the marginal gain. Both effects induce households to accumulate a larger fraction of claims through entrepreneurs rather than workers. This makes physical investment even more attractive at the margin. As a result, the demand for acquiring private financial claims through workers falls, exerting downward pressure on the asset price q.

Additionally, there is a much less obvious dynamic effect on entrepreneurs' optimal amount of investment arising from future expected selling costs. This is because the endogenous degree of financing constraints ρ is essentially forward-looking. Lower asset liquidity in the future, interacting with κ, implies that claims created today will be more costly to sell in the future. Anticipating this, households demand less physical investment today, relaxing entrepreneurs' financing constraints, i.e. pushing ρ down. This effect on ρ reduces the marginal cost of investment for any given q.

If the demand effects dominate the negative supply effect mentioned in the case with $\kappa = 0$ before, current or future adverse liquidity shocks can increase the marginal benefit of physical investment more than its marginal cost, for any given q. The asset demand from workers falls more than the asset supply from entrepreneurs; the asset price q would, thus, need to fall with a drop in ϕ in order to satisfy the optimality condition for investment.

Let $\tilde{\phi} \leq 1$ denote the highest level of asset liquidity, such that when $\phi \geq \tilde{\phi}$ the financing constraint becomes slack, i.e., $\rho = 0$. In the steady state with binding financing constraint, ρ does not depend on q according to the Euler equation for bonds (13). Then, a permanent reduction in ϕ reduces asset price q, i.e., $\partial q/\partial \phi > 0$, if and only if ϕ is small enough. Intuitively, demand is sensitive to changes in asset liquidity when asset liquidity is sufficiently low, because it then disproportionately affects the effective intermediation cost $\kappa(\phi^{-1} + f^{-1})$.

Proposition 1. *Suppose $\kappa > 0$, $p_b > \beta$, and $q > 1$. In the steady state,*

$$\rho = \frac{\beta^{-1} p_b - 1}{\chi} \equiv \rho^* > 0,$$

is a constant according to (13). Then, $\partial q/\partial \phi > 0$ across steady states if and only if

$$0 \leq \phi < \min\{\phi^*, \tilde{\phi}\}, \;\; \textit{where } \phi^* = \frac{\kappa + \sqrt{\kappa^2 + \kappa \left(\rho^*\right)^{-1} \left[\kappa + \left(\rho^* - \frac{\kappa}{f}\right)\left(\frac{1}{\rho^*} + 1\right)\right]}}{\kappa + \left(\rho^* - \frac{\kappa}{f}\right)\left(\frac{1}{\rho^*} + 1\right)}.$$

Proof. See Appendix A.1. □

By way of comparison, in Ajello (2016), the overall intermediation cost $\tilde{\kappa} = \kappa(\phi^{-1} + f^{-1})$ is exogenous and independent of ϕ. A temporary, but persistent, reduction in ϕ pushes up asset price q in his simulation.[18] Shocks to intermediation cost $\tilde{\kappa}$, on the other hand, can reduce q for *fixed* asset liquidity ϕ. If we replace $\kappa(\phi^{-1} + f^{-1})$ by $\tilde{\kappa}$ in our model, the asset

[18] Ajello (2016) shows that one can only revert this relationship by introducing a number of additional frictions, such as sticky prices and inertial monetary policy rules. That is why his paper focuses on shocks to the intermediation costs instead of shocks to liquidity ϕ.

price shown before becomes

$$q = \frac{1 + \rho - \tilde{\kappa}(1-\phi)}{1 + \phi\rho},$$

again by using equation (12). Then, $\partial q/\partial\phi > 0$ holds in the steady state whenever $\tilde{\kappa} > \rho$. It turns out that this parameter restriction implies that the steady-state $q < 1$, which is unrealistic, at least for the long run.[19] In other words, with reasonable parameters, the asset price and liquidity cannot move in the same direction, in an economy with binding investment financing constraints and exogenous intermediation costs.

In order to generate $\partial q/\partial\phi > 0$, Proposition 1 highlights some specific relationship between asset liquidity and intermediation costs (and the tightness of the financing constraint) that needs to be satisfied, at least in the steady state. Then, to generate $\partial q/\partial\phi > 0$ off the steady state, it is likely that researchers need to exogenously move both κ and ϕ together. This can be avoided by endogenising asset liquidity. Indeed, in our full model in the next section, which simultaneously features endogenous intermediation cost κ, asset liquidity ϕ, and asset price q, the asset price and liquidity can still move in the same direction.

3 General Equilibrium with Endogenous Liquidity

As before, we focus on the interesting equilibrium in which private claims circulate, and we now endogenise asset liquidity ϕ and embed it into a general equilibrium setup. All prices and lump sum taxes are also going to be determined in equilibrium.

3.1 The Full Model

This part describes details of other economic participants in the environment.

Consumption Goods Producers. Firms in the final consumption goods sector produce

[19] The lower bound on q could be (slightly) below one, as long as $q^w - 1 - \phi(q^w - q) > 0$ in (12). The reason is that investment through entrepreneurs saves transaction costs, compared to the case when claims are purchased by workers. In the case of $\tilde{\kappa}$, (12) becomes $q^w - 1 - \phi\tilde{\kappa} \geq (1 - \phi q)\rho$ and we know that $q \geq 1 - \tilde{\kappa}(1 - \phi)$. We check that $\tilde{\kappa} > \rho$ does not violate the lower bound.

output y^g by renting capital k^g and hiring labour ℓ^g from households, according to

$$y^g = AF^g(k^g, \ell^g),$$

where F^g is a homogeneous function in k^g and l^g with degree one, and A measures exogenous aggregate productivity realised in the beginning of period t. In view of production technology and frictionless capital and labour markets, the rental rate of capital and the wage rate equal the corresponding marginal products denoted as

$$r = AF_k^g \text{ and } w = AF_\ell^g. \tag{15}$$

Financial Intermediaries. Buyers and sellers put a certain number of order requests through intermediaries. These orders are processed by intermediaries at unit cost κ. Competitive intermediaries have a production technology that uses capital and labour to process asset orders from households. Then, intermediaries operate a matching function to execute the processed orders on the market, determining the transaction price for successful matches, settling trades, and monitoring their execution. We first describe the production technology and then the matching technology.

Financial Production Technology. Consider an intermediary j, the processing of buy and sell orders is measured by $AF^f\left(k_j^f, \ell_j^f\right)$, where F^f has constant returns to scale. Each intermediary can freely choose how many buy or/and sell orders to process.

Financial intermediaries pay rental and wage incomes to capital owners and workers. All participants are price takers in these factor markets. In addition, financial intermediaries need to rent an exogenous fraction Δ of capital and labour to settle trades and monitor their execution. Δ measures the cost-effectiveness of financial intermediaries, or the degree of extra inputs that the financial intermediaries need to produce financial (matching) services.

Let κ_j be the consumption goods price of a unit buy or a unit sell order, processed by an intermediary j. Since intermediary j chooses capital k_j^f and labour input ℓ_j^f to minimize the cost of delivering the unit asset order, κ_j is the solution to the following cost minimization problem

$$\kappa_j = (1+\Delta) \min_{k_j^f, \ell_j^f} \left\{ r k_j^f + w \ell_j^f \right\} \text{ s.t. } AF^f(k_j^f, \ell_j^f) \geq 1.$$

Thanks to the constant-return-to-scale technology and the unit order processed, κ_j is also the Lagrange multiplier attached to the constraint $AF^f(k_j^f, \ell_j^f) \geq 1$. Because of perfect competition, $\kappa_j = \kappa$ across all intermediaries and we can write

$$\kappa \equiv \frac{(1+\Delta)r}{AF_k^f(k^f, \ell^f)} = \frac{(1+\Delta)w}{AF_\ell^f(k^f, \ell^f)}, \tag{16}$$

where $k^f \equiv \int k_j^f dj$ and $\ell^f \equiv \int l_j^f dj$ are the effective total capital stock and labour hours used by intermediaries for processing orders.[20] The zero profit condition (3) still holds because of free entry, but now the cost for intermediating one unit of asset transactions, $q^w - q = \kappa \left(\frac{1}{\phi} + \frac{1}{f} \right)$, is endogenous.

Δk^f reflects capital cushion and captures the risk-bearing capacity of financial intermediaries. $\Delta \ell^f$ may capture the additional labour hours that intermediaries need to hire for monitoring, insurance, and accounting purposes. They are intermediate inputs for financial services. In the model, only $k^f$and ℓ^f are effectively used for processing orders/producing financial services.

As a concrete example, we look again at the case of an IPO. Its success is measured by the smoothness of the discovery process for the opening trading price, the period in which a designated market maker (different from underwriters) working on setting the opening price in NYSE with both large and small investors. Note that this period is *after* initial appropriate institutional investors have been found and granted the shares at the initial offering price, which is necessary for price stability considerations mentioned in the introduction.[21]

If the price during discovery falls below the initial offering price, underwriters (who care

[20]Notice that capital Δk^f and hours $\Delta \ell^f$ may or may not be counted as capital stock and hours in the financial sector in practice. See the interpretation in the next paragraph.

[21]As explained before, search for the appropriate (institutional) investors is crucial in this process. Underwriters typically seek to avoid placing a large number of shares with investor who are likely to flip them (i.e., wait until the price spikes upon the opening trade and then immediately dump the position).

about their reputation in the industry) tend to shore up demand by purchasing shares, using the capital cushion (Δk^f).[22] This cushion may fluctuate as a function of market conditions. If underwriters feel more uncertain about the quality of the investment and/or the price discovery process at NYSE, Δ may rise. An increase in Δ amounts to an efficiency loss of financial services, which, ceteris paribus, puts downward pressures on intermediaries' profits. In equilibrium, the variation in Δ will translate into a shock to the intermediation cost κ for asset transactions faced by workers and entrepreneurs.[23]

Matching Technology. For a seller, the probability of a successful match with a buy order is ϕ. Conditional on a match, the claim is sold at some price q^f (to be determined later). Hence, free entry of intermediaries implies that the price charged for a successful match is κ/ϕ. The total selling price of the claim, net of the intermediation cost is, $q = q^f - \kappa/\phi$. For a buyer, similarly, the total price of a claim, inclusive of intermediation cost is $q^w = q^f + \kappa/f$. Then, we obtain the same expected relationship between q^w and q, as in (3) of the partial equilibrium model.

Now, let N_{Sell} be the total number of sell orders, and let N_{Buy} be the total number of buy orders. Let asset market tightness θ be the ratio of total purchase orders divided by total sale orders (the same as the total amount of assets on sale)

$$\theta \equiv \frac{N_{Buy}}{N_{Sell}}.$$

Let the matching technology be captured by a matching function $M(N_{Sell}, N_{Buy})$, which is homogeneous of degree one, and continuous and increasing in both the measures of sell and buy orders. Therefore, $M(1, \theta)$ is a non-decreasing and concave function w.r.t. θ. For regularity purposes, we assume that $M(1, 0) = 0$ and $M(1, \theta) \leq 1$ for all θ; in addition,

[22]There are other examples of such capital cushions: not all funds deposited in banks are lent out to firms with long-term investment projects, because financial intermediaries need to have enough liquid funds for potential withdrawals. Government policy measures such as increasing reserve requirements can raise Δ. Market makers may also refrain from using all available funds to purchase inventory assets because their prices may fluctuate substantially.

[23]We will show that shocks to Δ are able to generate volatile and pro-cyclical asset prices which co-move positively with asset liquidity and find that this is an important driver of U.S. business cycles.

$\lim_{\theta \to \infty} M\left(\theta^{-1}, 1\right) = 0$ and $\lim_{\theta \to 0} M\left(\theta^{-1}, 1\right) = \infty$.

The matching technology implies that, on the sell-side, asset liquidity captures the fraction of assets that can be sold *ex post* in a given period, which is a function of the tightness

$$\phi = \phi(\theta) = \frac{M(N_{Sell}, N_{Buy})}{N_{Sell}} = M(1, \theta). \tag{17}$$

On the buy-side, a fraction

$$f = f(\theta) = \frac{M(N_{Sell}, N_{Buy})}{N_{Buy}} = M\left(\theta^{-1}, 1\right) \tag{18}$$

of purchase orders is satisfied on average through successful matches *ex post*. Once asset orders are matched, financial intermediaries settle the transaction price on behalf of buyers and sellers through Nash bargaining (see details in the equilibrium characterisation).

Government. Each period the government spends g, sets tax/transfers τ collected lump-sum from the household, redeems all matured bonds, and issues an amount B_+ of new real bonds. The government budget constraint can be written as

$$g + B = \tau + p_b B_+, \tag{19}$$

where p_b is again the price of bonds. We do not focus on government policies, and the quantities (g, B_+) are assumed to be positive constants $(\bar{g}, \bar{B})$. The lump-sum τ must then vary to satisfy the government budget constraint.

3.2 Equilibrium Characterisation

Let K be the aggregate capital stock at the beginning of each period. Then, the aggregate state becomes $\Gamma \equiv \{K, B, A, \Delta\}$. The financial market variables κ and ϕ, which were treated as exogenous state variables in the partial equilibrium analysis, are now functions of the aggregate state Γ. The household's optimality conditions (10) - (14) remain valid. We still need to characterise the asset market equilibrium.

Asset Market in Equilibrium

Recall that the total number of sell orders from households can be written as $N_{Sell} = \chi\left[i + (1-\delta)s\right]$, which includes the (sell) orders for new investment and existing claims from all entrepreneurs, who can sell at most ϕ fraction of new investment and existing claims. The total number of buy orders is $N_{Buy} = (1-\chi)\left[s_{+}^{w} - (1-\delta)s\right]/f$, because each worker accumulates $s_{+}^{w} - (1-\delta)s$ units of assets and needs to post $\left[s_{+}^{w} - (1-\delta)s\right]/f$ units of buy orders (note: f is taken as given by workers). In equilibrium, the demand of buy and sell orders must be met by the ability of processing the orders, i.e.,

$$N_{Sell} + N_{Buy} = \int AF^{f}(k_{j}^{f}, \ell_{j}^{f})dj = AF^{f}(k^{f}, \ell^{f}),$$

which implies that the tightness is directly linked with other real variables

$$\theta = \frac{N_{Buy} + N_{Sell}}{N_{Sell}} - 1 = \frac{AF^{f}(k^{f}, \ell^{f})}{\chi\left[i + (1-\delta)s\right]} - 1. \tag{20}$$

Now, we derive q^{f}. Once a sell and a buy orders have been matched, intermediaries bargain on behalf of sellers (entrepreneurs) and buyers (workers) over the transaction price. Let $\tilde{q}^{f}$ denote this transaction price offered by intermediaries to either side of a match. Following a related concept in the labour-search literature, the transaction price is determined by bargaining at the margin, i.e. over an incremental asset transaction in a successful match (see Shimer (2010)). Specifically, we compute the marginal transaction surplus of individual buyers and individual sellers at an arbitrary price $\tilde{q}^{f}$ relative to the outside option of not engaging in an additional transaction.

A Worker's Marginal Transaction Surplus. Consider a worker who has the opportunity to purchase an incremental amount of private assets $\epsilon > 0$ at an arbitrary price $\tilde{q}^{f}$ this period. All prices revert to equilibrium prices next period. After modifying (6) accordingly, the value for the worker is

$$\hat{v}^w(\tilde{q}^f, \epsilon; \Gamma) = U\left(c^w, \ell\right) + \beta \mathbb{E}_\Gamma\left[v(s_+ + \epsilon, b_+; \Gamma_+)\right] \text{ s.t.}$$

$$c^w + q^w\left[s_+^w - (1-\delta)\, s\right] + \tilde{q}^f \epsilon = w\ell + rs + b - p_b b_+^w - \tau,$$

where b_+^w and s_+^w are chosen as per the household's instructions. Differentiating this value function w.r.t. to ϵ and evaluating the derivative at $\epsilon = 0$, we obtain the worker's marginal value of an incremental asset transaction

$$v_s^w(\tilde{q}^f; \Gamma) = -U_c \tilde{q}^f + \beta \mathbb{E}_\Gamma\left[v_s(s_+, b_+; \Gamma_+)\right]. \tag{21}$$

An Entrepreneur's Marginal Transaction Surplus. On the other side of the trade, an entrepreneur has an incremental ϵ units of investment, the claims to which he can sell at price $\tilde{q}^f$. He invests ϵ and delivers the ϵ units of claims to capital, retaining $\left(\tilde{q}^f - 1\right)\epsilon$ as profit. After we modify (5), the value for the entrepreneur is

$$\hat{v}^e(\tilde{q}^f, \epsilon; \Gamma) = u\left(c^e, \zeta\right) + \beta \mathbb{E}_\Gamma\left[v(s_+ + i_\epsilon, b_+; \Gamma_+)\right] \text{ s.t.}$$

$$c^e + (1 - \phi q)\left(i + i_\epsilon\right) = rs + (1-\delta)s + b + (\tilde{q}^f - 1)\epsilon - \tau,$$

where i_ϵ is the extra investment implemented after obtaining the additional resources from selling the ϵ units of claims. Notice that the entrepreneur again can issue a fraction ϕ of the incremental investment i_ϵ at the equilibrium price q.

Because the entrepreneur is financing constrained, he would not spend the additional resources on liquid assets or consumption, but invest them fully into new capital. Since entrepreneurs can leverage the additional resources, they can fund an incremental investment of size $i_\epsilon = (\tilde{q}^f - 1)\epsilon/(1 - \phi q)$. Appendix A.2 contains a formal proof of this claim. Differentiating $\hat{v}^e(\tilde{q}^f, \epsilon)$ w.r.t. to ϵ and evaluating the derivative at $\epsilon = 0$, we obtain the entrepreneur's surplus of an additional unit of successful transactions

$$v_s^e(\tilde{q}^f;\Gamma) = \frac{\tilde{q}^f - 1}{1-\phi q}\beta\mathbb{E}_\Gamma\left[v_s(s_+, b_+;\Gamma_+)\right]. \tag{22}$$

Price Settlement. Assume that there are gains from trade, i.e., there is a price $\tilde{q}^f$ satisfying both $v_s^w(\tilde{q}^f) \geq 0$ and $v_s^e(\tilde{q}^f) \geq 0$. We require that the bargained asset price maximizes the (generalized) Nash product

$$\left[v_s^w\left(\tilde{q}^f\right)\right]^{1-\omega}\left[v_s^e\left(\tilde{q}^f\right)\right]^{\omega}, \tag{23}$$

where $\omega \in (0,1)$ is the bargaining weight assigned to entrepreneurs. In equilibrium, $\tilde{q}^f = q^f$.[24] The solution is presented below, and we again show the co-movement of asset price and asset liquidity.

Proposition 2. *The solution of the Nash bargaining problem satisfies $q^f = (1-\omega) + \omega q^w$, after we use $q^f = \tilde{q}^f$. Together with the zero profit conditions (3), we have*

$$q = \max\left\{1, \quad 1 + \kappa\left(\frac{\omega}{1-\omega}\frac{1}{f} - \frac{1}{\phi}\right)\right\}. \tag{24}$$

Suppose the economy is in the steady state and p_b is given by a certain government policy, then $\rho = \rho^*$ is a constant; in addition, $\partial q/\partial\phi > 0$ across steady states if and only if

$$\rho^* + 1 < \frac{\left[1 - M(1,\theta)\right]^2}{\left[\omega\theta - (1-\omega)\right]\left[M(\theta^{-1},1) + \theta M_\theta(\theta^{-1},1)\right]}. \tag{25}$$

Proof. See Appendix A.3. □

Equation (24) is similar to the entry condition commonly found in the asset search literature (Rocheteau and Weill (2011); Vayanos and Wang (2007)). If the Euler equation for private assets determines the asset price, then demand and supply conditions as captured

[24] Otherwise, intermediaries could earn positive profits ($\tilde{q}^f < q^f$) or would run losses ($\tilde{q}^f > q^f$).

by the matching probabilities ϕ and f need to be such that condition (24) is satisfied in order to induce individual agents to participate in the market.

As regards the relationship between the price and liquidity of private assets, the general equilibrium framework confirms the intuition developed in the partial equilibrium setting: both can move in the same direction as long as i) financial intermediation is costly, and ii) the demand for private assets falls relative to their supply. To see the last point, notice that if entrepreneurs are more financing constrained, ρ increases and the marginal cost of investment is higher; then, it is more difficult for condition (25) to be met.

Recursive Equilibrium

A *recursive competitive equilibrium* with private claims and liquid assets consists of a mapping of state $\Gamma = (K, B, A, \Delta) \to \Gamma_+$ and equilibrium objects that are functions of Γ: the household endowment of private claims and government bonds $\{s,\, b\}$, policy functions for consumption, labour, investment, and portfolio choices $\{c^e,\, c^w,\, \ell,\, i,\, s_+,\, b_+\}$, the demand for factor inputs $\{k^g, \ell^g, k^f, \ell^f\}$, asset market features $\{\theta, \phi, f\}$, and a collection of prices $\{q,\, p_b,\, w,\, r,\, \kappa\}$, lump-sum taxes (or transfers) τ, such that given government policy $(g, B_+) = (\bar{g}, \bar{B})$ the following conditions hold:

(1) given prices, the policy functions satisfy the household's optimality conditions (10), (11), (12), (13), and (14), and the household's constraints (5) and (7);

(2) the firms' and intermediaries' optimality conditions (15) and (16) hold;

(3) given market tightness $\theta \in [0, +\infty)$ in (20), the probability of accommodating demand for assets and asset liquidity satisfy $f = M(\theta^{-1}, 1)$ and $\phi = M(1, \theta)$, respectively, and the price settlement condition (24) holds;

(4) the government budget constraint (19) holds, and the markets for capital and private claims, labour, and liquid assets, clear, i.e.,

$$s = K = k^g + (1 + \Delta)k^f,\ (1 - \chi)\ell = \ell^g + (1 + \Delta)\ell^f,\ \text{and}\ b_+ = B_+; \tag{26}$$

(5) the law of motion of the aggregate capital stock is consistent with the aggregation of individuals' investment $K_+ = (1-\delta)K + \chi i$.

Remark 1: $s = K$ states the fact that there are claims on all capital, and the supply of capital K equals the demand for capital $k^g + (1+\Delta)k^f$. The supply of labour hours $(1-\chi)\ell$ equals the demand for labour hours $\ell^g + (1+\Delta)\ell^f$. Finally, we verify Walras' law by checking the goods market clearing condition

$$c + \chi i + g = AF^g(k^g, \ell^g) \equiv y, \tag{27}$$

where y is aggregate output and is spent on consumption c, investment χi, and government expenditures g.

Remark 2: One might expect that the aggregate output y is the same as the total factor payments $rK + w(1-\chi)\ell$. But financial services for investment should be excluded, as they are used as intermediate inputs consistent with the convention used by national income accounting.[25] To see this, the value added or the income from the financial sector is $rk^f + w\ell^f$, which equals $\kappa AF^f(k^f, \ell^f)/(1+\Delta)$. Notice that $\kappa AF^f(k^f, \ell^f)$ is spent by households, which is treated as intermediate inputs for investment. Therefore, the total return on holding capital, net of the cost of investment, is $rK - \kappa AF^f(k^f, \ell^f) = rK - (1+\Delta)\left(rk^f + w\ell^f\right)$ from the point of view of the households. Together with wage compensation $w(1-\chi)\ell$, we also know that the aggregate output can be computed as $y = rK - (1+\Delta)\left(rk^f + w\ell^f\right) + w(1-\chi)\ell = rk^g + w\ell^g$, which is consistent with the definition $y \equiv AF^g(k^g, \ell^g)$.

The Convenience Yield

Before closing the model, we discuss how we translate the liquidity premium into a measurable object. The idea that government-provided assets are more liquid than private claims is the central feature of our model. As a result of this feature, agents are willing to pay

[25] In practice, many types of financial services (such as advisory services) are included in the service component of final consumption. In our model, the financial services are intermediate inputs for investment which affects the return on capital. In the quantitative analysis, we thus only target financial services for investment in the data.

a (liquidity) premium for holding government bonds, such that their price exceeds their fundamental value. The value that investors assign to the liquidity and/or safety attributes offered by government debt is also often referred to as the "convenience yield" as expounded in Krishnamurthy and Vissing-Jorgensen (2012). Similar to Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017), this convenience yield arises in our model because liquid assets can be used fully to relax agents' future financing constraints.

In practice, treasuries are also traded on over-the-counter markets; but these markets are extremely liquid (see the discussion in "Portfolio Adjustment Frictions" before). We take this feature as given in this paper. One benefit of using government debt as the benchmark liquid assets is that the measured convenience yield properly reflects the liquidity premium for investment purposes. As discussed before, many treasury securities are long-term, and they usually serve as collateral assets for investment.

To map the convenience yield into an observable quantity, it is convenient to express it as a ratio. Consider a one-period bond, which is similar to government bonds except that only a fraction ϕ is liquid. This type of bonds is in zero net supply. An entrepreneur owning this asset needs to retain a fraction $(1-\phi)$, which is returned to the household.[26] Such a bond would satisfy the Euler equation

$$1 = \mathbb{E}_{\Gamma}\left[\frac{\beta U_{c,+}}{U_c}\frac{1}{\tilde{p}_b}\left(1+\chi\phi_{+}\rho_{+}\right)\right], \tag{28}$$

where $\chi\phi_{+}\rho_{+}$ reflects the fact that only a ϕ_{+} fraction of bonds can relax the financing constraint should a worker become an entrepreneur with probability χ. The ratio between the real return on this bond, which provides a limited liquidity service, and government bonds, which are fully liquid, is defined as the convenience yield

$$CY \equiv \frac{(\tilde{p}_b)^{-1}}{(p_b)^{-1}} = \frac{p_b}{\tilde{p}_b}.$$

[26]In the model, this bond would arise, for instance, if it payed off after entrepreneurs have to finance investment opportunities and consumption.

To understand the relationship between the convenience yield and entrepreneurs' financing constraint, we again consider the steady state in which $\bar{x}$ is used to denote the steady-state value of x. First, the asset pricing equation for government bonds (13) implies that $\bar{\rho} = \chi^{-1}\left(\beta^{-1}\overline{p_b} - 1\right)$. If entrepreneurs' financing constraint binds, we have $\bar{\rho} > 0$ and thus $\overline{p_b} > \beta$. In other words, the real interest rate on liquid assets $1/\overline{p_b}$ has to be lower than the rate of time preference β^{-1} in such a constrained economy, reflecting the liquidity premium. Second, to measure the liquidity premium, we use (13) and (28)

$$\overline{\tilde{p}_b} = \frac{\chi\bar{\phi}\bar{\rho} + 1}{\chi\bar{\rho} + 1}\overline{p_b} = \overline{p_b} - \frac{\chi(1-\bar{\phi})}{\chi + \bar{\rho}^{-1}}\overline{p_b} < \overline{p_b},$$

because $\phi \in [0, 1)$. By providing a full liquidity service, government debt mitigates financing constraints better than other assets that have limited liquidity service. Therefore, government debt carries a positive convenience yield, $\overline{CY} = \overline{p_b}/\overline{\tilde{p}_b} > 1$ in the steady state.

From the above discussion, either a fall in asset liquidity $\bar{\phi}$ or a rise in the multiplier $\bar{\rho}$ pushes down $\overline{\tilde{p}_b}$, raising the convenience yield. In the following quantitative analysis, we find that aggregate productivity shocks and intermediation shocks generate different dynamics of the convenience yield.

4 Quantitative Analysis

Having set up a framework that endogenously links asset prices to asset liquidity, we confront the model with macroeconomic and financial data and assess its dynamic properties. The quantitative exercise will further highlight the role of financial market frictions in transmitting aggregate shocks.

4.1 Functional Forms

The production function has a standard Cobb-Douglas form

$$F(k^g, \ell^g) = (k^g)^\alpha (\ell^g)^{1-\alpha} \text{ and } F^f(k^f, \ell^f) = A^f \left(k^f\right)^\alpha \left(\ell^f\right)^{1-\alpha},$$

where α and $1-\alpha$ refer to the capital and labour share and A^f is a scaling parameter. We then use the conventional definition of total factor productivity (TFP)

$$TFP \equiv \frac{y}{K_{-1}^\alpha \left[(1-\chi)\ell\right]^{1-\alpha}} = \frac{A\,(k^g)^\alpha (\ell^g)^{1-\alpha}}{\left[k^g + (1+\Delta)k^f\right]^\alpha \left[\ell^g + (1+\Delta)\ell^f\right]^{1-\alpha}}. \tag{29}$$

The matching function is specified as

$$M(1,\theta) = \xi\theta^{1-\eta},$$

where η is the matching elasticity and ξ is the matching efficiency parameter. Similar to the functional forms typically used in the labour search, this specification implies that the number of matches exhibits constant return to scale in the ratio of purchase orders to sale orders. The entrepreneurs' and workers' utility functions are specified, respectively, as

$$u(c,\zeta) = \tilde{u}(c,\zeta) \text{ and } U(c,\ell) = \tilde{u}(c,\ell), \text{ where } \tilde{u}(c,\ell) \equiv \frac{\left(c - \frac{\mu\ell^{1+\nu}}{1+\nu}\right)^{1-\sigma} - 1}{1-\sigma}.$$

Recall that ζ is a scaling parameter, and it reflects the efforts from entrepreneurs in implementing productive investment projects. We choose to focus on the substitution effect on labour supply, since the wealth effect is already affecting portfolio choices. That is, $\tilde{u}(c,\ell)$ follows a GHH (Greenwood, Hercowitz, and Huffman (1988)) utility function taking the form where σ is the relative risk-aversion parameter, ν is the labour supply elasticity, and μ is a parameter that governs the steady-state hours of work.

We consider standard AR(1) processes for aggregate productivity and the efficiency in financial intermediation. Without loss of generality, we specify the steady state level $\bar{A} = 1$. In the baseline estimation, we specify:

$$\ln A_t = \rho_A \ln A_{t-1} + \varepsilon_t^A, \quad 0 < \rho_A < 1,$$

$$\ln\left(1 - \frac{1}{\Delta_t + d} + \frac{1}{\bar{\Delta} + d}\right) = \rho_f \ln\left(1 - \frac{1}{\Delta_{t-1} + d} + \frac{1}{\bar{\Delta} + d}\right) + \varepsilon_t^f, \quad 0 < \rho_f < 1,$$

where $\bar{\Delta}$ is steady-state level of Δ, d is an arbitrary constant, and both $\varepsilon_t^A \sim N(0, \sigma_A^2)$ and $\varepsilon_t^f \sim N\left(0, \sigma_f^2\right)$ are i.i.d. normal random innovations. The innovations are referred to as (aggregate) productivity shocks and (financial) intermediation shocks later. σ_A^2 and σ_f^2 are thus the variances of the two innovations. The reason for the specific process form for Δ_t is that it is comparable to the process for aggregate productivity, and d will be chosen such that the size of the two shocks are similar. Finally, we will show the exercise later when the two shocks are contemporaneously correlated, and the correlation is denoted as σ_{Af}.

4.2 Parameterisation

Calibration

One period is set to a quarter. We calibrate the steady state of the model to match several characteristics of the U.S. economy in the sample period 1982Q1-2017Q2 (see Table 1).[27]

We set $\sigma = 1.5$ in order to limit the degree of risk aversion. We also choose $\nu = 1.5$, which is common in macroeconomic models as it falls in the range of Frisch labour supply elasticity estimates. $\beta = 0.99$ is a conventional value in a quarterly macro model.

Investment and Capital. Because of our assumption of an even distribution of household resources among its members, χ captures the share of household wealth accruing to entrepreneurs. We calibrate χ to 0.04, to target a steady-state purchase price of private assets $q^w = 1.1$.[28] The purchase price q^w captures Tobin's Q (excluding transaction costs),

[27] The reason for choosing 1982 as the starting point is that the years before 1982 may still be in the transition to financial liberalisation.

[28] Note that the number χ is smaller than the one used in Shi (2015)(who targets the share of firms that implement investment), but larger than the one used in Del Negro, Eggertsson, Ferrero, and Kiyotaki

which ranges from 1.11 to 1.21 in the U.S. economy according to COMPUSTAT data. The higher q^w is, the more important financial frictions will be. The calibration target for q^w implies a steady-state (re-)sale asset price $q = 1.03$.

The capital share in production function $\alpha = 0.252$ is set to target the investment-to-output ratio, which is about 17% since 1990Q1 based on quarterly data from the US National Income and Product Account (NIPA) obtained from Bureau of Economic Analysis (BEA). Note that output is the sum of private consumption, private investment, and government expenditures, which is consistent with the model.

To calibrate the steady-state depreciation rate δ, we construct the value of capital qK in the private sector from the quarterly flow-of-funds data (see Appendix C for details), which corresponds to the value of all claims to capital in the model. We can further obtain the capital value-to-output ratio (real output measured in terms of annual rates). This ratio also becomes stable since 1990Q1, and has a sample average of 1.9. Since $q = 1.03$ in the steady state, we thus set the capital-to-output ratio as 1.85. Using both the capital-to-output and investment-to-output ratios, we pin down the annual depreciation rate in the steady-state, which is about 9%, implying $\delta = 0.023$ in the model with quarterly frequency.

Table 1: **Steady state calibration**.

Parameter	Baseline Value	Target/Source
β: Household discount factor	0.99	Exogenous
σ: Relative risk aversion	1.50	Exogenous
ν: Labour supply elasticity	1.50	Frisch elasticity = 1/1.50
μ: Utility weight on leisure	3.125	Total hours of work = 30%
χ: Mass of entrepreneurs	0.039	$q^w = 1.1$
ζ: Entrepreneurs' effort	0.798	Price of government bonds $p_b = 1/1.005$
δ: Depreciation rate of capital	0.023	Investment-to-capital ratio: 9%
α: Capital share	0.252	Investment-to-output ratio: 17%
$\bar{A}$: Steady-state aggregate productivity	1	Normalisation
A^f: Financial productivity parameter	50.85	Financial hours share of total hours: 1.7%
$\bar{\Delta}$: Fraction of extra input required for financial services	0	Normalisation
ω: Bargaining weight	0.623	Financial income / intermediated assets: 2%
ξ: Matching efficiency	0.521	Annualized convenience yield: 0.97%
g: government expenditures	0.113	Government spending share of output: 20%
$\bar{B}$: government debt	0.363	Government debt to output ratio: 64%

The Financial Sector. The extra input of financial services $\bar{\Delta}$ is normalised to be zero,

(2017), reflecting modelling differences in our paper.

because the efficiency parameter A^f adjusts. We target the size of the financial sector relative to the total economy in terms of hours of work, which calibrates A^f. To do so, we obtain total hours of work, as well as the hours of work in the financial sector, from the "Labor Productivity and Costs" section published by Bureau of Labor Statistics (see Appendix C for details). Notice that the counterpart of the model's financial sector is a subset of the "financial sector" in the data, and we need industry level data. The 3-digit and 4-digit industry work hours are available at annual frequency from 1987 onwards. We therefore only use the annual hours of work in the financial industry to calibrate the steady state of the model.

We focus on a subset of the financial sector,[29] specifically, the NACIS 3-digit categories 522 "Credit intermediation and related activities" (CI) and 523 "Securities, commodity contracts, and investments" (SI). These speak directly to the model, as they affect new investment and the resale of capital. For example, according to the US Census Bureau,[30] CI attracts deposits and makes loans for investment; some companies under CI deal with transaction clearing. SI includes investment banking and securities dealing, as well as investment advice. The hours worked in 2017 in CI and SI are presented below, with 4-digit industry decomposition.

Table 2: Financial hours of work in 2017.

Industry	NAICS code	Hours (in millions)
Depository credit intermediation	5221	3055.69
Nondepository credit intermediation	5222	1146.36
Activities related to credit intermediation	5223	559.12
Securities and commodity contracts intermediation	5231	807.17
Securities and commodity exchange	5232	9.50
Other financial investment activities	5239	969.04
The whole U.S. economy	N/A	273,310.00

To compute the model counterpart of "financial hours", we exclude hours in non-

[29]The financial sector, under 2-digit (NAICS) code 52, is formally labeled as "Finance and Insurance". The 3-digit industries under this category include Monetary authorities (521), Credit intermediation and related activities (522), Securities, commodity constracts, and investments (523), Insurance carriers (524), and Funds, trusts, and other financial vehicles (525).

[30]https://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2017.

depository credit intermediation (5222) as most activities in this sector are related to credit cards and housing mortgages, though some activities correspond to secondary market financing (i.e., buying, pooling, and repackaging loans for sale). We also exclude hours in securities and commodity exchanges (5232) in which hours are related to stocks, options, and commodity exchanges, and hours in other financial investment activities (5239) because most activities are investment advice and portfolio management. The share of financial hours to total hours in the US economy was about 2.05% in 1987 and 1.62% in 2017, possibly reflecting financial innovation during this period. We use the sample average 1.7% from 1990.

Search and Matching. The parameters $\{\xi, \omega, \eta\}$ govern the matching function and bargaining on the asset market, which mainly affect the ease of financing for entrepreneurs. First, we tie our hands by setting $\bar{\phi} = \bar{f}$ in the steady state, so that $\theta = \phi/f = 1$ (see a similar treatment by Shimer (2005)). This reflects our modeling choice of capturing primary and secondary markets together to simplify the algebra. Second, since $\phi = \xi\theta^{1-\eta}$, we immediately know that $\xi = \bar{\phi}$ and η does not affect the steady state. That said, we estimate η in our empirical exercise as it is important for the model's dynamics. We are then left with two parameters ξ and ω, and we shall choose two targets.

Because ϕ directly affects the degree of financing constraint and thus the convenience yield, we will use the latter to pin down ξ. We follow Krishnamurthy and Vissing-Jorgensen (2012) and Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017) and measure this yield by the ratio of annualised yields between 20 year Moody Aaa-rated corporate bonds and long-term Treasury bonds (see Appendix C for details). As argued by Krishnamurthy and Vissing-Jorgensen (2012), Aaa bonds have almost zero default risks, such that the yield spread with Treasuries of similar maturity almost entirely reflects liquidity risks. The sample mean is 97 basis points (annualised). This calibration results in $\xi = 0.52$, so that $\phi = \xi = 0.52$ in the steady state. This relatively low degree of frictions stacks the odds against the quantitative importance of liquidity frictions in our setup.[31] ω affects the bargaining

[31] For $\phi = 0.52$, $1 - (1 - \phi)^4 = 94.7\%$ of new investment can be issued to outsiders after one year. The

outcome and therefore the "financial income". Philippon (2015) finds that the ratio of financial income to total intermediated assets (including privately-issued assets and liquid assets) is 1.5-2%. ω is calibrated to be 0.62, implying about 2% for this ratio, which is close to the estimate by Philippon (2015) given that our model does not feature bank deposits (which are part of intermediated assets in the data).[32] [33]

The Government. We set the ratio of government spending to total output to 20%, similar to that in the data. We also set the inverse of the price of government bonds to $1/p_b = 1.005$ to pin down the entrepreneurs' effort ζ, which affects the incentive to hold liquid assets. This implies an annual return of 2%, well in line with the 1.72% return of US government liabilities with one year residual maturity and about 2.2% for 20 year maturity (Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017)).

In addition, government debt in the flow-of funds data corresponds to all liabilities of the Federal Government, that is, Treasury securities net of holdings by the central bank and the budget agency plus reserves, vault cash and currency net of remittances to the Federal government (again following Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017)). This is about 64% of total output since 1982. ζ indicates the importance of entrepreneurs in the household. It determines their consumption (and investment) and thus the need to carry

asset liquidity frictions are conservative compared to the literature. Nezafat and Slavik (2010) use the US flow-of-funds data for non-financial firms to estimate the stochastic process of ϕ. The long-run average is close to 0.30, which would imply a stronger degree of financial frictions than in our calibration. In Kiyotaki and Moore (2012) and Shi (2015), $\phi = 0.2$ and $\phi = 0.273$ respectively. Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017) have $\phi = 0.31$, while the initial issuance can fund 79%. This means that the household can issue $79\%+21\% \left[1-(1-31\%)^3\right] = 93.1\%$ of new investment after one year, which is smaller than that in our case. Also notice that the fraction of wealth allocated to constrained entrepreneurs in their paper is smaller than 1%, while we have about $\chi = 4\%$. Ajello (2016) estimates his model with COMPUSTAT data. He finds that firms can issue 68% initially and can resell a fraction of $\phi = 16\%$ (we obtain this number after running his code), which hits the financing gap in the data. After one year, $68\% + 32\% \left[1-(1-16\%)^3\right] = 81\%$ of new investment can be issued to outsiders.

[32] Total financial income in the model is $rk^f + w\ell^f$, and the total volume of intermediated assets is $\phi\chi\left[i + (1-\delta)K\right] + B$. Note that we include liquid assets as part of the intermediated assets to match the data. This is consistent with Philippon (2015), who includes all liquid assets in his calculation. While we assume for ease of exposition that liquid assets do not need to be intermediated, one could equivalently assume that they are intermediated at close to zero costs.

[33] The implied gross spread for private claims $(q^w - q)/q^w$ is about 6.5% in the model. This corresponds broadly to the fees incurred in initial public offerings on the primary market (11.0%) and on one type of secondary markets (seasoned equity offerings, 7.1%). For bonds, the average direct costs are 3.8%. See Lee, Lochhead, Ritter, and Zhao (1996) and Chen and Ritter (2000) for detail.

liquid assets. We calibrate ζ such that the ratio of the real value of liquid assets to output, B/Y, is 64% in the steady state.

Estimation

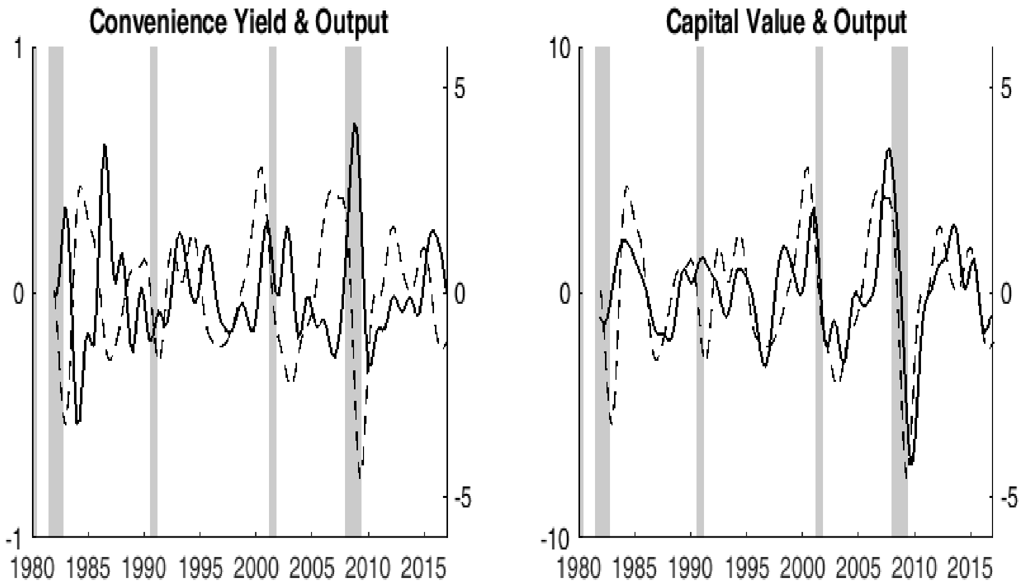
Given the dynamic implications of the model following productivity and intermediation cost shocks, the three key series for its estimation are the cyclical components of the convenience yield, capital value, and output. We use the data for these variables described in the calibration exercise, applying the band pass filter with the typical business cycle frequency 6-32 quarters to de-trend the data after taking log transformation, and then focus on the cyclical components in Figure (1).[34] The standard deviation of output is about 1.5%. Relative to that the convenience yield and the capital value have a standard deviation of 0.16 and 1.33, respectively. The convenience yield correlates negatively with output (-0.42). The correlation between output and the capital value is 0.67.

The model is log linearised around the deterministic steady state and cast in state-space form, so that we can apply a standard Kalman filter. Using the maximum likelihood method, we can numerically calculate the likelihood, conditioning on observations, and estimate the parameters associated with the two structural shock processes. Since the matching sensitivity η cannot be determined in the calibration, we also estimate η. Finally, to avoid stochastic singularity, we add an observational error $\varepsilon^{OE} \sim N(0, \sigma^2_{OE})$ on the capital value. Another reason for doing this is that we abstract from typical capital adjustment costs (which could significantly affect asset prices), but we still can use the cyclical information from the capital value.

The estimated productivity process (column 1 of Table 3) is more persistent than the intermediation cost process ($\rho_A = 0.91 > \rho_f = 0.88$), implying a half-life - the time required for the variable to reduce to half its initial value - of about 1.8 years and 1.4 years, re-

[34]By using the band pass filter, we do not pick up high-frequency movements in the convenience yield and capital value, which are related to "prices" in financial markets. The cyclical components of output, consumption, investment, and hours of work are quite similar under the band-pass filter and the standard HP filter with a smoothing coefficient of 1600 for quarterly data.

Figure 1: **Deviations of output, the convenience yield, and capital value**. Shown in percentage deviations from their trends, band-pass filtered 6-32 quarters. Output is represented by dashed lines with the scale on the right of each sub plot.



spectively. As we show below, intermediation shocks generate more persistent endogenous output dynamics than aggregate productivity shocks. We choose the value $d = 12$ so that the estimated sizes of the shocks in the aggregate productivity and intermediation costs processes are comparable.[35] Finally, the value η is close to 1, so that $\phi'(\theta) = (1-\eta)\xi\theta^{-\eta}$ is small and condition (25) is easily satisfied. That is, the asset price is likely to fall with a falling asset liquidity ϕ.

4.3 Equilibrium Dynamics

With the calibrated and estimated parameters in hand, we simulate the model's dynamics after aggregate productivity and intermediation cost shocks. Importantly, both shocks generate the positive co-movement between asset liquidity and the asset price. However, we find that these two types of shocks generate opposite convenience yield dynamics; productivity shocks also generate less volatile asset price movements than intermediation shocks.

[35] The following quantitative results are extremely robust to a wide range values $d \in [1, 20]$. The reason is the following: the model is (log) linearly approximated and the size of the intermediation shocks adjusts when we change d, while impulse responses and variance decomposition are unaffected.

Table 3: **Estimated parameters**. Note: standard errors are in brackets.

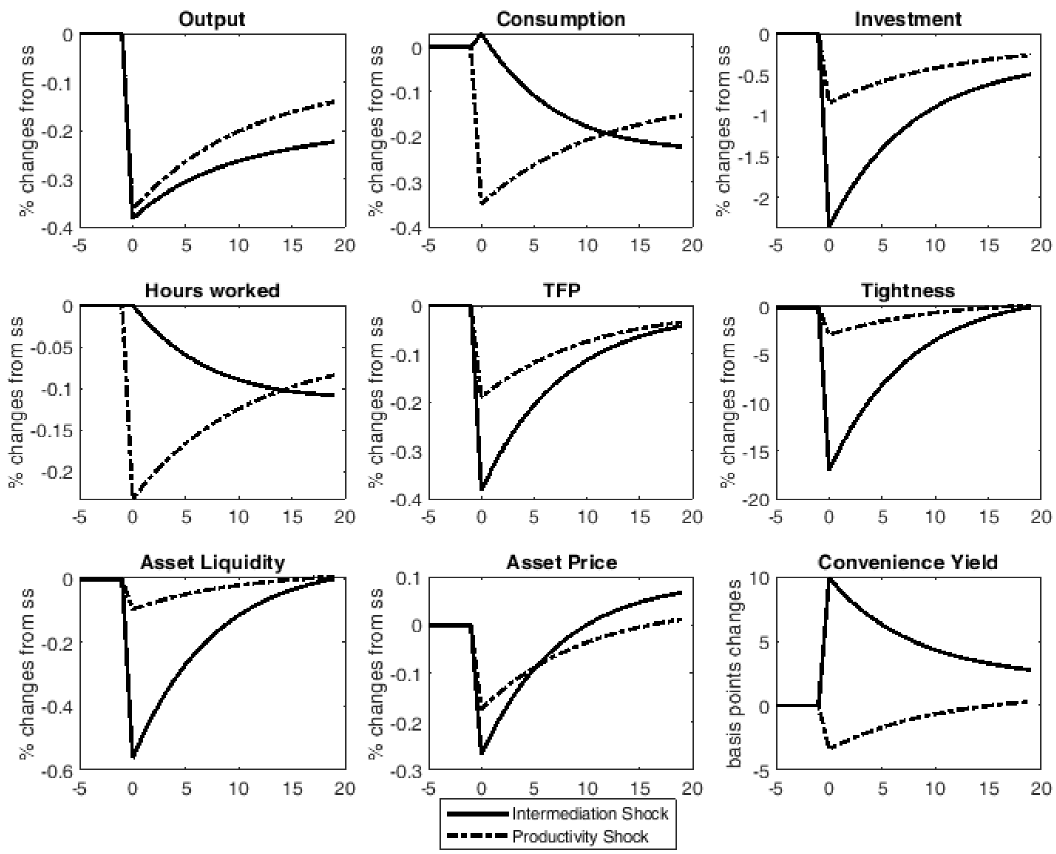
	Parameter	Baseline	Correlated shocks	Correlated shocks + sub-sample
Persistence (aggregate productivity)	ρ_A	0.9076 (0.0271)	0.9238 (0.0226)	0.9294 (0.0260)
Persistence (intermediation)	ρ_f	0.8791 (0.0328)	0.8269 (0.0412)	0.8545 (0.0457)
St.d. of productivity shocks	σ_A	0.0021 (0.0001)	0.0022 (0.0001)	0.0020 (0.0001)
St.d. of intermediation shocks	σ_f	0.0022 (0.0002)	0.0020 (0.0002)	0.0020 (0.0002)
Correlation of the two shocks	σ_{Af}	0 (N/A)	-0.2333 (0.1069)	-0.1450 (0.1184)
Observational errors	σ_{OE}	0.0138 (0.0009)	0.0139 (0.0009)	0.0127 (0.0009)
Sensitivity of matching	η	0.9670 (0.0042)	0.9591 (0.0064)	0.9600 (0.0072)

Negative Productivity Shocks. Suppose that, at time 0, a negative aggregate productivity shock with one standard deviation hits the economy (Figure 2). This shock depresses TFP by 0.18% on impact, reducing the marginal product of capital and its value to the household. Output falls by 0.34% on impact because labour hours drop around 0.23% as a response to the TFP fall. With a half-life of around 4 and 2 years, output and TFP are more persistent than the exogenous aggregate productivity process, which halves after 1.8 years. This is because of the simultaneous fall in asset price and asset liquidity explained below.

With the fall in TFP, search for investment becomes less attractive and the amount of purchase orders from workers for private financial claims drops. The demand-driven fall is reflected in the endogenous drop in asset market intensity θ and asset liquidity ϕ, which amplifies the initial shock in two ways: (1) it reduces the quantity of assets that entrepreneurs are able to sell; (2) the asset price falls (about 0.17% on impact). Both effects tighten entrepreneurs' financing constraints. As a result, investment falls, with a 0.8% drop on impact - lower investment feeds into a more sluggish recovery of the capital stock, which in turn increases the persistence of the response of output. Consumption also falls (0.33% drop initially) because fewer resources are produced at the lower level of aggregate productivity.

In principle, the liquidity service of government debt becomes more valuable to households when the liquidity of private claims declines. However, in the case of a persistent aggregate productivity shock, lower expected returns to capital make *future* investment less

Figure 2: **Impulse responses after a one standard deviation shock at time 0**. "ss" stands for the steady state value.



attractive. This effect weakens the incentive to hedge against asset illiquidity for future investment, although the annualised interest rate on government debt falls by 0.11% (not shown in the Figure). The former effect has a positive impact on the convenience yield, while the latter has a negative impact.

In our calibration, the decline in the profitability of investment projects is sufficient to reduce the convenience yield. Therefore, the demand for liquid assets falls, which is reflected in the reduction in the convenience yield by about 4 basis points on impact. To the extent that productivity reverts back to the steady state, while asset liquidity is still subdued, hedging becomes more attractive, which explains the initial small reduction and relatively fast recovery (1-year half-life) of the convenience yield.

Note that the 0.08% fall in asset liquidity ϕ following aggregate productivity shocks is much less pronounced than in the case of intermediation shocks (about 0.58%). The 2.5% fall in search intensity is also small compared to 17% after intermediation shocks. That is, negative productivity shocks reduce asset liquidity ϕ, but the search-and-matching process with Nash bargaining mitigates this effect, as their impact is mostly absorbed by the asset price (see a similar discussion in the context of labour markets in Shimer (2005)).

Adverse Intermediation Shocks. Suppose that, at time 0, a one-standard deviation positive innovation to intermediation cost hits the economy (Figure 2). Rather than affecting the production frontier of the economy directly, intermediation shocks only impair the capacity of the financial sector to intermediate funds between workers and entrepreneurs. On impact, the share of capital in the financial sector used as a cushion rises from 0% to about 0.36% of aggregate capital stock.[36]

Since current and future participation in financial markets is more costly, households seek to reduce their exposure to private claims. On the asset supply side, financing-constrained entrepreneurs would still like to sell as many assets as possible in order to take full advantage of profitable investment opportunities. Therefore, asset demand on the search market shrinks relative to supply, as reflected in the sharp decline in asset market tightness θ. This reduces the likelihood for assets on sale to be matched with buy orders. Asset liquidity drops by 0.58% on impact, about 1.5 times the fall in output. As a comparison, the fall in asset liquidity is only a quarter of that in output under aggregate productivity shocks.

Because it is harder to transform one unit of consumption goods into one unit of final investment goods, the intermediation shock also translates into a reduction of measured TFP. For example, more capital cushion Δk^f is used, which reduces the capital used for producing final goods and thus the measured TFP in (29). The fall in TFP is 0.39% on impact. Productivity shocks reduce A directly and hence affect all sectors. Intermediation shocks only hit the financial sector on impact, keeping aggregate productivity A unaffected. So the wage rate (and the rental rate of capital) stays the same, which explains why hours of

[36] A one standard deviation shock pushes up Δ from 0 to 0.3. ℓ^f and k^f fall by 9%. Since k^f is 1.7% of total capital stock in the steady state (the same as the share of financial hours in total hours), the capital cushion Δk^f goes up from 0 to about 0.36%.

work are unchanged at the beginning. But more capital is shifted away from the production of final output, and the production of financial services falls. On net, output falls by 0.39%.

The sharp drop in asset liquidity tightens entrepreneurs' financing constraints substantially. Investment falls by 2.4% on impact, and the marginal product of capital rises after the initial shock, putting upward pressure on the asset price.[37] But the demand effect dominates (again reflected in asset market tightness θ), such that the re-sale value of capital q also falls by 0.27%. This depresses entrepreneurs' net worth further, amplifying the initial shock. This effect is mirrored by a significant decline of investment activity, the impact response of which is about 6 times stronger than that of output.

As saving via the financial market becomes more expensive with higher intermediation costs, workers reduce their labour supply and consume more after the initial shock. Entrepreneurs, on the other hand, have to cut back on consumption significantly in view of their tightly binding financing constraints. Given the small population share of entrepreneurs, aggregate consumption increases by a small amount initially (0.03%). However, lower investment into the capital stock soon reduces the marginal product of labour and the wage rate, and the effect is persistent and hump shaped. As labour income of workers falls, consumption persistently drops below the steady state. Output is thus also persistently compressed. Additionally, recall that intermediation shocks are less persistent than aggregate productivity shocks, but output in response to intermediation shocks has a half-life of almost 6 years, one and half times as long as that under aggregate productivity shocks.

While the intermediation cost shock depresses the demand for and the liquidity of private assets, it substantially increases demand for liquid assets. Future investment remains profitable since the productivity of capital is not affected by the shock. To take advantage of future investment opportunities, households seek to hedge against the persistent illiquidity of private claims by rebalancing their asset holdings towards liquid government bonds. The annualised interest rate falls by almost 0.9% on impact. This is also reflected by the 10 basis points increase on impact, rather than decrease, in the convenience yield. The half-life

[37] We check that the marginal product of capital r is persistently above the steady state.

of the convenience yield is 2 years, twice as long as its response to aggregate productivity shocks.

The accumulation of government bonds relaxes future financing constraints: on the one hand, entrepreneurs can finance more out of their stock of liquid assets; on the other hand, buyers have more liquid resources to purchase private claims. Both effects improve liquidity conditions in the private asset market going forward. As a result, the asset price overshoots above its steady-state levels after about 2 years. Together, the sharp decline of the asset price on impact and its subsequent overshooting enable intermediation shocks to generate more asset price volatility than productivity shocks.

4.4 Further Empirical Properties

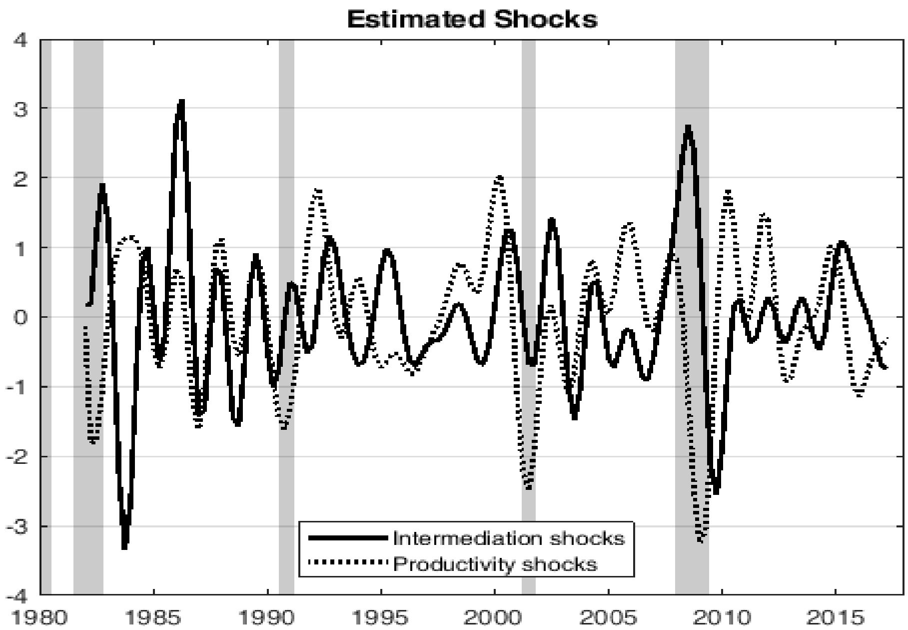
The previous exercise illustrates the transmission channels of productivity and intermediation shocks. We now assess the model's performance along the business cycle dimension. In practice, the two exogenous shocks might be correlated.[38] In this part, to better capture the data, we allow the correlation of the two shocks to be non-zero as reported in the second column of Table 3.

When estimating with correlation, we allow variation in productivity shocks to affect intermediation shocks, but not the other way around. The way we choose minimizes the impact of financial shocks. In fact, the estimated size of productivity shocks goes up, while the size of intermediation shocks goes down. The persistence of productivity shocks goes up by 0.016 (or 1.8%), and the standard error is smaller. The persistence of intermediation shocks goes down by 0.052 (or 6%), but the standard error becomes larger, reflecting the fact that there is no unique way of introducing correlation.

Estimated Shocks. Intermediation shocks generate countercyclical convenience yields, mimicking the deterioration of private assets' liquidity relative to publicly issued liquid assets typically observed in recessions. As a result, the convenience yield can serve as

[38] For example, negative financial shocks may also worsen capital allocation among heterogeneous firms, which reduces aggregate productivity. Negative productivity shocks squeeze available resources, which could reduce the risk bearing capacity, pushing up Δ.

Figure 3: **Estimated shocks.** The figure shows the means of the estimated shocks (ε_t^f and ε_t^A) through the Kalman smoother algorithm. Both shocks are normalised by their respective standard deviations. Shaded areas indicate NBER-dated recessions.

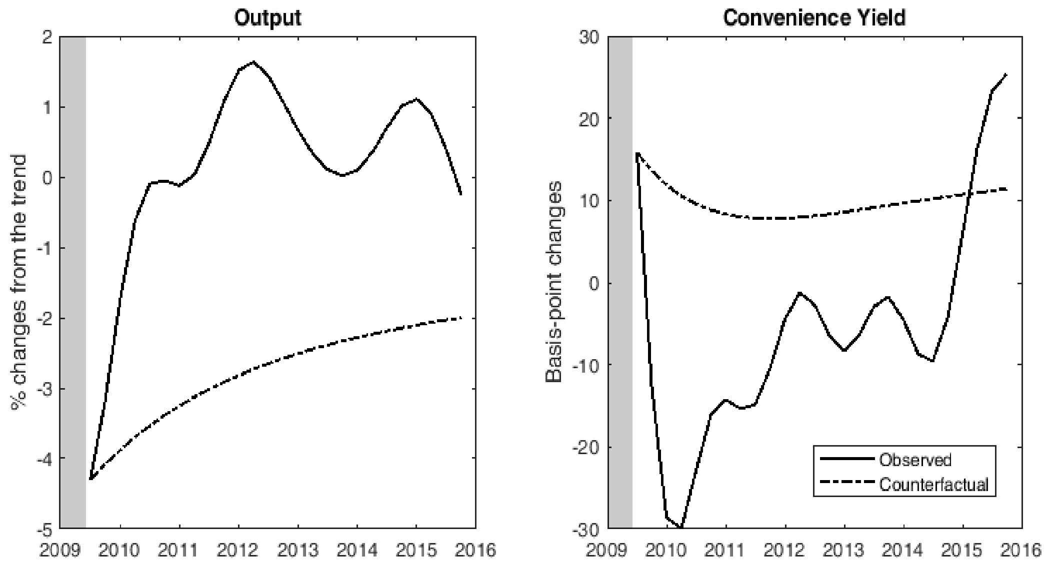


a discriminant between the sources of recessions. In addition, they generate more volatile asset prices than aggregate productivity shocks as discussed before. Based on these dynamic properties, we estimate the shock series shown in Figure 3.

Through the lens of the model, the 2007-09 recession stands out as being driven by a combination of exceptionally large (e.g., 2.7 standard deviations in 2008) rise in intermediation shocks and negative aggregate productivity shocks. The sharp fall in intermediation costs in 2009-10 may be related to the asset-purchase programmes implemented by the Federal Reserve. These programmes replaced illiquid private assets, such as mortgage-backed securities, with highly liquid central bank reserves in the hands of banks and households, thereby preventing the intermediation capacity of financial markets from collapsing further and stabilizing aggregate demand.[39] Intermediation shocks have also contributed to some extent to the 1990-91 recession and to the economic boom in the wake of the bursting of

[39]See the effect of liquidity transformation during 2009-2010 in Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017) on investment. See also the impact of such transformation in Cui and Sterk (2018) on deposits held by heterogeneous households and precautionary savings during 2009-2015.

Figure 4: **Stabilising policy effect.** The figure shows the counterfactual when there are no shocks during 2009Q3-2015Q4. The parameters are estimated using the sub-sample 1982Q1-2008Q2. Shocks are computed to generate the observed 2008Q3-2009Q2 recession.

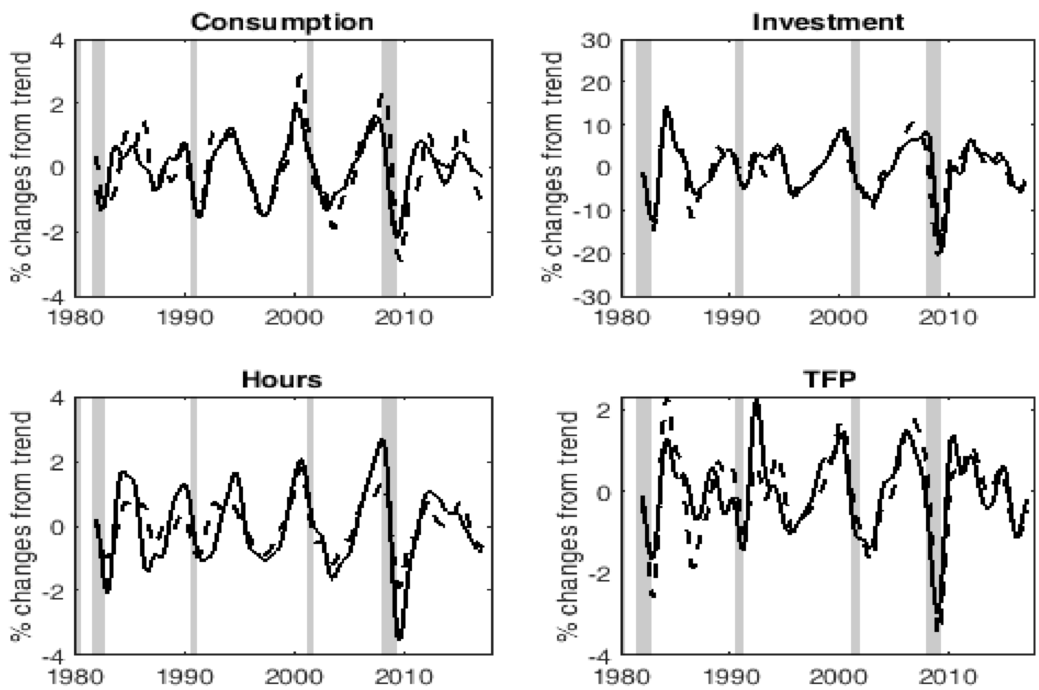


the dotcom bubble in the early 2000s.

We illustrate the stabilising effect of liquidity policies by re-estimating the model up to 2008Q2 (before the start of global financial crisis). The reason behind this approach is that this model does not feature government policy, therefore the sharp fall in intermediation costs arising from government policy could bias the estimation. Most of the estimates do not change much (see column 3 of Table 3), although the correlation of the two shocks becomes much smaller (from -0.23 to -0.15) and insignificant (the standard error is now 0.12).

After the new estimation, we feed in productivity and intermediation shocks, which generate the observed NBER recession during 2008Q3-2009Q2. Thereafter, we do not impose further shocks and check the impulse response during the period 2009Q3-2015Q4, when the liquidity injection policy was implemented (and the nominal interest rate was constrained at zero). We interpret any shocks that drive the wedge between observed output and the convenience yield and the counterfactual impulses during 2009Q3-2015Q4 as stabilising policy shocks. Figure 4 shows that policy was indeed effective in bringing down the convenience

Figure 5: **Model and data.** The figures show the comparison between the model generated variables (dash lines) and the data (solid lines).



yield up until 2015 and in preventing a further fall in output (around 2%-2.5% in 2010 and almost 4.5% in 2012).

Business-Cycle Statistics. We now assess how the model fares empirically with regard to the data that are not targeted in the estimation. As a comparison, we use the same filter to de-trend consumption, investment, hours of work, and a measure of TFP (constructed by Fernald (2014)). Figure 5 shows the model-generated time series together with the data by using the estimated shocks, and Table 4 summarises relevant statistics from the figure. The exercise suggests that the model captures the dynamics of key macro variables, which we do not target, reasonably well.

In the data, the volatility of consumption is 0.56 times that of output, while investment volatility is 3.75; both are procyclical, with correlations of 0.86 and 0.96 with output. The model-generated consumption and investment dynamics are close to the data, particularly for investment correlation. However, the volatility of consumption and investment in the model are higher (0.73 and 4.16). The correlation of hours with output is almost the same as in the data (0.85 compared to 0.84), but the volatility is about 60% of the data, reflecting the perfect labour market assumption we use. TFP generated by the model is more persistent (0.94 compared to 0.74) and more volatile (0.72 compared to 0.63) than the data, but still broadly in line with it: TFP is procyclical and is less volatile than output.

Table 4: **Business cycle statistics.** Note: the data counterparts are in brackets.

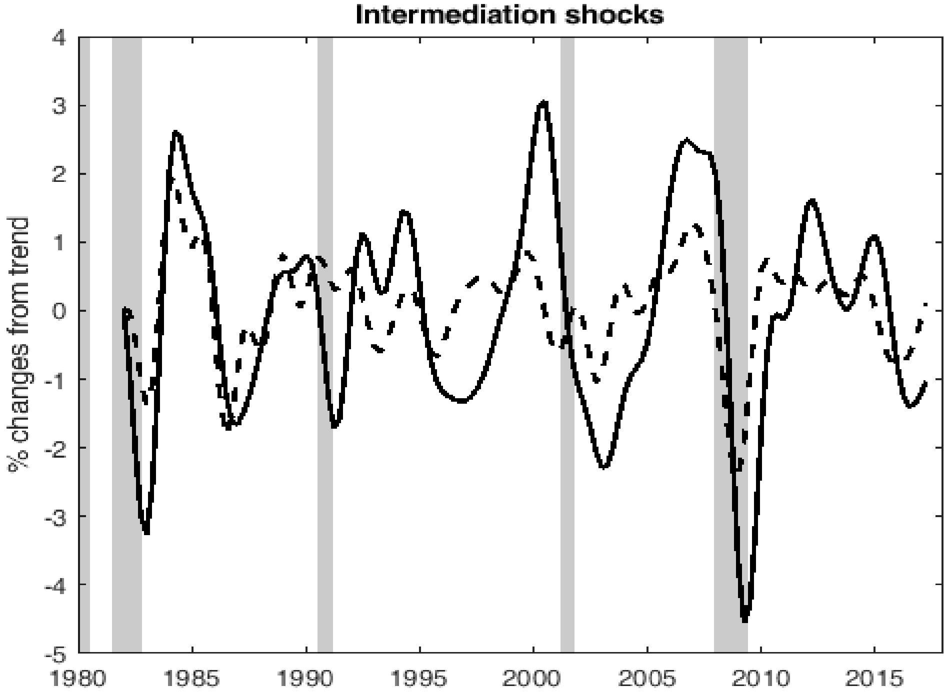
	Std. Dev. relative to output	Correlation with output
Consumption	0.73 (0.56)	0.77 (0.86)
Investment	4.16 (3.75)	0.91 (0.96)
Hours of Work	0.47 (0.79)	0.85 (0.84)
TFP	0.72 (0.63)	0.94 (0.74)

The Contribution of Intermediation Shocks. Figure 6 shows the historical contribution of intermediation shocks to output. By construction, the remainder is explained by productivity shocks. Financial intermediation shocks generate about 3% fall in output around the 2008-2009 recession, from the peak above the trend to the bottom below the trend, compared to 7% fall in the data. The shocks, however, can only account for about 0.3% fall in output out of 2.1% during the 1990-1991 recession. This is why productivity shocks seem to matter less during the 2008-2009 recession when we compare it with the 1990-1991 recession.

Intermediation shocks do not matter significantly between 1990 and 2005, while they seem to be important prior to 1990 and also important for the boom before 2008. For example, intermediation shocks pushed output 2% above trend in 1984 (compared to 2.6% in the data), while 1.5% can be seen in early 2007. The financial liberalisation and innovations before 1990 and the development of mortgage-back securities are potential reasons for the result.

Variance Decomposition. Finally, we present the variance decomposition attributed to intermediation shocks and productivity shocks based on simulating the estimated model. We first present output, the capital value, and the convenience yield since these are directly

Figure 6: **The contribution of intermediation shocks.** The figure shows output deviations. The solid line represents the data. The dash line corresponds to the case when only intermediation shocks are active. Shaded areas indicate NBER-dated recessions.



targeted (see Table 5). We then show the contribution of the two shocks to consumption, investment, hours of work, and TFP using the same decomposition.

Table 5: **Variance decomposition in percent.** OE stands for observational errors.

	Intermediation Shocks	Productivity Shocks	OE
Output	36.84	63.16	0
Convenience Yield	78.02	21.98	0
Capital Value	37.30	46.61	16.09
Consumption	34.16	65.84	0
Investment	56.08	43.92	0
Hours of work	29.85	70.15	0
TFP	47.45	52.55	0

Intermediation shocks alone explain about 37% of output variation, with aggregate productivity explaining the remainder. This result is not surprising, as intermediation shock can be caused by productivity shocks because of the correlation structure. One can view the 37% result for intermediation shocks as the lower bound.

Given the counterfactual response in the convenience yield to aggregate productivity shocks, intermediation shocks are the main driving force for the variation in the convenience yield (78%). Intermediation shocks explain most of the variation in investment (56%), but only 34% of the variation in consumption. 37.3% of the variation in capital value qK is attributed to intermediation shocks, while 46.6% is explained by productivity shocks, because productivity shocks correlate positively with intermediation shocks, which move the asset price significantly more than productivity shocks alone. The observational errors can account for 16.1%, implying that the model does reasonably well in explaining the asset price and capital value dynamics.

As hours respond only mildly to intermediation shocks, they explain less than one third of hours fluctuations. Both intermediation and productivity shocks are almost equally important for the variation in TFP (47.45% and 52.55%). After all, intermediation shocks are also efficiency shocks to the financial sector.

4.5 Robustness

Against the backdrop of these results, we perform a number of robustness checks.

Varying Asset Liquidity. We first look at comparative statics when asset liquidity changes. Since asset liquidity ϕ is endogenous, we vary only the matching efficiency parameter ξ to generate different values for asset liquidity, keeping all other parameters (including government policies g and B) as in the baseline calibration. Other equilibrium objects will change in response. Table 6 shows the steady-state values of asset liquidity, the asset price, the convenience yield, hours of work, and investment under the different parameterisations of matching efficiency.

The message of the exercise is straightforward: as long as ϕ is between 0.506 and 0.533 in the model, the steady state of the macro variables is hardly affected; in addition, in this range, the model generates convenience yields between 46 basis points to 167 basis points,

Table 6: **Comparative statics**.

ξ	$\bar{\xi}/1.03^2$	$\bar{\xi}/1.03$	$\bar{\xi}$	$1.03\bar{\xi}$	$1.03^2\bar{\xi}$
Investment	99.33%	99.65%	100%	100.35%	100.69%
Hours	0.2994	0.2997	0.3000	0.3003	0.3006
Asset liquidity	0.506	0.514	0.521	0.527	0.533
Asset price	1.055	1.039	1.025	1.012	1.001
Convenience yield (in basis points)	167	130	97	69	46

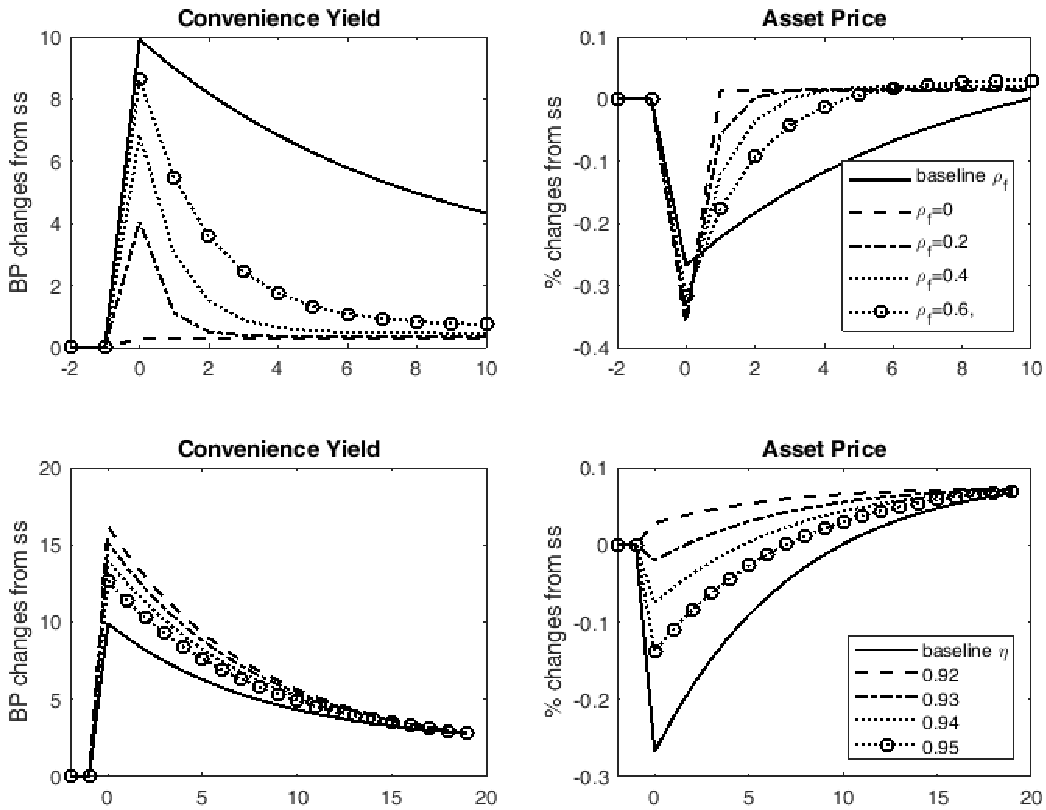
which covers a wide range of yields of AAA corporate bonds (with 20+ year maturity) relative to long-term government debt with different maturities.[40] If we were to include money and government debt with less than one year maturity in the category of liquid assets, then the convenience yield should be even higher and one should target an equilibrium ϕ that is even lower. In this case intermediation shocks would become more important. Finally, when ξ decreases, asset liquidity ϕ falls across steady states. The supply effect dominates, and we see an increase in the asset price q, as we check that the condition (25) in Proposition 2 is not satisfied.

The Impact of Intermediation Shocks. Rising intermediation costs raise the hedging value of liquid assets, while depressing the asset price as shown in Section 4.2. To generate this opposite relationship, the hedging value needs to increase strongly such that the demand for privately-issued assets falls more than supply. Whether this is true depends on agents' expectation about the future. To simplify the discussion in the following, we use the baseline parameters (i.e., $\sigma_{Af} = 0$, or there is no correlation between financial shocks and aggregate productivity shocks).

As shown in Figure 7, less persistent adverse intermediation shocks have milder effects on the convenience yield both on impact and in the future as they tighten financing constraints less. For example, when $\rho_f = 0.2$, the yield only goes up by 4 basis points, and after 2 quarters the yield is almost zero.The asset price falls more on impact, but overshoots earlier, as the shock process becomes less persistent. When $\rho_f = 0$, the asset price drops

[40]In the sample period 1982Q1 to 2017Q2, the average convenience yield relative to 30-year treasury is about 95 basis points, and the average convenience yield relative to 10-year treasury is 122 basis points.

Figure 7: **Robustness of intermediation shocks.** Impulse response functions after the same innovation in intermediation costs, but with different persistence ρ_f in the top row and with different elasticity η in the bottom row. "ss" stands for the steady state value, and BP stands for basis points.



by 0.37% on impact and rises 0.01% above its steady-state level immediately after. The persistence of the asset price response is governed by that of intermediation shocks. The stronger initial asset price reaction with less persistent shocks is explained by the reaction in the convenience yield. With a milder response of the convenience yield, entrepreneurs are less financing constrained so that the decrease in asset supply is more limited and hence pushes less against the fall in the asset price. When the persistence is zero, the inverse relationship between the convenience yield and the asset price almost disappears.

By contrast, the inverse relationship between the convenience yield and the asset price breaks down when η - the parameter that controls the sensitivity of the mapping from intensity θ to asset liquidity ϕ - is between 0.92 and 0.93. The higher the value of η, the more sensitive is ϕ to θ. This implies that asset liquidity becomes more sensitive to current and future asset demand fluctuations. Intermediation shocks can push down the asset price while at the same time raising the convenience yield only when asset liquidity is sufficiently sensitive to asset demand. This result reflects the condition in Proposition 2, in which the matching function now depends on η.

The Impact of Productivity Shocks. While rising intermediation costs increase the hedging value of government bonds and the convenience yield as shown in Section 4.2, productivity shocks may have an ambiguous effect on the incentive to hold liquid assets. A fall in aggregate productivity reduces marginal product r_t on both the right-hand sides of entrepreneurs' and workers' constraints (5) and (6). There are two effects from productivity shocks.

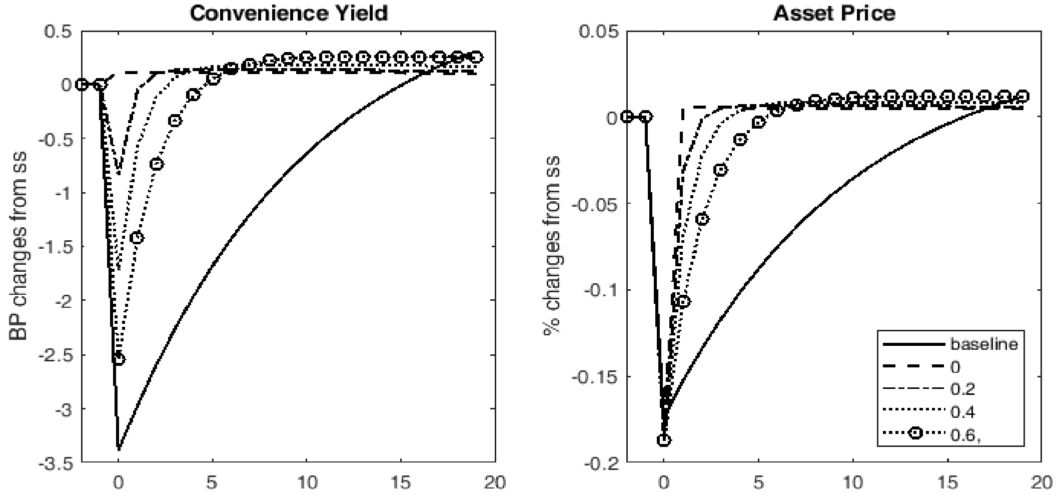
Persistently low productivity diminishes the return on capital and financial claims, such that investing in private claims and capital becomes less profitable and the willingness to hedge idiosyncratic investment risks shrinks. This effect relaxes entrepreneurs' financing constraint and pushes down the yield, because the need for investment falls. At the same time, low productivity depresses entrepreneurs' net worth, such that financing constraints become more binding. This effect should raise the hedging motive and the workers' willingness to hold liquid assets. In the baseline experiment in Figure 2, the first effect dominates the second effect, such that the yield contracts after negative productivity shocks.

Figure 8 demonstrates that the convenience yield falls after all but non-persistent (i.e., $\rho_A = 0$) productivity shocks. The asset price, by contrast, falls on impact even with non-persistent productivity shocks, by 0.17%-0.19%. With intermediation shocks, the persistence of productivity shocks governs that of the asset price reaction beyond its initial fall.

With less persistent productivity shocks, the demand for investment will be restored faster, such that the convenience yield falls less and reverts back to the steady-state faster. When ρ_A drops from the baseline value to 0.6, the initial yield reaction falls from 3.4 to 2.5 basis points. In relative terms, this reduction is similar to that in the persistence parameter.

We discuss the limiting case of $\rho_A = 0$ to sharpen the intuition for our results. Lower productivity today tends to tighten entrepreneurs' financing constraints because they gen-

Figure 8: **Robustness of productivity shocks.** Impulse response functions after the same innovation in productivity, but with different persistence ρ_A. "ss" stands for the steady state value, and BP stands for basis points.



erate less resources to use as "down-payment" for investment, keeping asset liquidity and target investment unchanged. Since $\rho_A = 0$, future productivity is unaffected by the shock. Workers therefore do not need to increase holdings of liquid assets to hedge against low future productivity. This is why the convenience yield barely moves, and increases slightly initially. Nevertheless, the negative productivity shock reduces workers' resources today. Demand for investment still falls, leading to a lower asset price.

When $\rho_A > 0$, workers anticipate that their future resources will fall, too. Low productivity in the future means that workers will invest less – and hence need to hedge less against future asset illiquidity. As a result, liquid asset holdings fall with higher persistence of productivity shocks. We therefore see a fall, rather than a rise, in the convenience yield on impact compared to the case when $\rho_A = 0$.

From the discussion above, the result, that the convenience yield falls after negative productivity shocks, would change if a specific *non-aggregate* productivity shock only affected the net worth of entrepreneurs who are financing constrained, but had no effect on the workers so that investment demand would not change.[41]

[41]For instance, in the seminal Kiyotaki and Moore (1997) model, financing constraints are tighter if a fall in productivity only affects constrained agents ("farmers" in their model), but not unconstrained agents ("gatherers" in their model). But this immediately raises the question of why only constrained agents should

To summarise, we find that the impact of *aggregate* productivity shocks on the return to capital - and hence on the demand for claims issued against capital - dominates that on entrepreneurs' net worth and on the tightness of their financing constraints. In contrast to intermediation shocks, it is, therefore, difficult for falling aggregate productivity to push up the convenience yield.

5 Conclusion

We endogenise asset liquidity in a macroeconomic model with search frictions. Assets are claims backed by physical capital. Endogenous variation in asset liquidity is triggered by shocks that affect asset demand and supply either directly (intermediation cost shocks), or indirectly (productivity shocks). By tightening entrepreneurs' financing constraints, these shocks feed into real activity. Agents hedge against endogenous financing constraints arising from illiquid assets by holding liquid government bonds.

We show that asset prices can positively co-move with asset liquidity. The *endogenous* nature of asset liquidity that interacts with intermediation costs is key to match this positive correlation, as adverse *exogenous* liquidity shocks that tighten financing constraints would induce asset price booms in recessions.

The liquidity service provided by government bonds is reflected in a liquidity premium or convenience yield. This premium rises as financing constraints bind more tightly. Shocks to the cost of financial intermediation, therefore, increase the hedging value of liquid assets, enabling our model to replicate the countercyclical nature of the liquidity premium during recent U.S. business cycles.

For future research, it may be fruitful to link risks/uncertainty to asset liquidity along the line of Lagos (2010), while maintaining the link between financing constraints and asset liquidity. Doing so will deepen our understanding of the links and differences between liquidity and safety and their impact on aggregate dynamics. In a recent paper, Del Negro,

be subject to productivity shocks.

Giannone, Giannoni, and Tambalotti (2017) find that both liquidity and safety premia associated with U.S. government debt have increased in recent years.

Regarding government interventions, our framework suggests that, as in KM, open market operations in the form of asset purchase programs can have real effects by easing liquidity frictions. However, government demand may crowd out private demand due to congestion externalities in an endogenous liquidity framework. Therefore, future research could focus on the optimal design of conventional and unconventional monetary as well as fiscal policy measures in the presence of illiquid asset markets.

Appendix A: Proofs

This section contains all the proofs to the propositions and claims in the main text.

A.1 Proof to Proposition 1

In steady state, $\rho = \rho^* = \chi^{-1}\left[\beta p_b^{-1} - 1\right] > 0$ is a constant according to the Euler equation for bonds (13). From the optimal condition for investment (12), we look at the function:

$$h(\phi, q) \equiv q - 1 + \kappa(1-\phi)\left(\frac{1}{\phi} + \frac{1}{f}\right) - \rho(1 - \phi q) = 0.$$

Now, we use the implicit function theorem:

$$\frac{\partial q}{\partial \phi} = -\frac{\partial h/\partial \phi}{\partial h/\partial q} = \frac{\kappa\left(\frac{1}{\phi} + \frac{1}{f}\right) + \kappa\frac{1-\phi}{\phi^2} - \rho q}{1 + \rho\phi}.$$

As $1 + \rho\phi > 0$, $\partial q/\partial \phi > 0$ iff the numerator is positive. Using $h(\phi, q) = 0$ again to express $q = 1 + \frac{1-\phi}{1+\phi\rho}\left[\rho - \kappa\left(\frac{1}{f} + \frac{1}{\phi}\right)\right]$ above, we find that $\partial q/\partial \phi > 0$ is equivalent to

$$l(\phi) = \left[\kappa + \left(\rho - \frac{\kappa}{f}\right)\left(\frac{1}{\rho} + 1\right)\right]\phi^2 - 2\kappa\phi - \frac{\kappa}{\rho} < 0. \tag{A.1}$$

Let $\tilde{\phi}$ denote the threshold asset liquidity level such that $\rho = 0$ if $\phi \geq \tilde{\phi}$. We know that $l(\phi)$ represents a parabola with the axis of symmetry $\phi = \kappa/\left[\kappa + (\rho - \kappa/f)(1/\rho + 1)\right]$, and $l(0) = -\kappa/\rho < 0$. Hence, if $\kappa + (\rho - \kappa/f)(1/\rho + 1) < 0$, any $\phi \in [0, \tilde{\phi})$ satisfies (A.1); if $\kappa + (\rho - \kappa/f)(1/\rho + 1) > 0$, (A.1) is equivalent to

$$0 \leq \phi < \min\{\phi^*, \tilde{\phi}\}, \text{ where } \phi^* = \frac{\kappa + \sqrt{\kappa^2 + \kappa(\rho^*)^{-1}\left[\rho^* + \left(\rho^* - \frac{\kappa}{f}\right)\left(\frac{1}{\rho^*} + 1\right)\right]}}{\rho^* + \left(\rho^* - \frac{\kappa}{f}\right)\left(\frac{1}{\rho^*} + 1\right)}.$$

Notice that $q > 1$ directly implies $\kappa + (\rho - \kappa/f)(1/\rho + 1) > 0$. To see this, from the condition $q = 1 + \frac{1-\phi}{1+\phi\rho}\left[\rho - \kappa\left(\frac{1}{f} + \frac{1}{\phi}\right)\right] > 1$, we know $\rho - \kappa/f > \kappa/\phi > 0$, and therefore $\rho + (\rho - \kappa/f)(1/\rho + 1) > 0$. □

A.2 Proof to the Claim about Marginal Surplus

The claim states that an entrepreneur spends all the additional resources on investment. We formally show this claim here. Recall that the value of an additional ϵ units of claims yields the value to the entrepreneur

$$\hat{v}^e(\tilde{q}^f, \epsilon) = u(c^e, \zeta) + \beta\mathbb{E}_\Gamma\left[v(s_+ + i_\epsilon, b_+; \Gamma_+)\right] \text{ s.t.}$$

$$c^e + (1-\phi q)(i+i_\epsilon) = rs + (1-\delta)s + b + (\tilde{q}^f - 1)\epsilon,$$

where i_ϵ is the extra investment implemented after obtaining the additional resources from selling the ϵ units of claims. Notice that the entrepreneur again can issue a ϕ fraction of i_ϵ at the equilibrium price q. We have already obtained the surplus when the entrepreneur spends all resources on investment. That is, specifying $i_\epsilon = (\tilde{q}^f - 1)\epsilon/(1-\phi q)$, differentiating $\hat{v}^e(\tilde{q}^f, \epsilon)$ w.r.t. to ϵ, and evaluating the derivative at $\epsilon = 0$, we obtain the entrepreneur's surplus of an additional unit of successful transactions

$$v_s^e(\tilde{q}^f) = \frac{\tilde{q}^f - 1}{1-\phi q}\beta \mathbb{E}_\Gamma \left[v_s(s_+, b_+; \Gamma_+)\right].$$

If the entrepreneur, instead, spends all the resource on consumption, we should set $i_\epsilon = 0$ and have $u_c\left(\tilde{q}^f - 1\right)$. We will prove that

$$u_c\left(\tilde{q}^f - 1\right) < \frac{\tilde{q}^f - 1}{1-\phi q}\beta \mathbb{E}_\Gamma \left[v_s(s_+, b_+; \Gamma_+)\right], \tag{A.2}$$

so that the entrepreneur does not want to consume the extra resources. (A.2) is equivalent to

$$(1-\phi q)u_c < \beta \mathbb{E}_\Gamma \left[v_s(s_+, b_+; \Gamma_+)\right].$$

Next, by using the envelope condition of the household problem, we have $\beta \mathbb{E}_\Gamma \left[v_s(s_+, b_+; \Gamma_+)\right] = U_c q^w$. Then, (A.2) is equivalent to

$$\frac{(1-\phi q)u_c}{U_c} < q^w,$$

which is true, because by using the first order conditions (11) and (12) we know

$$\frac{(1-\phi q)u_c}{U_c} = (1-\phi q)(1+\rho) = (1-\phi q)\frac{(1-\phi)q^w}{1-\phi q} = (1-\phi)q^w < q^w. \quad \square$$

A.3 Proof to Proposition 2

The bargaining solution simplifies to (after using the first-order condition for private claims and $\tilde{q}^f = q^f$):

$$\frac{1-\omega}{q^w - q^f} = \frac{\omega}{q^f - 1}.$$

Therefore, $q^f = (1-\omega) + \omega q^w$. Together with the zero profit condition $q^f = q^w - \kappa/f = q + \kappa/\phi$, we obtain

$$q = 1 + \kappa\left(\frac{\omega}{1-\omega}\frac{1}{f} - \frac{1}{\phi}\right),$$

as in the main text. Now, let us substitute out κ. From (12), we know that

$$q = 1 + \frac{1-\phi}{1+\phi\rho}\left[\rho - \kappa\left(\frac{1}{f} + \frac{1}{\phi}\right)\right].$$

The above two equations can solve κ, and we express the asset price q as a function of ρ, ϕ, and f only:

$$q = 1 + \frac{\rho}{\frac{1+\phi\rho}{1-\phi} + \frac{\phi+f}{\tilde{\omega}\phi - f}},$$

where $\tilde{\omega} = \frac{\omega}{1-\omega}$. Again, in the steady state, $\rho = \rho^*$. Therefore, if and only if $\partial\{\frac{1+\phi\rho}{1-\phi} + \frac{\phi+f}{\tilde{\omega}\phi-f}\}/\partial\theta < 0$, $\partial q/\partial\theta > 0$ and $\partial q/\partial\phi > 0$ (because $\partial\phi/\partial\theta > 0$). Notice that we can write $f = M(\theta^{-1}, 1) = \mu(\theta)$ and $\phi = \theta\mu(\theta) = M(1, \theta)$, and we can simplify

$$\frac{\partial\{\frac{1+\phi\rho}{1-\phi} + \frac{\phi+f}{\tilde{\omega}\phi-f}\}}{\partial\theta} = \frac{(\rho+1)\left[\mu(\theta) + \theta\mu'(\theta)\right]}{\left[1-\theta\mu(\theta)\right]^2} - \frac{1}{(1-\omega)(\tilde{\omega}\theta - 1)}.$$

We thus know that $\partial q/\partial\phi > 0$ is equivalent to

$$\rho + 1 < \frac{\left[1-\theta\mu(\theta)\right]^2}{(1-\omega)(\tilde{\omega}\theta-1)\left[\mu(\theta)+\theta\mu'(\theta)\right]} = \frac{\left[1-\theta\mu(\theta)\right]^2}{\left[\omega\theta - (1-\omega)\right]\left[\mu(\theta)+\theta\mu'(\theta)\right]}. \quad \square$$

Appendix B: Equilibrium Conditions

This section contains the equilibrium conditions we use in the quantitative exercise.

We list the equilibrium conditions in the following. We use the functional forms assumed in the quantitative exercise. Given the aggregate state variables $\Gamma = (K, B, A, \Delta)$, the exogenous laws of motion of (A_+, Δ_+), and government policy $g = \bar{g}$ and $B = B_+ = \bar{B}$, the equilibrium maps Γ to $\Gamma' = (K_+, B_+, A_+, \Delta_+)$ such that

$$\{K_+, i, c^e, c^w, \ell, \ell^g, \ell^f, k^g, k^f, \rho, \theta, \phi, f, q, q^w, r, w, \kappa, p_b, \tau\}$$

satisfy the following equilibrium conditions obtained from the main text:

1. The representative household's optimality conditions:

$$w = \mu\ell^\nu \tag{B.1}$$

$$\left(c^e - \frac{\mu\zeta^{1+\nu}}{1+\nu}\right)^{-\sigma} = (1+\rho)\left(c^w - \frac{\mu\ell^{1+\nu}}{1+\nu}\right)^{-\sigma} \tag{B.2}$$

$$1 = \mathbb{E}_\Gamma\left[\frac{\beta U_{c,+}}{U_c}\left[\frac{r_+ + (1-\delta)\,q_+^w}{q^w} + \frac{r_+ + (1-\delta)\,\phi_+ q_+}{q^w}\chi\rho_+ - \frac{(1-\delta)\,\phi_+\chi\left(q_+^w - q_+\right)}{q^w}\right]\right] \tag{B.3}$$

$$p_b = \mathbb{E}_\Gamma \left[\frac{\beta U_{c,+}}{U_c} \left(1 + \chi \rho_+\right) \right] \tag{B.4}$$

$$q^w - 1 - \phi(q^w - q) = (1 - \phi q)\, \rho \tag{B.5}$$

$$i = \frac{\left[r + (1-\delta)\, \phi q\right] K + B - c^e - \tau}{1 - \phi q} \tag{B.6}$$

2. Firms' optimality conditions:

$$r = \alpha A \left(\frac{k^g}{\ell^g}\right)^{\alpha - 1} \text{ and } w = (1-\alpha) A \left(\frac{k^g}{\ell^g}\right)^{\alpha} \tag{B.7}$$

$$(1+\Delta) r = \kappa \alpha A A^f \left(\frac{k^f}{\ell^f}\right)^{\alpha - 1} \text{ and } (1+\Delta) w = \kappa (1-\alpha) A A^f \left(\frac{k^f}{\ell^f}\right)^{\alpha} \tag{B.8}$$

$$q^w - q = \kappa \left(\frac{1}{f} + \frac{1}{\phi}\right) \tag{B.9}$$

$$q = 1 + \kappa \left(\frac{\omega}{1-\omega} \frac{1}{f} - \frac{1}{\phi}\right) \tag{B.10}$$

$$\phi = \xi \theta^{1-\eta} \text{ and } f = \xi \theta^{-\eta} \tag{B.11}$$

$$(1+\theta)\chi \left[i + (1-\delta) K\right] = A A^f \left(k^f\right)^{\alpha} \left(\ell^f\right)^{1-\alpha} \tag{B.12}$$

3. Government budget constraint:

$$(1 - p_b)\bar{B} + g = \tau \tag{B.13}$$

4. Capital accumulation:

$$K_{+1} = (1-\delta)\, K + \chi i \tag{B.14}$$

5. Market clearing:

   (a) The consumption goods market

$$\chi c^e + (1-\chi) c^w + \chi i + g = A \left(k^g\right)^{\alpha} \left(\ell^g\right)^{1-\alpha} \tag{B.15}$$

   (b) Factor markets

$$(1+\Delta) k^f + k^g = K \text{ and } (1+\Delta)\ell^f + \ell^g = (1-\chi)\ell \tag{B.16}$$

(B.1) - (B.16) represent the equilibrium conditions. Notice that in the steady state we calibrated, A^f is not a free parameter because the equilibrium restrictions (B.8) imply that $A^f = \frac{(1+\Delta) r}{\kappa \alpha A} \left(\frac{k^f}{\ell^f}\right)^{1-\alpha}$.

Appendix C: Data

This section contains the detail of the data we use for the quantitative exercises.

Macroeconomic Data. Real consumption, investment, and government expenditures are from standard BEA Table 1.1.6. Hours of work are from "Hours and Employment by Industry" and "Hours Worked in Total U.S. Economy and Subsectors" tables. These tables are under the Labor Productivity and Costs section published by the BLS.[42] Financial hours used in the paper are obtained under a subset of "Finance, Insurance, and Real Estate" (see the detail description in the main text). To the best of our knowledge, there is no quarterly table.

We also obtain the growth rate of a measured TFP series from the productivity study from the San Francisco Fed, led by John Fernald (see Fernald (2014)). We normalise the initial observation in 1982Q1 to be one for TFP, and then we use the growth rate to construct the TFP series. Finally, we take log transformation and de-trend the series.

The Convenience Yield. The Moody's Aaa index is constructed from a sample of long-maturity ($\geq$ 20 years) industrial and utility bonds (industrial only from 2002 onward). We use the yields on 10-year maturity, 20-year maturity, and 30-year maturity treasury bonds. We take the average of 10-year, 20-year, and 30-year treasury to represent the return from government bonds. Notice that the model has only one type of government-issued assets, while in practice there are many different types which are liquid. We view averaging yields across these treasuries as a reasonable compromise. All data series are from the FRED database (series AAA, GS10, GS20, and GS30). The convenience yield is then computed as the ratio of the gross return of Aaa bonds and that of treasury bonds.

The Value of Capital. Using flow-of-funds data from the Federal Reserve Board (i.e., Z1 report), we consolidate the balance sheet of non-profit organization (B.100), the non-financial non-corporate sector (B.103), the non-financial corporate sector (B102), and the financial sector (the balance sheet account in S.6.a Financial Business) to obtain the market value of aggregate capital.

For non-profit organizations, we sum real estate and equipment and software. For the non-corporate sector, we sum real estate, equipment and software, intellectual property products, and inventories. For the corporate sector, we obtain the market value of the capital stock by summing the market value of equity and liabilities net of financial assets. We then subtract from the market value of capital for the private sector the government credit market instruments, TARP, and trade receivables. For the financial sector, we sum structures, equipments, and intellectual property products.

[42]https://www.bls.gov/lpc/tables.htm

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