Central bank interventions and asset market liquidity

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ABSTRACT

Central banks around the world routinely engage in asset purchases in secondary markets as part of implementing monetary policy or enhancing market liquidity, but the effects of such interventions are not yet fully understood. We develop a multi-asset general equilibrium model in which the liquidity of an asset is *endogenous* and depends on the terms of trade in each asset's respective secondary market, which are, in turn, driven by agents' market entry decisions and the possibility of central bank intervention. We use our model to qualitatively and quantitatively rationalize the superior liquidity of U.S. Treasuries over corporate bonds of comparable safety. Our model highlights and quantifies an unexplored link between fiscal and monetary policy: central bank interventions in the market for Treasuries increase secondary market liquidity for these securities, thus indirectly aiding the Treasury to borrow at lower rates. Our results also reveal that central bank interventions can have spillover effects on markets where the bank does not participate, offering a cautionary note to both policymakers and empirical researchers.

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1 Introduction

The Federal Reserve System of the United States and most central banks around the world routinely engage in asset purchases in secondary markets, as a means of implementing monetary policy or improving market liquidity. Although most economists presume that the intervention of such a large and powerful player is expected to have significant effects on asset liquidity and prices, these effects are not yet fully understood. Some of the existing papers studying the effects of central bank intervention on asset prices are not explicit on the microfoundations of asset liquidity, and most do not model the secondary markets where this intervention is supposed to take place. However, it is hard to imagine that the decision (and announcement) of a central bank to enter a specific market in order to purchase bonds will not affect the decision of investors to visit (or, for that matter, avoid visiting) that market. A more complete understanding of how central bank purchases affect asset liquidity and prices requires careful modeling of the central bank's secondary market intervention and how such intervention affects investors' decisions to visit that market (or opt for one in which the central bank does not participate).

To that end, we develop a multi-asset general equilibrium model with an empirically relevant concept of asset liquidity, and an explicit mechanism through which central bank market participation affects that liquidity. After making their portfolio decisions, agents receive an idiosyncratic shock that determines whether they will have a consumption opportunity in that period; active consumers visit secondary asset markets to sell/liquidate assets for money, and inactive consumers are the providers of liquidity. Thus, in our model, assets cannot be used as media of exchange or collateral to purchase consumption, but they are *indirectly* liquid, as they can be sold for money in their respective secondary market. Consequently, the liquidity of an asset is not determined by some *ad hoc* assumption regarding how much "convenience" it provides to the holder or how "pledgeable" it is in transactions. The liquidity of an asset is *endogenous* and depends on the probability and the terms of trade in each asset's respective secondary market, which depend on the agents' investment and market entry decisions and are, in turn, influenced by a possible central bank intervention. A characteristic that makes our analysis empirically relevant and sets our paper apart from much of the existing literature on central bank asset purchases is that secondary asset markets are modeled as Over-the-Counter (OTC) markets characterized by search and bargaining.[1]

[1] Adopting an OTC market structure allows us to explicitly capture key concepts, such as the probability of (not) finding a trading partner, the terms of trade that investors can negotiate in bilateral meetings, and, crucially, the idea that, if the central bank is actively purchasing assets in a certain market, that affects not only the trade probability of an asset seller, but also her "outside option" in a private negotiation (i.e., the

More concretely, we consider a two-asset model in which each asset trades in a distinct OTC market (OTC$_A$ and OTC$_B$) and agents choose to visit the market with the best expected trading conditions. A key theoretical innovation is that the central bank intervenes in one of these markets (without loss of generality, OTC$_A$) with a certain probability known to all participants. When active, the central bank does not influence the matching function that brings together buyers and sellers of assets in OTC$_A$. Rather, it acts as a buyer of last resort by committing to purchase any amount of asset A at an announced price. This intervention affects the prospects of sellers in OTC$_A$ in two ways: first, it offers sellers an additional opportunity to sell assets if they do not meet a private buyer, and second, it affects trades between private investors since sellers can threaten to walk away and sell their assets to the central bank instead. In this environment, we study how a central bank intervention in OTC$_A$ affects agents' market entry decisions and eventually the liquidity and equilibrium prices of *both* assets.

In our model, agents buy assets in the primary market before knowing whether tomorrow they will turn out to be buyers or sellers, but are willing to pay a high premium today if they expect to be able to *sell* assets at favorable terms down the road. The presence of the central bank improves the prospects of sellers in OTC$_A$, both in case they match with a private buyer, through an improved outside option, and in the event that they sell assets directly to the central bank. Thus, a more frequent central bank intervention (or a higher announced price) tends to increase investors' willingness to pay a higher premium to hold asset A. However, in addition to this direct effect, a central bank intervention in OTC$_A$ also generates a *spillover effect* in OTC$_B$. This effect operates through the entry decisions of asset buyers, who are *crowded out* of OTC$_A$ (and into OTC$_B$), as they realize that the presence of the central bank in that market serves as a bargaining chip in the hands of sellers. The decreased (increased) entry of buyers in OTC$_A$ (OTC$_B$) raises the probability of a match with a private buyer in OTC$_B$, thus inducing investors to pay a higher liquidity premium for asset B. (Sellers like markets awash with buyers because they imply high trading probabilities.) This spillover effect is a novel theoretical insight that arises in our framework because of the carefully modeled general equilibrium market entry decisions, and highlights that central bank market purchases can increase liquidity even in markets where the bank does not participate.

To demonstrate the applicability of our model, we use it to study the superior liquidity of U.S. Treasuries, i.e., the well-known fact that U.S. government-issued bonds sell at higher prices than corporate (or municipal) bonds of similar characteristics, even after

credibility of a threat to walk away and sell to the central bank instead). For a careful justification of the empirical relevance of OTC markets, see Hugonnier, Lester, and Weill (2025).

controlling for safety (Krishnamurthy and Vissing-Jorgensen, 2012). Our paper makes a twofold contribution. First, it shows that a calibrated version of our model can *quantitatively explain* the yield differential between Treasuries and safe corporate bonds seen in the data and attribute the well-established liquidity advantage of Treasuries to the observed interventions of the Federal Reserve in the secondary market for these particular securities. Additionally, our quantitative analysis shows that the presence of the Fed in the Treasury market accounts for 17% of the total liquidity premium of U.S. Treasuries, a component which we dub the *central bank premium*.[2] We also provide a comparative statics analysis that explores how changes in the two key policy parameters, the frequency of central bank intervention and the announced purchase price, affect the various components of the Treasury liquidity premium.

The second contribution of our paper is to highlight an unexplored *link between monetary and fiscal policy* (which in the macroeconomics textbook are supposed to be independent of each other). Once the U.S. Treasury has issued its securities, these securities trade in a secondary market that is not in any way controlled by the Treasury. However, this market happens to be the one in which the Federal Reserve has traditionally performed its open market operations.[3] Our model emphasizes that central bank asset purchases in a specific *secondary* market, in this case the one for Treasuries, raise the resale value of these assets and, through our indirect liquidity mechanism, increase the willingness of investors to pay higher prices in the *primary* market, thus allowing the Treasury to borrow funds at a lower rate. Our counterfactual exercise reveals that the U.S. Treasury saves around 10 billion dollars per quarter (on the issuance of 10-year Treasuries alone) due to the increased liquidity of its securities, compliments of the Fed's interventions in their secondary market. The calibrated model also allows us to assign a number on the spillover effect described earlier: the central bank presence in the Treasury market saves firms around a billion per quarter on the issuance of corporate bonds.

Our results deliver two cautionary notes, one for policymakers and one for empirical

[2] The central bank premium can be further decomposed into an *outside option* as well as a *last resort* component. The former reflects the additional gain a seller obtains by threatening to sell to the central bank if the buyer offers an unfavorable price, while the latter arises when the seller fails to meet a private buyer and, hence, sells directly to the central bank. For details, see Section 5.3.

[3] Even though open market operations has ceased to be the primary means through which the Fed manipulates the federal funds rate since the Global Financial Crisis, they still form an important piece of the monetary policy toolbox and they are quantitatively significant—see Section 5.1 for details. In particular, the Fed uses them to maintain an ample supply of reserves in the system, an integral aspect of the floor/ample reserves monetary policy regime implemented after 2008. For institutional details, see: https://www.federalreserve.gov/monetarypolicy/openmarket.htm, https://www.federalreserve.gov/aboutthefed/files/the-fed-explained.pdf and https://www.stlouisfed.org/publications/page-one-economics/2020/08/03/the-feds-new-monetary-policy-tools.

researchers. First, regarding policy implications, our spillover effect result suggests that liquidity in a particular market can be improved without direct intervention in this market. On the flip side, our results also imply that central bank interventions can crowd out private market interactions, thus mitigating the effectiveness of asset purchase programs on liquidity. This concern was explicitly voiced by Ben Bernanke, the chairman of the Fed, in his 2012 Jackson Hole speech:

> One possible cost of conducting additional large-scale asset purchases is that these operations could impair the functioning of securities markets... Conceivably, *if the Federal Reserve became too dominant a buyer in certain segments of these markets, trading among private agents could dry up*, degrading liquidity and price discovery. As the global financial system depends on deep and liquid markets for U.S. Treasury securities, significant impairment of those markets would be costly, and, in particular, could impede the transmission of monetary policy. (Bernanke 2012; emphasis added)

The second cautionary note applies to empirical researchers aiming to tease out the causal effect of central bank interventions by comparing the market where the intervention took place ("treated") with some other market where the central bank was not active ("control"). The lesson drawn from our analysis is that the time window around which this comparison takes place has to be very short to enable the identification of the causal effect of the central bank intervention. Eventually, investors may exit the treated market and enter the control one, in which case the comparison between the two markets will be contaminated by the spillover effect, which can be substantial according to our model.

1.1 Related Literature

The present paper belongs to the branch of the New-Monetarist literature that provides microfoundations for asset liquidity, including Geromichalos, Licari, and Suárez-Lledó (2007), Lagos (2010), Nosal and Rocheteau (2013), Hu and Rocheteau (2013), Andolfatto, Berentsen, and Waller (2014), Lee and Jung (2020), and Lee (2020); see Lagos, Rocheteau, and Wright (2017) for an overview. Some recent papers employ the indirect liquidity approach also adopted here, i.e., they assume that assets do not serve directly as media of exchange or collateral in transactions but can be liquidated for money in secondary markets upon the arrival of a consumption need.[4] Examples include Geromichalos and

[4] Since the liquidation of assets takes place in OTC secondary markets, our paper is also related to the literature initiated by the seminal paper of Duffie, Gârleanu, and Pedersen (2005), e.g., Weill (2007), Lagos and Rocheteau (2009), Chang and Zhang (2015), Üslü (2019), and Gabrovski and Kospentaris (2021).

Herrenbrueck (2016), Mattesini and Nosal (2016), and Altermatt, Iwasaki, and Wright (2023). Our model shares some ingredients with Geromichalos, Herrenbrueck, and Lee (2023a,b), which feature two-asset models in which agents make optimal market entry decisions. However, none of these works features the key ingredient of the present paper, which is central bank intervention in secondary markets, and how it affects liquidity in general equilibrium.

Given our focus on the impact of central bank interventions on asset prices, our paper is also related to several papers aiming to understand this connection, such as Gertler and Karadi (2011, 2013), Del Negro, Eggertsson, Ferrero, and Kiyotaki (2017), and Kiyotaki and Moore (2019). However, these works do not explicitly model the secondary markets in which central bank intervention takes place. Closer to our approach are papers from the New-Monetarist literature that study central bank interventions with explicit micro-foundations such as Berentsen, Marchesiani, and Waller (2014), Afonso and Lagos (2015), Chiu and Koeppl (2016), Armenter and Lester (2017), Rocheteau, Wright, and Xiao (2018), Madison (2019), and Geromichalos and Herrenbrueck (2022). A distinctive characteristic of our model is that it features two financial assets together with optimal investment and market entry decisions that determine each asset's liquidity endogenously. This is crucial because it allows us to study the spillover effects between the two asset markets and the unintended consequences of central bank interventions on markets other than the one where interventions take place. Importantly, as the list of asset markets where central bank interventions take place has been expanding over the past 20 years, our multi-asset general equilibrium model could provide useful insights regarding how the intervention in a new market can affect liquidity and asset prices across the board.[5]

Although the standard treatment in the undergraduate textbook implies that fiscal and monetary policies (are supposed to) act independently, there is an important literature, starting with Sargent and Wallace (1981) and Wallace (1981) and reviewed by Bassetto and Sargent (2020), studying their interaction. More recently, this interaction has been explored in the context of Heterogeneous Agents New Keynesian models (Kaplan, Moll, and Violante, 2018; Alves, Kaplan, Moll, and Violante, 2020), as well as in models of the fiscal theory of the price level (Cochrane, 2021). The channel through which monetary policy affects fiscal policy in our model is unexplored, since it rests on the explicit modeling of the secondary asset market and the behavior of participants therein. In reality, and in our model, the Fed does not aid the Treasury by purchasing bonds directly from it.

[5] Before the Global Financial Crisis, the idea that the Fed would purchase assets other than Treasuries seemed inconceivable. Analogously, one cannot rule out the future expansion of central bank activity in (what today is deemed) exotic markets and, hence, the need for multi-asset general equilibrium models that are well suited to study these expansions.

But it ends up assisting the Treasury by increasing liquidity in the secondary market, thus increasing the willingness of investors to buy bonds from the Treasury at higher prices. In that sense, our channel is closer to an important Industrial Organization literature that highlights the importance of secondary market activity for the determination of prices in the primary market (Rust, 1985, 1986).

Finally, our paper is conceptually related to a growing literature that highlights the importance of financial markets and investor sentiment for the transmission of monetary policy (Bauer, Bernanke, and Milstein, 2023; Kashyap and Stein, 2023). This literature was inspired by Ben Bernake's famous quote that "Quantitative Easing (QE) works in practice but not in theory", referring to the observation that QE has been effective in stimulating economies, despite not being fully explained by conventional macroeconomic models. The general idea running through this literature is that changes in policy rates affect the willingness of investors to tolerate risk and, thus, the risk premiums on a range of financial assets. For example, when rates are very low, investors may raise their exposure to risky assets in an effort to maintain their current level of consumption (a behavior often referred to as "reaching for yield"; see Campbell and Sigalov 2022). Our model provides an alternative explanation for why central bank interventions in specific markets can have widespread effects throughout the financial system.

The rest of the paper is organized as follows. Section 2 describes the model and offers a discussion of some key assumptions. In Section 3, we analyze the model and in Section 4 we characterize the equilibrium. Section 5 describes our calibration strategy and illustrates our main results. Finally, Section 6 concludes.

2 The model

Our model is an adaptation of the indirect asset liquidity model of Geromichalos and Herrenbrueck (2016), which in turn is a hybrid of Lagos and Wright (2005) (LW henceforth) and Duffie et al. (2005). Time is discrete with an infinite horizon. Each period consists of three sub-periods, where different economic activities take place. During the first sub-period, two distinct OTC asset markets open, denoted by OTC$_j$, $j \in \{A, B\}$. Agents who hold assets of type j can sell them for money (only) in the designated market OTC$_j$. Without loss of generality, let OTC$_A$ be the market in which the central bank participates to purchase assets. In the second sub-period, agents visit a decentralized goods market as in LW, where trade is bilateral and the usual frictions, such as anonymity and imperfect commitment, make a medium of exchange (i.e., money) necessary. We refer to this market as the DM. During the third sub-period, economic activity takes place in a centralized market, which is the settlement market of LW, and we refer to it as the CM. There are two types of agents, consumers and producers, named by their role in the DM, and the measure of both types is normalized to the unit. All agents are infinitely lived.

Before we move on with the description of the environment, a quick comment on terminology is in order. Since the DM "consumers" are the only agents who make meaningful portfolio and market entry decisions, henceforth, when we say "agents", it is understood that we refer to the "consumers". The agents who produce in the DM will not play an important role in the analysis; on the rare occasions these agents come up we refer to them as "producers". Importantly, we reserve the terms "buyer" and "seller" to refer exclusively to agents who buy and sell assets in OTC markets.

We now move on to a detailed description of the various sub-periods. In the third sub-period, agents choose their money holdings for the next period, and we let φ_t denote the real price of money. The supply of money is controlled by the central bank and follows the rule $M_{t+1} = (1+\mu)M_t$, $\mu > \beta - 1$. New money is introduced, or withdrawn if $\mu < 0$, via lump-sum transfers in the CM. Agents can also purchase any amount of asset j, $j \in \{A, B\}$, at (nominal) price p_j. Both of these assets are 1-period discount bonds, i.e., each unit of (either) asset purchased in period t's CM, will pay 1 dollar in the CM of period $t+1$ with certainty. Although both assets are risk-free, agents may seek to sell them before maturity, and our goal is to examine how the central bank's decision to purchase (type-A) assets in OTC$_A$ will affect *both* assets' liquidity properties.

After making portfolio decisions in the CM, agents receive an idiosyncratic shock: a measure $\ell < 1$ will be active in the forthcoming DM, and we refer to them as C-types. The remaining $1 - \ell$ agents will be referred to as N-types ("not consuming" in the current period). Since agents made their portfolio choices before the idiosyncratic shock was realized, N-types will typically hold some money that they do not need in the current period, and C-types will hold an insufficient amount of cash, since carrying money across periods is costly. The OTC round of trade, which takes place before the DM, but after the realization of the idiosyncratic consumption shock, allows the reallocation of money into the hands of the agents who value it most, namely the C-types.

We now describe the structure of the OTC round of trade. OTC markets are distinct: an agent who wants to sell or buy assets is free to enter OTC$_A$ or OTC$_B$, but must choose one market at a time. This assumption (which we discuss in Section 2.1) has an important implication. In equilibrium, assets will carry a liquidity premium due to their ability to be transformed into money, thus relaxing a binding liquidity constraint. Agents will be unwilling to pay that premium for assets whose liquidity they cannot utilize. Since agents can only enter one OTC market per period and anticipate having to choose between OTC$_A$

and OTC_B eventually, they will choose *ex ante* (i.e., in the CM) to "specialize" in asset A or B (although there is no exogenous constraint forcing them to hold only one asset).

We now move to the most novel feature of our model, the central bank asset market intervention. As we have mentioned, the central bank participates in OTC_A to purchase that specific type of asset. We assume that the intervention in OTC_A takes place with probability $\pi \in (0, 1)$. This probability is public information, but the associated uncertainty will only be resolved at the end of the CM, which means that agents make their portfolio decisions without yet knowing whether the central bank will be active in next period's OTC_A. When the central bank participates in OTC_A, it commits to purchasing *any amount* of asset A at the predetermined price $\overline{p}$, which we treat as one of the policy parameters of the model. (See a detailed discussion in Section 2.1.)

Since secondary markets are OTC, we must take a stance on how C-types (asset sellers) meet with individual buyers versus the central bank. Suppose for the moment that the idiosyncratic consumption shock has been realized and all C- and N-types have decided which OTC market they wish to visit. (These choices are far from obvious, and we describe them in detail in Section 4.1, but for now we consider a partial equilibrium argument.) Letting C_j, N_j denote the measure of sellers and buyers in OTC_j, $j = \{A, B\}$, respectively, we assume that the constant return to scale matching function

$$f(C_j, N_j) = \delta \, \frac{C_j N_j}{C_j + N_j}, \quad \delta \geq 0, \tag{1}$$

brings together C-types and N-types in OTC_j, where δ is a matching efficiency parameter.

The matching function f describes how individual buyers and sellers meet in either OTC market. But we still need to specify how C-types in OTC_A sell assets to the central bank (when the bank is active). We assume that C-types who enter OTC_A, but do not match with a buyer, proceed to sell assets to the central bank (at the stated price $\overline{p}$). To make things interesting and empirically relevant, we also assume that C-types who meet a buyer in OTC_A can threaten their trading partners to walk away from the match and sell their assets to the central bank. With agents negotiating the terms of trade based on the egalitarian bargaining solution (Kalai, 1977), the C-types will never carry out their threat on the equilibrium path. However, the presence of the central bank in OTC_A and its commitment to purchase any supplied amount of asset A at the stated price, offers asset sellers a valuable *outside option* in their negotiations.[6] In sum, the central bank interven-

[6] See also Lee (2024), who exploits this outside option channel to explain why in some crises the Federal Reserve must purchase assets on a large scale, while in others just announcing that they will purchase a certain amount of assets can be sufficient without massive purchases.

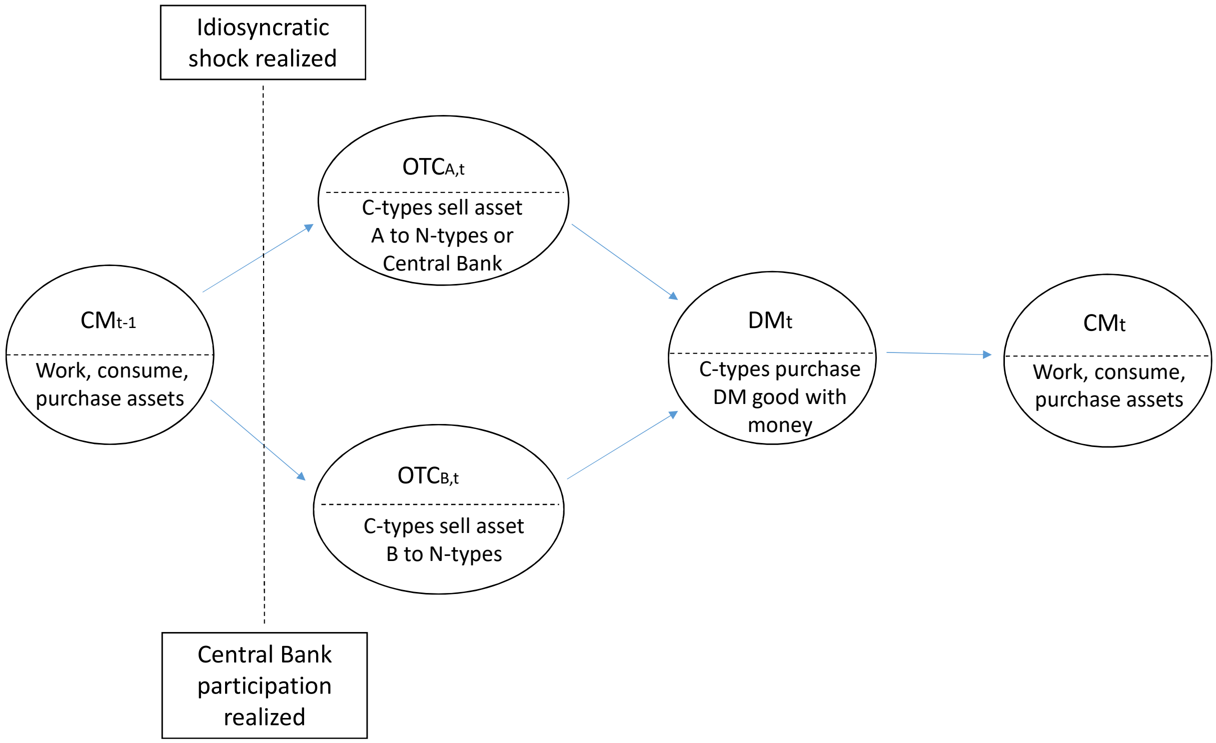

Figure 1: Timing of events.

tion in OTC$_A$ not only offers an additional opportunity to sell assets for C-types who did not match with a buyer, but also influences the attainable terms of trade for C-types who did match with a buyer. To close the description of the OTC round of trade, let $\theta \in (0, 1)$ denote the bargaining power of the C-type in any private OTC meeting.

Lastly, consider the second sub-period, which is the standard DM of LW. C-type agents meet bilaterally with producers and negotiate the terms of trade. Exchange necessitates a medium of exchange, and only money can serve that role. Since all the interesting results of the paper follow from agents' interaction in the OTC round of trade, we keep the DM as simple as possible, assuming that all C-types meet a producer and they make a take-it-or-leave-it offer.

Figure 1 summarizes the timing of the main events. This is a good point to emphasize that the matching efficiency (δ) and the seller's bargaining power (θ), i.e., the parameters that jointly capture what authors refer to as "market microstructure", are identical between OTC$_A$ and OTC$_B$. This means that our model does not assume an exogenous liquidity advantage of asset A over asset B: any liquidity differential in favor of asset A that arises in equilibrium originates from the central bank intervention in OTC$_A$.

2.1 Discussion of key modeling choices

Since our paper studies the effects of central bank asset purchases within the context of a new, microfounded model of asset liquidity, some of the model's ingredients are non-standard and require further justification.

A key assumption in our analysis is that secondary markets are segmented and agents can visit only one per period. The first part of this assumption is totally realistic. For example, Treasuries and corporate or municipal bonds trade in secondary markets that are completely distinct from each other. What is perhaps a stronger assumption is that agents can visit only one OTC market per period. (Recall that agents are free to hold both assets, but *choose* to specialize only on one to avoid paying a premium for the liquidity services of an asset that they will not utilize.) This assumption is not meant to be taken literally and is just a stark way of capturing the idea that trading a particular type of asset is costly, and agents will visit more frequently the secondary market where they expect to find the best terms of trade. For the interested reader, Geromichalos et al. (2023a) consider a more general model where agents have the option to trade both assets in the OTC round but choose not to exercise it, thus providing some microfoundations for the asset specialization result.

Next, in our model the central bank purchases assets in an OTC market characterized by search and bargaining.[7] Therefore, we need to take a stance on how asset sellers meet and trade with this new "big player" versus individual buyers. Our assumption that the central bank acts as a buyer of last resort purchasing bonds at a predetermined price offers a tractable way of capturing an empirically relevant fact: asset sellers obtain both a direct and an outside option benefit from the central bank's presence in a specific market. Although in reality it is more common that central bank announcements specify interventions of a particular size, market participants are able to build expectations from those announcements about the price at which they can sell assets to the central bank.[8] More formally, in Appendix B we show that for any equilibrium of the model where the central bank fixes the purchase price, there exists a corresponding purchase size that can generate the same equilibrium. Thus, we could also model the central bank intervention

[7] We assume that the central bank intervenes only in OTC_A, which for the most part we interpret as the secondary market for Treasuries, and study how this intervention can materialize into a liquidity advantage for Treasuries/asset A. Although in recent years the Federal Reserve has expanded its operations to the secondary markets of other asset classes, the market for Treasuries is still the one where central bank interventions are the most prominent. The main results of the paper would not change significantly if we assumed that the central bank intervenes in both OTC markets, but more often so in OTC_A.

[8] A similar point is made in the recent paper by Haddad, Moreira, and Muir (2025), where the authors show that investors can infer the purchasing price of bonds from the central bank's announcement about the purchase size.

assuming that the bank announces the size of the asset purchase rather than the price, but out of the two, we favor the more tractable approach.

3 Analysis of the model

3.1 Matching probabilities

The probability that an individual agent matches in the OTC market of her choice is constructed as follows. Let $e_i \in [0,1]$, $i \in \{C, N\}$, denote the fraction of type-i agents who choose to enter OTC$_A$. Recall from the discussion in Section 2 that C-type agents effectively make this decision in the CM, since they choose to specialize in one asset. On the other hand, N-types want to buy assets and their money is good in either OTC, so these agents do not have to precommit.[9] The measures of asset sellers and buyers in OTC$_A$ are denoted by $e_C\ell$ and $e_N(1-\ell)$, respectively, while the corresponding measures in OTC$_B$ are $(1-e_C)\ell$ and $(1-e_N)(1-\ell)$. The terms $e_i \in [0,1]$, $i \in \{C, N\}$, will be endogenously determined in equilibrium.

Let $\alpha_{ij} \in [0,1]$ denote the matching probability of a type-i agent in OTC$_j$, where $i \in \{C, N\}$ and $j \in \{A, B\}$. These probabilities are given by

$$\alpha_{CA} = \frac{f\big(e_C\ell,\, e_N(1-\ell)\big)}{e_C\ell}, \qquad \alpha_{CB} = \frac{f\big((1-e_C)\ell,\, (1-e_N)(1-\ell)\big)}{(1-e_C)\ell}, \tag{2}$$

$$\alpha_{NA} = \frac{f\big(e_C\ell,\, e_N(1-\ell)\big)}{e_N(1-\ell)}, \qquad \alpha_{NB} = \frac{f\big((1-e_C)\ell,\, (1-e_N)(1-\ell)\big)}{(1-e_N)(1-\ell)}. \tag{3}$$

3.2 Value functions

We begin with the description of the value functions in the CM. Consider first an agent who enters this market with m units of fiat money and d_j units of asset $j = \{A, B\}$. The Bellman equation of the agent is given by:

$$W(m, d_A, d_B) = \max_{X,H,m',d'_A,d'_B} \left\{ X - H + \beta \mathbb{E}_i \Big[\max \Big\{ \Omega_{iA}(m', d'_A, d'_B), \Omega_{iB}(m', d'_A, d'_B) \Big\} \Big] \right\},$$
$$\text{s.t. } X + \varphi(m' + p_A d'_A + p_B d'_B) = H + \varphi(m + T + d_A + d_B),$$

where variables with primes denote portfolio choices for the next period, and $\mathbb{E}_i$ is the expectations operator over the realization of the various shocks (the idiosyncratic con-

[9] For simplicity we assume that N-types decide which OTC market to visit before the uncertainty about the central bank's participation in OTC$_A$ is realized.

sumption shock and the uncertainty regarding the central bank's involvement in OTC$_A$). The function Ω_{ij} represents the value function in OTC$_j$, $j \in \{A, B\}$, for an agent of type $i \in \{C, N\}$. Next, we substitute $X - H$ from the budget constraint into W, and we decomposed Ω_{ij} into its various components to re-write the value function as

$$
\begin{aligned}
W\left(m,\ d_A, d_B\right) = \varphi(m + T + d_A + d_B) + \max_{m', d'_A, d'_B} \Bigg\{ & -\varphi\left(m' + p_A d'_A + p_B d'_B\right) \\
& + \beta\ell \max\left\{\pi\Omega^{\mathcal{A}}_{CA}\left(m', d'_A, d'_B\right) + (1-\pi)\Omega_{CA}\left(m', d'_A, d'_B\right), \Omega_{CB}\left(m', d'_A, d'_B\right)\right\} \\
& + \beta(1-\ell)\max\left\{\pi\Omega^{\mathcal{A}}_{NA}\left(m', d'_A, d'_B\right) + (1-\pi)\Omega_{NA}\left(m', d'_A, d'_B\right), \Omega_{NB}\left(m', d'_A, d'_B\right)\right\} \Bigg\}.
\end{aligned}
$$

In the last expression, we have used the fact that the representative agent becomes a C-type with probability ℓ, and that the central bank participates in OTC$_A$ with probability π. Note that the Ω functions that are multiplied by π inside the maximum operator feature the superscript $\mathcal{A}$, e.g., $\Omega^{\mathcal{A}}_{iA}$. This notation indicates the agent's value function when the central bank is "Active" in OTC$_A$.

As is standard in models that build on LW, the agent's optimal choice does not depend on the current state (due to the quasi-linearity of $\mathcal{U}$), and the CM value function is linear. We write:

$$W(m, d_A, d_B) = \varphi(m + d_A + d_B) + \Upsilon. \tag{4}$$

where Υ collects the remaining terms that do not depend on the state variables.

As is well-known, a producer will not wish to leave the CM with positive amounts of money and bond holdings. Therefore, when entering the CM a producer will only hold money that she received as payment in the preceding DM, and her CM value function is given by:

$$
\begin{aligned}
W^P(m) = \max_{X,H} \left\{X - H + V^P\right\} \\
\text{s.t.} \quad X = H + \phi m,
\end{aligned}
$$

where V^P denotes the producer's value function in the forthcoming decentralized market (DM). We can again use the budget constraint to substitute $X - H$ and show that W^P is linear:

$$W^P(m) = \phi m + V^P \equiv \Upsilon^P + \phi m. \tag{5}$$

We now turn to the description of the OTC value functions in the various states. Before we go to details, we offer a mnemonic rule that will help the reader comprehend the notation that follows. As may be expected, the various terms of trade in OTC$_A$ depend crucially on whether the central bank is actively purchasing bonds in the current period. Generally, variables that involve the "tilde" symbol (e.g., $\widetilde{x}$) will denote terms of trade that are negotiated *between individual agents in the presence* of a central bank intervention. (Recall that the terms of trade between individual investors may be affected by the presence of the central bank through the outside option channel.) In addition, variables that involve a "bar" symbol (e.g., $\overline{x}$) will denote the terms of trade that agents receive when they are *directly trading with the central bank*.

Given this discussion, let $\widetilde{\xi}_A$ and $\widetilde{x}_A$ denote, respectively, the amount of money transferred to the C-type and the amount of asset A sold by the C-type (and transferred to the N-type) in a typical match in OTC$_A$ when the central bank is active. Also, in accordance with the notation remark made above, let $\overline{\xi}_A$ and $\overline{x}_A$ denote the amount of money transferred to the C-type and the amount of asset A sold by the C-type when that agent trades directly with the central bank. The terms ξ_A and x_A will denote the corresponding money and asset transfers in OTC$_A$ when the central bank is not active.[10] The determination of these terms is described in Lemmas 2, 3, 4, and 5. Using the matching probabilities defined in equations (2)-(3) and the CM value functions defined above, we can now describe the OTC value functions $\Omega_{iA}^{\mathcal{A}}$ and Ω_{ij}, which we introduced earlier. We have:

$$\begin{aligned}
\Omega_{CA}^{\mathcal{A}}(m, d_A, d_B) =& \alpha_{CA} V\left(m + \widetilde{\xi}_A, d_A - \widetilde{x}_A, d_B\right) + (1 - \alpha_{CA}) V\left(m + \overline{\xi}_A, d_A - \overline{x}_A, d_B\right) \\
=& V\left(m + \overline{\xi}_A, d_A - \overline{x}_A, d_B\right) + \alpha_{CA}\widetilde{S}_{CA}, \qquad (6) \\
\Omega_{NA}^{\mathcal{A}}(m, d_A, d_B) =& \alpha_{NA} W\left(m - \widetilde{\xi}_A, d_A + \widetilde{x}_A, d_B\right) + (1 - \alpha_{NA}) W(m, d_A, d_B) \\
=& W(m, d_A, d_B) + \alpha_{NA}\widetilde{S}_{NA}, \qquad (7) \\
\Omega_{CA}(m, d_A, d_B) =& \alpha_{CA} V(m + \xi_A, d_A - x_A, d_B) + (1 - \alpha_{CA}) V(m, d_A, d_B) \\
=& V(m, d_A, d_B) + \alpha_{CA} S_{CA}, \qquad (8) \\
\Omega_{NA}(m, d_A, d_B) =& \alpha_{NA} W(m - \xi_A, d_A + x_A, d_B) + (1 - \alpha_{NA}) W(m, d_A, d_B) \\
=& W(m, d_A, d_B) + \alpha_{NA} S_{NA}, \qquad (9) \\
\Omega_{CB}(m, d_A, d_B) =& \alpha_{CB} V(m + \xi_B, d_A, d_B - x_B) + (1 - \alpha_{CB}) V(m, d_A, d_B) \\
=& V(m, d_A, d_B) + \alpha_{CB} S_{CB}, \qquad (10) \\
\Omega_{NB}(m, d_A, d_B) =& \alpha_{NB} W(m - \xi_B, d_A, d_B + x_B) + (1 - \alpha_{NB}) W(m, d_A, d_B) \\
=& W(m, d_A, d_B) + \alpha_{NB} S_{NB}. \qquad (11)
\end{aligned}$$

[10] The terms ξ_B and x_B will never feature a "tilde" or a "bar" since the central bank does not participate in OTC$_B$ in the baseline model.

Consistent with the mnemonic rule described earlier, $\widetilde{S}_{iA}$ (S_{iA}) denotes the trade surplus of type i in a bilateral investor meeting in OTC$_A$ with (without) central bank intervention. These terms will be described in detail in the subsequent sections. The term V denotes an agent's value function in the DM. Notice that N-type agents proceed directly to the next period's CM. Finally, $V\left(m+\overline{\xi}_A, d_A-\overline{x}_A, d_B\right)$ in equation (6) is the value function of an agent who is about to walk into the DM and has traded in OTC$_A$ with the central bank. For future reference, we can re-write it as

$$\begin{aligned} V\left(m+\overline{\xi}_A, d_A-\overline{x}_A, d_B\right) =& V\left(m, d_A, d_B\right)+\overline{S}_{CA}, \\ =& W\left(m, d_A, d_B\right)+S_D+\overline{S}_{CA}, \end{aligned} \tag{12}$$

where S_D and $\overline{S}_{CA}$ denote the seller's trading surplus in the DM and in a pairwise meeting with the central bank in OTC$_A$, respectively, and they are described in what follows.

To finish this subsection, consider the value functions in the DM. Let q denote the quantity of goods traded, and τ the total payment in units of fiat money. These terms are described in detail in the subsequent section. The DM value function for a buyer who enters that market with portfolio (m, d_A, d_B) is given by:

$$V(m, d_A, d_B) = u(q) + W(m-\tau, d_A, d_B) = W\left(m, d_A, d_B\right) + S_D,$$

and the DM value function for a producer (who enters this market with no money or assets) is given by:

$$V^P = -q + \beta W^P(\tau).$$

3.3 Terms of trade in the DM

Consider a meeting between a C–type agent with portfolio (m, d_A, d_B) and a producer who, at the start of the DM sub-period, has no money and no assets. The parties bargain over a quantity q to be produced by the producer and a cash payment τ to be made by the consumer. The consumer makes a take-it-or-leave-it offer that maximizes her surplus, subject to the producer's participation constraint and the cash constraint.

$$\max_{\tau, q} S_D$$

$$\text{s.t. } -q + W^P(\tau) - W^S(0) = 0, \quad 0 \leq \tau \leq m,$$

where a C-type agent's surplus S_D equals $u(q) + W\left(m-\tau, d_A, d_B\right) - W\left(m, d_A, d_B\right)$.

Substituting the value functions W and W^P from equations (4) and (5) reduces the problem to

$$\max_{\tau,q} u(q) - \varphi\,\tau$$

$$\text{s.t. } q = \varphi\,\tau, \quad 0 \leq \tau \leq m.$$

Lemma 1. *Let m^* be the amount of cash required to purchase the first-best quantity q^* at the centralized-market price of money φ, i.e. $m^* = q^*/\varphi$. Then the solution is*

$$\tau(m) = \min\{m,\, m^*\}, \qquad q(m) = \varphi\, \min\{m,\, m^*\}.$$

Proof. The proof is standard and it is, therefore, omitted. □

As is standard in models that build on LW, the terms of trade in the DM are fully driven by whether the agent (here, the C-type agent) carries enough money to purchase the first-best quantity q^*. Of course, whether she carries that critical amount of money m^* will depend on her trading history in the OTC round of trade. We now move to the description of the terms of trade in that round.

3.4 Terms of trade in OTC markets

We begin by considering a meeting between a seller and the central bank. Recall that the central bank commits to purchasing any quantity of asset A at the predetermined price $\overline{p} \leq 1$ (see Section 2 for more details). The surplus of a C-type who enters the OTC round of trade with portfolio (m, d_A, d_B) and trades with the central bank is given by:

$$\begin{aligned}\overline{S}_{CA} &= V\left(m + \overline{\xi}_A, d_A - \overline{x}_A, d_B\right) - V\left(m, d_A, d_B\right), \\ &= V\left(m + \overline{p}\,\overline{x}_A, d_A - \overline{x}_A, d_B\right) - V\left(m, d_A, d_B\right) = u\left(q\left(m + \overline{p}\,\overline{x}_A\right)\right) - u(q(m)) - \varphi\overline{x}_A,\end{aligned}$$

where $\overline{\xi}_A, \overline{x}_A$ and the value functions V were defined in Section 3.2. Therefore, if the C-type/asset seller finds herself in a transaction with the central bank, she solves the following problem:

$$\max_{\{\overline{x}_A, \overline{\xi}_A\}} \ \overline{S}_{CA},$$
$$\text{s.t. } 0 \leq \overline{x}_A \leq d_A \text{ and } \overline{\xi}_A = \overline{p}\,\overline{x}_A.$$

The solution to this maximization problem is described in the following lemma.

Lemma 2. *Define $\overline{q}$ and $\overline{m}$ such that $u'(\overline{q}) = 1/\overline{p}$ and $\overline{m} = \overline{q}/\varphi$, respectively. The terms of trade between the seller and the central bank are characterized as follows.*

If $m < \overline{m}, then$
$\overline{x}_A = \min\{d_A, (\overline{m} - m)/\overline{p}\}, \overline{\xi}_A = \min\{\overline{p}d_A, \overline{m} - m\}, m + \overline{p}\,\overline{x}_A = m + \overline{\xi}_A = \min\{m + \overline{p}d_A, \overline{m}\}.$

If $m \geq \overline{m}, then$
$\overline{x}_A = 0, \overline{\xi}_A = 0, m + \overline{p}\,\overline{x}_A = m + \overline{\xi}_A = m.$

Proof. See appendix. □

Lemma 2 is intuitive. Every unit of asset A that the C-type sells to the central bank allows her to boost her money holdings and her DM consumption. However, since the C-type agent takes $\overline{p}$ as given, she has to balance this liquidity boosting benefit against the discount/haircut that she receives on every unit of asset sold. (Recall that $\overline{p} \leq 1$, and the agent can receive 1 dollar per unit of asset if she holds on to them until the forthcoming CM.) The term $\overline{q} \leq q^*$ is the amount of DM good that maximizes the C-type's overall OTC surplus, and $\overline{m} \leq m^*$ is the associated amount of money the C-type would hold as she leaves the OTC. The lemma states that the terms of trade in the scenario under consideration are driven by whether the C-type entered the OTC round with money holdings that exceed $\overline{m}$. If this is the case, the agent will choose to not trade at all with the central bank. But if $m < \overline{m}$, then the agent will sell just enough assets (at price $\overline{p}$) so that her money holdings are equal to $\overline{m}$ when OTC trade has concluded.

Next, we consider inter-investor meetings. Let (m, d_A, d_B) denote the portfolio of the typical asset seller (C-type) and $(\hat{m}, \hat{d}_A, \hat{d}_B)$ the portfolio of the typical asset buyer (N-type). We distinguish two cases: Case 1, with central bank intervention, and Case 2, without central bank intervention. In Case 1, the seller's outside option turns out to depend critically on whether her money holdings exceed the critical amount $\overline{m}$ when she enters OTC$_A$. Accordingly, we divide Case 1 into two sub-cases: Case 1.1, where $m < \overline{m}$, and Case 1.2, where $m \geq \overline{m}$. As before, the seller and the buyer split the available surplus through proportional bargaining, with $\theta \in (0, 1)$ denoting the seller's bargaining power.

Case 1.1: $m < \overline{m}$. The surplus terms for the seller and the buyer are given by:

$$\begin{aligned}
\widetilde{S}_{CA} &= V\left(m + \widetilde{\xi}_A, d_A - \widetilde{x}_A, d_B\right) - V\left(m + \overline{\xi}_A, d_A - \overline{x}_A, d_B\right) \\
&= u\left(q\left(m + \widetilde{\xi}_A\right)\right) - u\left(q\left(m + \overline{\xi}_A\right)\right) - \varphi\widetilde{x}_A + \varphi\overline{x}_A. \qquad (13) \\
\widetilde{S}_{NA} &= W\left(\hat{m} - \widetilde{\xi}_A, \hat{d}_A + \widetilde{x}_A, \hat{d}_B\right) - W\left(\hat{m}, \hat{d}_A, \hat{d}_B\right) \\
&= -\varphi\widetilde{\xi}_A + \varphi\widetilde{x}_A, \qquad (14)
\end{aligned}$$

where equations (13) and (14) exploit the definitions of the functions V and W. The bargaining problem is given by:

$$\max_{\widetilde{\xi}_A, \widetilde{x}_A} \widetilde{S}_{CA} \quad \text{s.t. } \widetilde{S}_{CA} = \frac{\theta}{1-\theta}\widetilde{S}_{NA}, \quad \widetilde{\xi}_A \le \hat{m}, \quad \widetilde{x}_A \le d_A.$$

and its solution is described in the following lemma.[11]

Lemma 3. *The bargaining solution in a match between a C- and an N-type in Case 1.1 is given by:* $\widetilde{x}_A(m, d_A) = \min\{\widetilde{\sigma}(m^* - m)/\varphi, d_A\}$, $\widetilde{\xi}_A(m, d_A) = \min\{m^* - m, \widetilde{\sigma}^{-1}(\varphi d_A)\}$, *where*

$$\widetilde{\sigma}\left(\widetilde{\xi}_A\right) = \varphi\widetilde{x}_A = (1-\theta)\left[u\left(q\left(m + \widetilde{\xi}_A\right)\right) - u\left(q\left(m + \overline{\xi}_A\right)\right) + \varphi\overline{x}_A\right] + \theta\varphi\widetilde{\xi}_A.$$

Proof. It is straightforward to check that the suggested answer satisfies the necessary and sufficient conditions for maximization in each case. □

The OTC bargaining solution is straightforward. Agents maximize the total surplus generated in the match, which rises with the cash transferred to the seller and attains its peak when the seller's post-trade balance satisfies $m + \widetilde{\xi}_A = m^*$ (i.e., when OTC trade allows the C-type to afford the first-best quantity in the DM). Financing this transfer requires the seller to hold enough assets; the critical asset level that supports $\widetilde{\xi}_A = m^* - m$ equals $\sigma_{\mathcal{I}}(m^* - m)/\varphi$. If the seller holds at least this amount, the first-best allocation is feasible: $\widetilde{\xi}_A = m^* - m$ and $\widetilde{x}_A = \sigma_{\mathcal{I}}(m^* - m)/\varphi$. Otherwise, she pledges all her assets, $\widetilde{x}_A = d_A$, and receives a smaller cash transfer, $\widetilde{\xi}_A = \sigma_{\mathcal{I}}^{-1}(\varphi d_A) < m^* - m$, which satisfies the Kalai constraint.

[11] In what follows we restrict attention to cases where the buyer's money holdings never limit the trade, i.e., the constraint $\widetilde{\xi}_A \le \hat{m}$ is slack. This condition will hold in equilibrium as long as inflation is not extremely high, and it significantly simplifies the analysis as it eliminates a large number of subcases that one would have to keep track of. For more details, see Geromichalos and Herrenbrueck (2016).

Case 1.2: $m \geq \overline{m}$. The surplus terms for the seller and the buyer are given by:

$$\begin{aligned} S_{CA} &= V(m+\xi_A,\, d_A - x_A,\, d_B) - V(m,\, d_A,\, d_B) \\ &= u\big(q(m+\xi_A)\big) - u\big(q(m)\big) - \varphi x_A, \end{aligned} \tag{15}$$

$$S_{NA} = W\Big(\hat{m} - \xi_A,\, \hat{d}_A + x_A,\, \hat{d}_B\Big) - W\Big(\hat{m},\, \hat{d}_A,\, \hat{d}_B\Big) = -\varphi\xi_A + \varphi x_A. \tag{16}$$

First, an important comment on notation is in order. Note that the surplus terms, and the terms that denote assets (x_A) and money (ξ_A) exchanged, do not feature the "tilde" symbol. Strictly speaking this violates the mnemonic rule we introduced in Section 3.2, since the central bank is active in this case. However, Lemma 2 established that if the C-type's money holdings exceed the critical level $\overline{m}$, she will choose to not sell any assets to the central bank. Since Case 1.2 considers the scenario in which $m \geq \overline{m}$, effectively the presence of the central bank in OTC$_A$ is irrelevant, and we choose to slightly abuse the notation rule we set by dropping the "tilde" symbols in this case.

Moving on to the bargaining problem for Case 1.2, we have

$$\max_{\xi_A, x_A} S_{CA} \quad \text{s.t.} \quad S_{CA} = \frac{\theta}{1-\theta} S_{NA},\ \xi_A \leq \hat{m},\ x_A \leq d_A,$$

The solution to this bargaining problem is described in the following lemma.

Lemma 4. *The bargaining solution is* $x_A(m, d_A) = \min\big\{\sigma\big(m^* - m\big)/\varphi,\, d_A\big\}$, $\xi_A(m, d_A) = \min\big\{m^* - m,\, \sigma^{-1}\big(\varphi d_A\big)\big\}$, *where* $\sigma(\xi_A) = \varphi x_A = (1-\theta)\Big[u\big(q(m+\xi_A)\big) - u\big(q(m)\big)\Big] + \theta\varphi\xi_A$.

Proof. It is straightforward to check that the suggested answer satisfies the necessary and sufficient conditions for maximization in each case. □

The intuition for Lemma 4 is the same as in Lemma 3. However, an important underlying difference is that in Case 1.2 the C-type's money holdings are plentiful enough ($m \geq \overline{m}$) so that the presence of the central bank is immaterial, as discussed earlier. This also implies that in this case the C-type cannot improve her outside option in her negotiations with the N-type.

We still need to describe the bargaining protocols in OTC$_A$ under Case 2 (no central bank intervention) and in OTC$_B$. However, it now becomes obvious that these bargaining protocols coincide with the one described under Case 1.2. The intuition is straightforward: in all these cases, trade with the central bank is either not a credible outside option or not feasible. Formally, define the seller and buyer surplus within a match in OTC$_j$,

$j \in \{A, B\}$, as

$$
\begin{aligned}
S_{Cj} &= V(m + \xi_j,\, d_A - \mathbb{1}\{j = A\}x_A,\, d_B - \mathbb{1}\{j = B\}x_B) - V(m,\, d_A,\, d_B) \\
&= u\big(q(m + \xi_j)\big) - u\big(q(m)\big) - \varphi x_j, \qquad (17) \\
S_{Nj} &= W\Big(\hat{m} - \xi_j,\, \hat{d}_A + \mathbb{1}\{j = A\}x_A,\, \hat{d}_B + \mathbb{1}\{j = B\}x_B\Big) - W\Big(\hat{m},\, \hat{d}_A,\, \hat{d}_B\Big) \\
&= -\varphi\xi_j + \varphi x_j. \qquad (18)
\end{aligned}
$$

The bargaining problem in these cases is given by

$$\max_{\xi_j, x_j} S_{Cj} \quad \text{s.t.} \quad S_{Cj} = \frac{\theta}{1-\theta} S_{Nj},\ \xi_j \le \hat{m},\ x_j \le d_j,$$

and its solution is described in the following lemma.

Lemma 5. *The bargaining solution is* $x_j(m, d_j) = \min\big\{\sigma\big(m^* - m\big)/\varphi,\, d_j\big\}$, $x_j(m, d_j) = \min\big\{m^* - m,\, \sigma^{-1}\big(\varphi d_j\big)\big\}$, *where* $\sigma(\xi_j) = \varphi x_j = (1-\theta)\Big[u\big(q(m + \xi_j)\big) - u\big(q(m)\big)\Big] + \theta\varphi\xi_j$.

Proof. Lemma 5 is essentially a repetition of Lemma 4, adjusting for the fact that it could hold for both OTC_B and OTC_A without central bank intervention. □

3.5 Objective functions

To obtain the objective function J, substitute the trading payoffs in the OTC markets and in the DM into the maximum operator of the CM value function W. Exploiting the linearity of the value function itself, we drop all terms that do not depend on the choice variables (m', d'_A, d'_B) and obtain the following objective function.

$$
\begin{aligned}
J(m', d'_A, d'_B) \equiv &-\varphi\left(m' + p_A d'_A + p_B d'_B\right) \\
&+ \beta\ell \max\left\{\pi\Omega^{\mathcal{A}}_{CA}\left(m', d'_A, d'_B\right) + (1-\pi)\Omega_{CA}\left(m', d'_A, d'_B\right), \Omega_{CB}\left(m', d'_A, d'_B\right)\right\} \\
&+ \beta(1-\ell) \max\left\{\pi\Omega^{\mathcal{A}}_{NA}\left(m', d'_A, d'_B\right) + (1-\pi)\Omega_{NA}\left(m', d'_A, d'_B\right), \Omega_{NB}\left(m', d'_A, d'_B\right)\right\},
\end{aligned}
$$

where the various Ω functions are described in equations (6)-(11). As expected, this expression will also differ depending on whether the representative agent chooses to carry money holdings that exceed the critical value $\overline{m}$. We distinguish between two cases:

Case 1: If $m' < \overline{m}$, the objective function is given by

$$\begin{aligned} J(m', d'_A, d'_B) = & - \beta i \varphi' m' - \beta \varphi' \left((1+i) p_A - 1 \right) d'_A - \beta \varphi' \left((1+i) p_B - 1 \right) d'_B \\ & + \beta \ell S_D \\ & + \beta \ell \max \left\{ \pi \left(\overline{S}_{CA} + \alpha_{CA} \widetilde{S}_{CA} \right) + (1-\pi) \alpha_{CA} S_{CA}, \alpha_{CB} S_{CB} \right\}. \end{aligned}$$

Case 2: If $m' \geq \overline{m}$, the objective function is given by

$$\begin{aligned} J(m', d'_A, d'_B) = & - \beta i \varphi' m' - \beta \varphi' \left((1+i) p_A - 1 \right) d'_A - \beta \varphi' \left((1+i) p_B - 1 \right) d'_B \\ & + \beta \ell S_D \\ & + \beta \ell \max \left\{ \alpha_{CA} S_{CA}, \alpha_{CB} S_{CB} \right\}. \end{aligned}$$

The objective function in both scenarios has a straightforward interpretation. The first line in each case represents the net cost an agent incurs to acquire the portfolio (m', d'_A, d'_B) in the CM. The second line captures the net consumption utility in the DM, contingent on the agent being a C-type, an event that occurs with probability ℓ. Up to this point all terms are identical between the two cases. However, the third line accounts for the expected benefit from participating in the OTC market, and this is where the two cases diverge. If the agent's money holdings are sufficiently scarce such that they would seek to acquire additional funds from the central bank, their expected benefit from trading in OTC$_A$ is influenced by the probability (π) of central bank participation, as shown in the third line under Case 1. On the other hand, if money holdings are plentiful, in the precise sense that $m' \geq \overline{m}$, the agent's expected benefit from OTC$_A$ depends only on the surplus she can derive from inter-investor trades.[12] This distinction is reflected in the third line of the objective function for Case 2.

4 Equilibrium

In the steady-state equilibrium, we summarize the cost of holding money via $i \equiv (1+\mu)/\beta - 1$, which represents the nominal yield on an illiquid asset.[13] (Thus, i should not be interpreted as, say, the yield on T-bills; see Geromichalos and Herrenbrueck, 2022 and Herrenbrueck and Wang, 2023.) In any equilibrium, it must be true that $p_j \geq 1/(1+$

[12] In this case, whether the central bank is active in OTC$_A$ is immaterial, and this could be either because the agent meets an N-type but she cannot take advantage of the outside option channel or because she "meets" with directly with the central bank, but she does not wish to perform any trades.

[13] In the background, we have assumed that the central bank rolls back the money supplied in OTC$_A$ in the following CM, so that the rule $M_{t+1} = (1+\mu)M_t$ holds in every period.

$i), j = \{A, B\}$, since otherwise there would be an infinite demand for the assets. A strict inequality implies that the assets carry a positive liquidity premium.

We have 13 endogenous variables. First, we have the equilibrium real balances $\{z_A, z_B\}$ held by the agent who chooses to specialize in asset A or B. Next, we have the equilibrium quantities $\{q_{0A}, q_{1A}, q_{0B}, q_{1B}, \overline{q}_{1A}, \widetilde{q}_{1A}\}$. The variables q_{0j} and q_{1j}, respectively, represent the quantity of DM goods purchased by a C-type agent who either does not trade in the OTC market (index 0) or does trade in the OTC (index 1), conditional on the agent's specialization in asset j, and in the absence of central bank intervention. Applying once again the notational convention described in Section 3.2, we let $\overline{q}_{1A}$ denote the quantity of DM goods purchased by a C-type who traded directly with the central bank in OTC$_A$. In the same spirit, $\widetilde{q}_{1A}$ will stand for the quantity of DM goods purchased by a C-type who traded with an N-type agent in OTC$_A$ while retaining the outside option of trading with the central bank. In addition, we have the prices of the three assets $\{\varphi, p_A, p_B\}$. Finally, we have the entry choices $\{e_C, e_N\}$, i.e., the fractions of C-types and N-types, respectively, who choose to enter OTC$_A$.

We now show that the variables $\{z_A, z_B, p_A, p_B, \varphi\}$ can be derived from the remaining eight variables, $\{q_{0A}, q_{1A}, q_{0B}, q_{1B}, \overline{q}_{1A}, \widetilde{q}_{1A}, e_C, e_N\}$, and we therefore refer to the latter as the *core variables* of the model. First, because a C-type who does not trade in the OTC round can purchase only what her own cash permits, we have $z_j = q_{0j}$, $j \in \{A, B\}$. Second, market clearing in the money market requires

$$\varphi M = e_C q_{0A} + \big(1 - e_C\big) q_{0B}. \tag{7}$$

Next, equilibrium prices satisfy

Case 1: $q_{0A} < \overline{q}$

$$\begin{aligned}(1+i)p_A - 1 = {} & \underbrace{\pi\ell(1-\alpha_{CA})\left(u'\left(\overline{q}_{1A}\right)\overline{p} - 1\right)}_{\text{marginal benefit from actual trade with the central bank}} \\ & + \underbrace{\pi\ell\alpha_{CA}\left(\left(1 - \frac{\theta}{w(\widetilde{q}_{1A})}\right)(u'(\overline{q}_{1A})\overline{p} - 1) + \frac{\theta}{w(\widetilde{q}_{1A})}(u'(\widetilde{q}_{1A}) - 1) - \frac{\theta}{w(q_{1A})}(u'(q_{1A}) - 1)\right)}_{\text{marginal benefit from central bank outside option}} \\ & + \underbrace{\ell\alpha_{CA}\frac{\theta}{w\left(q_{1A}\right)}\left(u'\left(q_{1A}\right) - 1\right)}_{\text{marginal benefit from bilateral trade with private buyers}}.\end{aligned} \tag{19}$$

$$(1+i)p_B - 1 = \ell\alpha_{CB}\frac{\theta}{w\left(q_{1B}\right)}\left(u'\left(q_{1B}\right) - 1\right),$$

where $w(q) \equiv 1 + (1-\theta)\left(u'(q) - 1\right)$.

Case 2: $q_{0A} \geq \overline{q}$

$$\begin{aligned}
(1+i)p_A - 1 =& \ell\alpha_{CA}\frac{\theta}{w\left(q_{1A}\right)}\left(u'\left(q_{1A}\right) - 1\right). \\
(1+i)p_B - 1 =& \ell\alpha_{CB}\frac{\theta}{w\left(q_{1B}\right)}\left(u'\left(q_{1B}\right) - 1\right).
\end{aligned}$$

As long as $q_{1j} < q^*$, an additional unit of the asset raises the agent's money holdings, and her DM consumption, so she is willing to pay a liquidity premium. When $q_{1j} = q^*$, the right-hand side of the steady-state asset-pricing condition equals zero, and we obtain $p_j = 1/(1+i)$, which is the fundamental value of a one-period nominal bond.

The liquidity premium on asset A depends on whether agents can bring real balances to OTC$_A$ that exceed the amount needed to purchase $\overline{q}$ in the forthcoming DM. When they cannot—Case 1—the premium comprises three components, as shown in equation (19). The first term captures the marginal benefit of actual OTC trade with the central bank. The second, novel to our setting, reflects the marginal benefit of retaining the outside option to trade with the central bank while in fact transacting with private asset buyers. The third term is the standard marginal benefit from bilateral trade with private asset buyers without the option to perform a meaningful (surplus generating) trade with the central bank.

The analysis so far shows that once the variables $\{q_{0A}, q_{1A}, q_{0B}, q_{1B}, \overline{q}_{1A}, \widetilde{q}_{1A}, e_C, e_N\}$ have been pinned down, the remaining five endogenous variables follow mechanically. We now turn to the equilibrium conditions that determine these core variables. Throughout this analysis, recall that the entry shares e_C and e_N (which we describe in Section 4.1 below) also influence the arrival rates α_{Cj} implicitly.

First, the money demand equations for agents specializing in asset j are given by

Case 1: $q_{0A} < \overline{q}$

$$\begin{aligned}
i =& \pi\ell\left(1 - \alpha_{CA}\frac{\theta}{\omega\left(\widetilde{q}_{1A}\right)}\right)\left(u'\left(\overline{q}_{1A}\right) - 1\right) + \pi\ell\alpha_{CA}\frac{\theta}{w\left(\widetilde{q}_{1A}\right)}\left(u'\left(\widetilde{q}_{1A}\right) - 1\right) \\
&+ (1-\pi)\ell\left(1 - \alpha_{CA}\frac{\theta}{w\left(q_{1A}\right)}\right)\left(u'\left(q_{0A}\right) - 1\right) + (1-\pi)\ell\alpha_{CA}\frac{\theta}{w\left(q_{1A}\right)}\left(u'\left(q_{1A}\right) - 1\right). \\
i =& \ell\left(1 - \alpha_{CB}\frac{\theta}{w\left(q_{1B}\right)}\right)\left(u'\left(q_{0B}\right) - 1\right) + \ell\alpha_{CB}\frac{\theta}{w\left(q_{1B}\right)}\left(u'\left(q_{1B}\right) - 1\right).
\end{aligned}$$

Case 2: $q_{0A} \geq \overline{q}$

$$i = \ell \left(1 - \alpha_{CA} \frac{\theta}{w\left(q_{1A}\right)}\right) \left(u'\left(q_{0A}\right) - 1\right) + \ell \alpha_{CA} \frac{\theta}{w\left(q_{1A}\right)} \left(u'\left(q_{1A}\right) - 1\right).$$
$$i = \ell \left(1 - \alpha_{CB} \frac{\theta}{\omega\left(q_{1B}\right)}\right) \left(u'\left(q_{0B}\right) - 1\right) + \ell \alpha_{CB} \frac{\theta}{\omega\left(q_{1B}\right)} \left(u'\left(q_{1B}\right) - 1\right).$$

Similar to the asset pricing conditions above, money demand equations also depend on whether agents can bring real balances to OTC$_A$ that exceed the amount needed to purchase $\overline{q}$ in the forthcoming DM.[14]

Next, the following four conditions describe the steady-state quantity variables.

$$\begin{aligned}
\overline{q}_{1A} &= q_{0A} + \varphi \overline{\xi}_A, \text{ where } \overline{\xi}_A = \min\left\{\overline{m} - m, \overline{p} d_A\right\} \\
&= \min\left\{\overline{q}, q_{0A} + \overline{p} \varphi d_A\right\}. \\
\widetilde{q}_{1A} &= q_{0A} + \varphi \widetilde{\xi}_A, \text{ where } \widetilde{\xi}_A = \min\left\{m^* - m, \widetilde{\sigma}^{-1}(\varphi d_A)\right\} \\
&= \min\left\{q^*, q_{0A} + \varphi \widetilde{\sigma}^{-1}\left(\varphi d_A\right)\right\}, \text{ where } \varphi d_A = (1-\theta)\left[u\left(q\left(m + \widetilde{\xi}_A\right)\right) - u\left(q\left(m + \overline{\xi}_A\right)\right) + \varphi \overline{x}_A\right] \\
&\quad + \theta \varphi \widetilde{\sigma}^{-1}\left(\varphi d_A\right) \\
&= \min\left\{q^*, q_{0A} + \frac{1}{\theta} \varphi d_A - \frac{1-\theta}{\theta}\left(u\left(\widetilde{q}_{1A}\right) - u\left(\overline{q}_{1A}\right) + \frac{\overline{q}_{1A} - q_{0A}}{\overline{p}}\right)\right\}. \\
q_{1A} &= q_{0A} + \varphi \xi_A, \text{ where } \xi_A = \min\left\{m^* - m, \sigma^{-1}\left(\varphi d_A\right)\right\} \\
&= \min\left\{q^*, q_{0A} + \varphi \sigma^{-1}\left(\varphi d_A\right)\right\}, \text{ where } \varphi d_A = (1-\theta)\left[u\left(q\left(m + \xi_A\right)\right) - u(q(m))\right] + \theta \varphi \sigma^{-1}(\varphi dA) \\
&= \min\left\{q^*, q_{0A} + \frac{1}{\theta} \varphi d_A - \frac{1-\theta}{\theta}\left(u\left(q_{1A}\right) - u\left(q_{0A}\right)\right)\right\}. \\
q_{1B} &= q_{0B} + \varphi \xi_B, \text{ where } \xi_B = \min\left\{m^* - m, \sigma^{-1}\left(\varphi d_B\right)\right\} \\
&= \min\left\{q^*, q_{0B} + \varphi \sigma^{-1}\left(\varphi d_B\right)\right\}, \text{ where } \varphi d_B = (1-\theta)\left[u\left(q\left(m + \xi_B\right)\right) - u(q(m))\right] + \theta \varphi \sigma^{-1}\left(\varphi d_B\right) \\
&= \min\left\{q^*, q_{0B} + \frac{1}{\theta} \varphi d_B - \frac{1-\theta}{\theta}\left(u\left(q_{1B}\right) - u\left(q_{0B}\right)\right)\right\}.
\end{aligned}$$

Note that in each of the four equations, the transition from the first to the second line applies the OTC bargaining solutions described in Lemmas 2, 3, 4, and 5. The transition from the second to the third line substitutes the money demand equations derived above into the second line.

[14] We set $\alpha_{ij} = 0$ whenever no agent enters market j. In that event, q_{0j} and q_{1j} remain well defined as limiting values, even though no trade actually occurs at those quantities.

4.1 Entry decisions

In the first sub-period of each period, all agents are divided into C-types and N-types and choose which OTC market they enter by comparing the expected surpluses. As discussed above, this decision is practically made in the previous CM for C-types because agents can enter only one OTC market per period, making it suboptimal to pay liquidity premia for both assets. Since an agent's optimal money holdings depend on what asset she specializes in, when agents compare the expected surplus from specializing in asset A or B (and visiting the designated OTC market if they turn out to be a C-type), these surplus terms must take into account the cost of holding both the asset and money. (This explains why the C-type's entry decision problem stated below is more involved than the N-type's problem that follows.) Letting $\mathbb{S}_{Cj}$ denote the net surplus of specializing in asset j in the CM, the equilibrium measure of C-types who choose asset A satisfies

$$e_C = \begin{cases} 1, & \mathbb{S}_{CA} > \mathbb{S}_{CB} \\ 0, & \mathbb{S}_{CA} < \mathbb{S}_{CB} \\ \in [0,1], & \mathbb{S}_{CA} = \mathbb{S}_{CB}\,, \end{cases}$$

where

$$\mathbb{S}_{CA} = \begin{cases} -iq_{0A} - ((1+i)p_A - 1)\,\frac{\varphi A}{e_C} + \ell\left(u(q_{0A}) - q_{0A} + \pi\left(\overline{S}_{CA} + \alpha_{CA}\widetilde{S}_{CA}\right) + (1-\pi)\alpha_{CA}S_{CA}\right), & q_{0A} < \overline{q} \\ -iq_{0A} - ((1+i)p_A - 1)\,\frac{\varphi A}{e_C} + \ell\left(u(q_{0A}) - q_{0A} + \alpha_{CA}S_{CA}\right), & q_{0A} \geq \overline{q} \end{cases},$$

$$\mathbb{S}_{CB} = -iq_{0B} - ((1+i)p_B - 1)\,\frac{\varphi B}{1-e_C} + \ell\left(u(q_{0B}) - q_{0B} + \alpha_{CB}S_{CB}\right),$$

$$\overline{S}_{CA} = u(\overline{q}_{1A}) - u(q_{0A}) - \frac{\overline{q}_{1A} - q_{0A}}{\overline{p}},$$

$$\widetilde{S}_{CA} = \theta\left[u(\widetilde{q}_{1A}) - u(\overline{q}_{1A}) - (\widetilde{q}_{1A} - q_{0A}) + \frac{\overline{q}_{1A} - q_{0A}}{\overline{p}}\right],$$

$$S_{CA} = \theta\left[u(q_{1A}) - u(q_{0A}) - (q_{1A} - q_{0A})\right],$$

$$S_{CB} = \theta\left[u(q_{1B}) - u(q_{0B}) - (q_{1B} - q_{0B})\right].$$

On the other hand, N-types can freely choose which market to go to regardless of the asset they chose to specialize in during last period's CM. (Their money is good in both OTC markets.) Therefore, N-types only care about the expected surplus in each OTC market. Accordingly, the measure of N-types entering OTC$_A$, e_N, is given by

$$e_N = \begin{cases} 1, & \alpha_{NA}S_{NA} > \alpha_{NB}S_{NB} \\ 0, & \alpha_{NA}S_{NA} < \alpha_{NB}S_{NB} \\ \in [0,1], & \alpha_{NA}S_{NA} = \alpha_{NB}S_{NB}\,, \end{cases}$$

where

$$S_{Nj} = (1-\theta)(u(q_{1j}) - u(q_{0j}) - q_{1j} + q_{0j}).$$

It should be noted that since the benefit of entering each OTC market depends on the entry decisions of other agents, there are always multiple equilibria including $(e_C, e_N) = (1,1)$ and $(e_C, e_N) = (0,0)$. Henceforth, the equilibrium that we pick out of the multiple equilibria is chosen by the following algorithm. First, we define the function $G : [0,1] \to \mathbb{R}$ by $G(e_N) = (\alpha_{NA}S_{NA} - \alpha_{NB}S_{NB})/(\alpha_{NA}S_{NA} + \alpha_{NB}S_{NB})$, where α_{ij} and S_{Nj} are evaluated in the partial equilibrium with e_N fixed. Note that G represents the relative surplus gains of entering OTC$_A$ over OTC$_B$ of any N-type taking other agents' choices as given. Second, we evaluate G at the initial value $e_N = A/(A+B)$ and adjust e_N according to the sign of G. That is, if $G(e_N) > 0\,(< 0)$, we slightly increase (decrease) e_N. We take $e_N = A/(A+B)$ as a natural starting point since it is consistent with N-types' entry decisions in the equilibrium where $e_C = e_N$, $q_{0A} = q_{0B}$, and $q_{1A} = q_{1B}$ under a CRS matching function and without the central bank intervention. Finally, we repeat the second step at the newly adjusted level of e_N until we reach an equilibrium robust to small trembles in e_N.

5 Quantitative Analysis

5.1 Calibration

We calibrate the model to U.S. data, focusing on the Federal Reserve's customary secondary market purchases of Treasuries. Our calibration period spans 2016 Q1 to 2019 Q2, a period of routine, non-crisis monetary operations. We exclude the immediate aftermath of the Great Recession, as asset purchases during that period still reflected extraordinary conditions that fall outside the scope of our model. Similarly, beginning in late 2019 and accelerating in 2020, Fed purchases again shifted in response to the emerging COVID-19 pandemic. By focusing on the 2016–2019 window, we isolate a period of steady and systematic asset purchases, consistent with our steady-state analysis.

In our quantitative analysis, we interpret the two assets in the model as Treasuries (asset A) and AAA/AA-rated corporate bonds (asset B). This pairing is chosen to ensure comparability across several dimensions aside from central bank participation. Treasuries are the primary asset class targeted by the Federal Reserve's secondary market operations, whereas AAA/AA-rated corporate bonds represent the highest-quality private assets, comparable to Treasuries in terms of credit risk, but not routinely purchased by the

	Description	Value
i	Nominal illiquid interest rate (annual)	7%
M	Money supply	1
A	Supply of Treasuries	0.1671
B	Supply of AAA/AA-rated corporate bonds	0.0308
γ	Elasticity of marginal utility	0.34
ℓ	Fraction of C-type agents	0.5
θ	Relative bargaining power of C-types	0.75
δ	Matching efficiency in the OTC markets	1.7961
π	Central bank intervention rate	0.5
$\overline{p}$	Central bank purchase price	0.9954

Table 1: Calibrated parameter values.

Fed. To further ensure comparability, we restrict attention to 10-year Treasuries, as the average maturity of AAA/AA-rated corporate bonds during our calibration period is also approximately 10 years. This maturity alignment allows us to isolate the effects of Fed intervention on liquidity and pricing, holding duration constant across the two markets.

We calibrate the model at a quarterly frequency, using the utility function $u(q) = q^{1-\gamma}/(1-\gamma)$. The values of ten parameters, listed in Table 1, are set based on a combination of external sources and internal calibration of the model to empirical moments. For the nominal illiquid interest rate i, no observed rate can be used directly, as no traded asset is perfectly illiquid. Instead, we adopt an estimate of 7%, based on time preference, expected real growth, and expected inflation, following Herrenbrueck and Wang (2023).[15] For the monetary aggregate, we use the MZM money stock from the Federal Reserve Economic Data (FRED), maintained by the Federal Reserve Bank of St. Louis. Since only the ratios of asset supplies to the money supply enter the equilibrium conditions, we normalize $M = 1$. Treasury supply data are drawn from the U.S. Treasury Monthly Statement of the Public Debt, and corporate bond supply data from the Mergent Fixed Income Securities Database (FISD). During the calibration period, the average outstanding amounts of 10-year Treasuries and AAA/AA-rated corporate bonds, relative to the monetary aggregate, are 0.1671 and 0.0308, respectively. We set $\ell = 0.5$ for symmetry (equal numbers of potential buyers and sellers in the OTC markets) and $\gamma = 0.34$ to match the slope of the empirical U.S. money demand, using the procedure of Rocheteau, Wright, and Zhang

[15] For comparison, Berentsen, Menzio, and Wright (2011) use an annual rate of 7.4%, while the average rate in the data from Lucas and Nicolini (2015) is 6.28%.

(2018). For the elasticity of the OTC matching function, we work with the constant returns to scale specification described in equation (1).[16] As for θ, in our model, the bargaining power of asset sellers in OTC trade symmetrically scales the liquidity premia of both assets, and a sufficiently large value of θ is needed to replicate the sizable liquidity premia observed in the data. Geromichalos et al. (2023a) identify a range of θ values that make this class of models work, which spans from $\theta = 0.6$ to $\theta = 0.99$. We set $\theta = 0.75$, which is close to the midpoint of this range but also avoids extreme bargaining asymmetries and preserves meaningful market entry decisions for asset buyers. Having said that, the main quantitative results are robust across all values of θ that generate the liquidity premia we see in the data.

The Federal Reserve Bank of New York provides detailed historical data on open market transactions, in compliance with the Dodd-Frank Wall Street Reform and Consumer Protection Act of 2010. During the calibration period, the Fed conducted asset purchases approximately once every six months. Since one period in the model corresponds to a quarter, we set $\pi = 0.5$, so that the central bank participates once every two periods on average. Regarding the purchase price, the assets in the model are one-period discount bonds that pay one dollar at maturity, and we set $\overline{p} = 0.9954$ to match the average yield at which the Fed purchased Treasuries during the calibration period.

The final parameter, δ, is calibrated to match the average quarterly yield spread between the two assets over the calibration window, which is 0.1285%. This spread captures the empirical liquidity differential that the model is designed to explain, and it is exactly matched by the model-implied spread. While the levels of the asset yields are not explicitly targeted, the model-implied values are close to their empirical counterparts. The empirical average quarterly yields are 0.5896% for Treasuries and 0.7181% for AAA/AA-rated corporate bonds, compared to model-implied yields of 0.8463% and 0.9748%, respectively.

5.2 The Effects of Central Bank Interventions

In this section, we present the implications of the model for the impact of central bank interventions. Specifically, we show how the steady state levels of several endogenous

[16] Geromichalos et al. (2023b) also examine the superior liquidity of Treasuries over high-quality corporate bonds. In that paper, however, Treasuries are assumed to trade in an OTC market with higher matching efficiency, and this assumption is required to match the data under constant returns; otherwise, increasing returns to scale are needed. In contrast, our model can match the observed liquidity differential even with constant returns and identical matching efficiencies, due to the presence of the central bank. Thus, central bank participation provides a novel alternative mechanism to explain the superior liquidity of Treasuries, without requiring increasing returns or exogenous differences in matching efficiency.

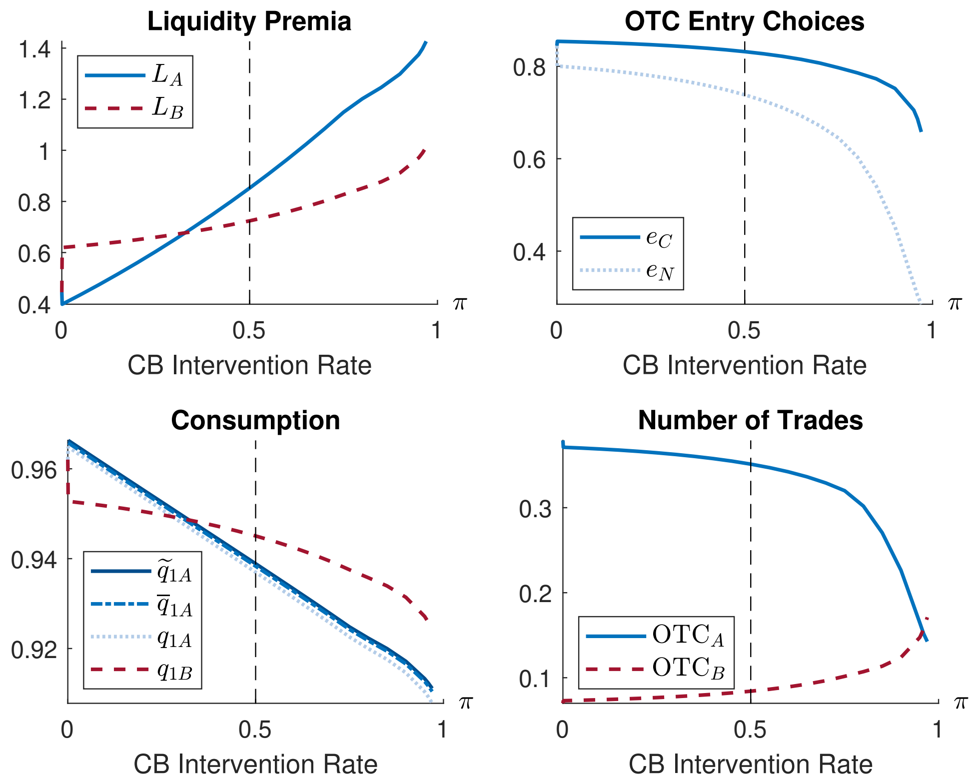

Figure 2: The impact of the central bank intervention rate on liquidity premia (in percentage terms), OTC entry choices, DM consumption, and the number of trades. The calibrated intervention rate is 0.5 and is marked with the vertical dashed lines.

variables respond to changes in the rate at which the central bank intervenes in OTC_A, π, and the price at which the central bank purchases asset A, $\overline{p}$.[17] This exercise helps us achieve two goals at once: lay out the model mechanisms as well as quantify the impact of central bank interventions on the workings of the secondary asset markets.

Figure 2 presents the impact of varying the central bank intervention rate from 0 to 1 (its calibrated value is $\pi = 0.5$). By raising the intervention rate in OTC_A, the central bank increases the liquidity premium of Treasuries (blue solid line in the top left panel). Intuitively, a larger π improves the seller's prospects in OTC_A either directly (by making it more likely to sell to the central bank if the seller does not match with a buyer) or indirectly (by raising the seller's outside option in case of a match). Both forces contribute to the rise in the liquidity premium of asset A which is also significant in quantitative terms (we present a detailed decomposition of the increase in liquidity premium among its different parts in Section 5.3). The bottom left panel of Figure 2 presents the implications

[17] Focusing on steady states is the approach followed by Berentsen et al. (2011) and is common practice in search theory (see, e.g., Hornstein, Krusell, and Violante (2005), Petrosky-Nadeau (2013), Ljungqvist and Sargent (2017), and Gabrovski, Geromichalos, Herrenbrueck, Kospentaris, and Lee (2025), among others).

of increases in π for the quantities purchased in the decentralized market (blue solid and dotted lines). Higher central bank intervention rates translate into lower quantities traded in the DM for reasons that are well-understood in models of indirect liquidity (Berentsen, Huber, and Marchesiani, 2014; Geromichalos and Herrenbrueck, 2016): as investors count more on the asset market to provide them with liquidity when they need it, they choose to hold less money in their portfolios. As a result, the total quantity of real balances available in the asset market decreases, which results in lower purchasing power of agents in the DM.

The most striking result in Figure 2 certainly lies in the behavior of the liquidity premium of the corporate bonds: it increases as π rises (red dashed line in the top left panel). In other words, increases in the central bank intervention rate in the Treasury market have a significant *spillover* effect on the price of corporate bonds. The mechanism behind this spillover effect is the entry choices of investors across asset markets. In particular, as can be seen in the top right panel of Figure 2, increases in the central bank intervention rate reduce the mass of investors who enter OTC$_A$ to trade. The drop in the mass of buyers (e_N) is faster but the mass of sellers (e_C) follows as π increases. Effectively, the central bank intervention crowds out asset buyers from the Treasury market into the market for corporate bonds and sellers soon follow because the probability to trade endogenously depends on the mass of investors in the other side of the market. The effects of the entry choices of investors are reflected in the total number of trades in each market (lower left panel of Figure 2) with the trades in OTC$_A$ decreasing and OTC$_B$ increasing as the central bank intervention rate rises.

It is important to highlight that the spillover effect of central bank actions significantly refines the behavior of liquidity premia and the resulting asset prices in the two markets. As can be seen in the top left panel of Figure 2, for values of π larger than 0.33 the liquidity premium of Treasuries is greater than the liquidity premium of corporate bonds. For smaller values of π, however, this pattern is reversed and the liquidity premium of corporate bonds is actually larger than that of Treasuries. Intuitively, the spillover effect of central bank interventions through investors' entry to OTC$_B$ trumps the direct effect on OTC$_A$ when the central bank intervention rate is modest. It is reassuring, however, that these rich asset pricing patterns do not lead to counterfactual trade patterns. The Treasury market remains more liquid than the corporate bond market in the sense that the total number of trades taking place in OTC$_A$ is larger than that in OTC$_B$ for almost all values of the central bank intervention rate (bottom right panel of Figure 2).

Figure 3 presents the results of varying the central bank purchase price from 0.96 to 1 (its calibrated value is $\overline{p} = 0.9954$). The lessons from these results reaffirm the insights

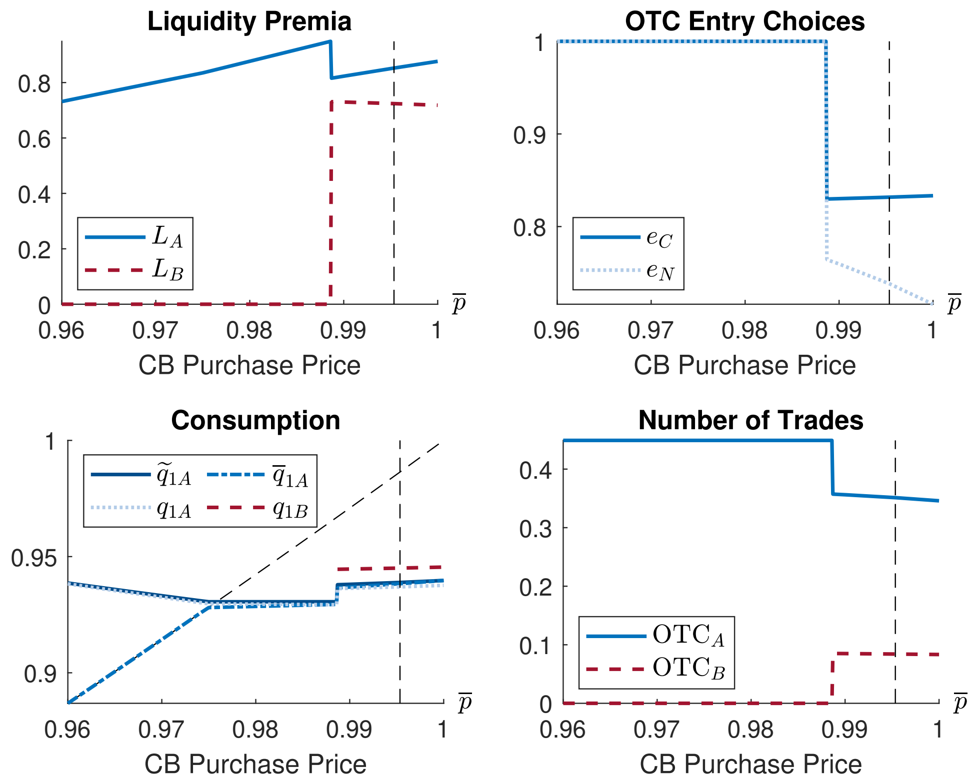

Figure 3: The impact of the central bank purchase price on liquidity premia (in percentage terms), OTC entry choices, DM consumption, and the number of trades. The calibrated purchase price is 0.9954 and is marked with the vertical dashed lines. In the bottom-left panel, the diagonal dashed line indicates $\overline{q}$, the optimal DM consumption level when selling assets to the central bank in OTC_A.

obtained thus far. First, there is a direct impact of the central bank intervention on the liquidity premium of Treasuries which, in turn, proliferates in the Treasury market. As the central bank buys Treasuries at lower prices, the liquidity premium of these assets declines (top left panel of Figure 3). Since Treasuries are cheaper, they provide lower purchasing power to C-type agents and the overall DM consumption decreases as $\overline{p}$ drops (bottom left panel of Figure 3).[18] Second, there is a spillover effect of the central bank intervention on the corporate bond market that works through investor entry choices. As the price of Treasuries declines, asset buyers (initially) and sellers (later) leave the corporate bond market and enter the Treasury market to benefit from lower prices and higher matching rates, respectively (top right panel of Figure 3). The magnitude of this

[18] This force is true both for C-types who trade with N-type investors and those who trade with the central bank. For low values of $\overline{p}$, however, the former group of agents substitute the lower liquidity from the OTC market with carrying more real balances and, as a result, their DM consumption increases (see the solid and dotted blue lines in the bottom left panel of Figure 3).

investor reallocation is so substantial that OTC_B shuts down when $\overline{p}$ is lower than 0.9886 and the Treasury market becomes the sole source of liquidity for agents.

5.3 Liquidity Premium Decomposition and the Central Bank Premium

In our model, assets carry an indirect liquidity premium, reflecting the benefit an agent receives from being able to sell the asset for money in a secondary market and subsequently use that money to fund expenses in the DM. This liquidity benefit is shaped by the OTC market microstructure, agents' market entry decisions, and central bank participation. To be more specific, the liquidity premium of asset A consists of three distinct components, each corresponding to a different source of liquidity value. First, the *baseline premium* captures the benefit from selling the asset to a buyer when a match occurs in the OTC market, regardless of central bank presence, and without leveraging the central bank as an outside option. Second, the *outside option premium* reflects the additional value an agent gains upon being matched, conditional on the central bank's presence, by threatening to sell to the central bank if the buyer offers unfavorable terms. Third, the *last resort premium* arises when the central bank is present and an agent fails to find a buyer but can still sell the asset directly to the central bank at the standing purchase price, effectively allowing the central bank to act as a buyer of last resort. Together, the outside option premium and the last resort premium comprise what we refer to as the *central bank premium*, which represents the portion of asset A's liquidity premium directly attributable to central bank participation.[19]

This decomposition is formalized in the following expression for the liquidity premium of asset A, which consists of three terms, each corresponding to one of the components described above: the baseline premium, the outside option premium, and the last resort premium. Each term maps the model's primitives to a distinct source of liquidity value:

[19] The liquidity premium of asset B includes only the baseline premium component. Note, however, that this baseline premium is not independent of the central bank's presence. The frequency of central bank intervention (π) implicitly affects investors' entry decisions, therefore the measures of buyers and sellers in OTC_B, therefore the matching probabilities in that market.

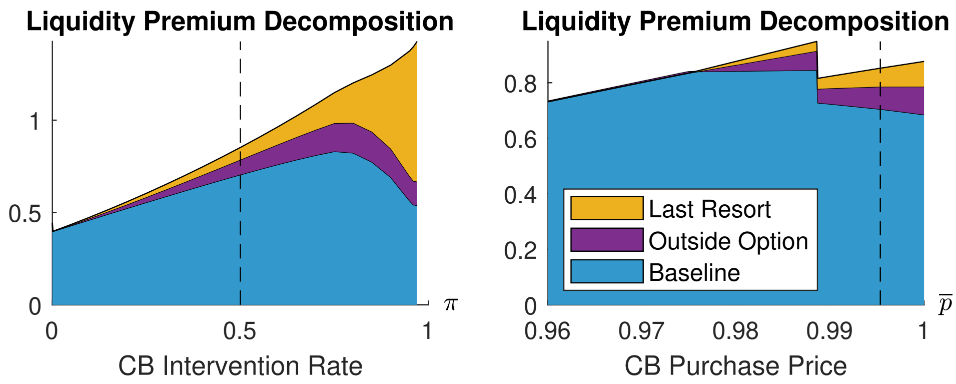

Figure 4: Liquidity premium decomposition under varying central bank intervention rate and purchase price. The figure decomposes asset A's liquidity premium into three components: the baseline premium, the outside option premium, and the last resort premium. The sum of the latter two defines the central bank premium. The calibrated intervention rate and purchase price are 0.5 and 0.9954, respectively, and are marked with the vertical dashed lines.

$$L_A = \underbrace{\ell \alpha_{CA} \frac{\theta}{w(q_{1A})}(u'(q_{1A}) - 1)}_{\text{Baseline premium}} \qquad \text{Central bank premium} = \text{Outside option premium} + \text{Last resort premium}$$

$$+ \underbrace{\pi \ell \alpha_{CA} \left[\left(1 - \frac{\theta}{w(\tilde{q}_{1A})}\right)(u'(\overline{q}_{1A})\overline{p} - 1) + \frac{\theta}{w(\tilde{q}_{1A})}(u'(\tilde{q}_{1A}) - 1) - \frac{\theta}{w(q_{1A})}(u'(q_{1A}) - 1) \right]}_{\text{Outside option premium}}$$

$$+ \underbrace{\pi \ell (1 - \alpha_{CA})(u'(\overline{q}_{1A})\overline{p} - 1)}_{\text{Last resort premium}}$$

Figure 4 can help visualize this decomposition for the liquidity premium of Treasuries, illustrating how each component varies with the central bank intervention rate (left panel) and purchase price (right panel). In both cases, the baseline premium is the dominant force shaping the Treasuries' liquidity premium for relatively small values of π and $\overline{p}$. Effectively, the importance of the central bank premium depends on the magnitude of π and $\overline{p}$ (see the last two terms in the equation above). As a result, the impact of the central bank premium on the total liquidity premium is modest for small values of the central bank intervention rate and purchase price. Analogously, the central bank premium accounts for a sizable fraction of the liquidity premium for relatively larger values of π and $\overline{p}$ (up to 62% when $\pi \approx 1$ and 17% at the calibrated values). Zooming in the central bank premium, the relative significance of the last resort premium compared to the outside option premium increases as the policy variables rise. The larger the values of π and $\overline{p}$, the larger the impact of the realized trades with the central bank in contrast to the improvement in agents' bargaining position which becomes less important. In total, the model implies a non-trivial role for the central bank premium on asset liquidity and prices, which becomes sizable at large levels of the central bank intervention rate and purchase price.

5.4 Borrowing Cost Implications and the Monetary-Fiscal Link

Beyond its implications for asset liquidity and prices, our model highlights a novel channel through which monetary policy affects fiscal policy. When the Fed intervenes in the secondary market for Treasuries, its actions increase the liquidity of these bonds, thereby raising their price and reducing the yield at which the U.S. Treasury can borrow. In other words, monetary policy lowers government borrowing costs, revealing a powerful link between monetary and fiscal policy that operates through secondary asset market liquidity. It is worth highlighting that this link exists even though the monetary authority in principle (and as specified in the standard macroeconomic textbooks) acts completely independently of any fiscal policy considerations. Moreover, because our model features spillover effects across different asset markets, Fed purchases of Treasuries also enhance the liquidity and pricing of corporate bonds, even though the Fed does not actively participate in that market.[20] These spillovers amplify the benefits of central bank interventions: not only does the Treasury save on borrowing costs, but corporations also enjoy lower financing costs. Using our calibrated model, we compute the counterfactual prices and yields of both Treasuries and corporate bonds under a scenario without Fed intervention. A comparison of this scenario with the results of the full model allows us to quantify, in steady state, the reduction in borrowing costs attributable to the Fed's secondary market activity.

Figure 5 presents the model-implied borrowing cost reductions for both Treasuries and corporate bonds under varying levels of the central bank intervention rate (left panel) and purchase price (right panel). The figure reports average quarterly savings, measured in billions of 2019 U.S. dollars, on the given issuance over the calibration period (2016 Q1 to 2019 Q2), relative to a counterfactual scenario in which the central bank ab-

[20] The Fed had never purchased corporate bonds until March 2020 when the launch of the Primary and Secondary Market Corporate Credit Facilities took place. Although it is beyond the scope of our paper, our model could be used to evaluate the consequences of such an intervention in OTC_B in general equilibrium.

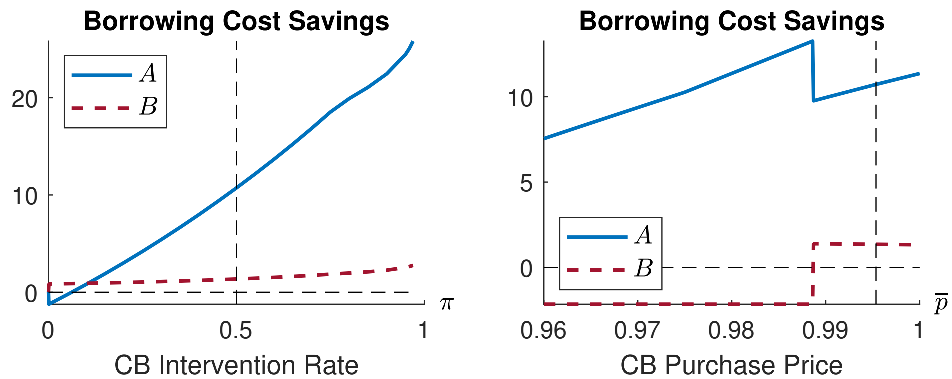

Figure 5: Borrowing cost savings for Treasuries and corporate bonds under varying central bank intervention rate and purchase price. The figure illustrates the average quarterly savings, in billions of 2019 U.S. dollars, on the given issuance, relative to a no-intervention scenario, over the calibrated period (2016 Q1 to 2019 Q2). The calibrated intervention rate and purchase price are 0.5 and 0.9954, respectively, and are marked with the vertical dashed lines.

stains from secondary market intervention. Specifically, we compute the equilibrium prices of assets A and B under central bank participation, denoted by p_A and p_B, and compare them to the counterfactual prices $\widehat{p}_A$ and $\widehat{p}_B$ obtained in the absence of central bank participation. The changes in the borrowing cost are then calculated as $(p_A - \widehat{p}_A)A$ for Treasuries and $(p_B - \widehat{p}_B)B$ for corporate bonds, where A and B denote the respective calibrated amounts outstanding in nominal terms (that is, we keep imposing the assumption that bond supply is exogenous in both markets).

The borrowing cost savings in Figure 5 mirror the behavior of the liquidity premia in the two markets (top left panels of Figures 2 and 3). This is natural since asset supply is exogenous and the reductions in borrowing costs are the result of increases in asset prices due to the presence of the central bank in the Treasury market. The most important takeaway of this exercise is the magnitude of the decline in borrowing costs at the calibrated parameters: the fiscal authority saves around 10 billion (in 2019 dollars) per quarter because of the Fed's routine secondary market interventions. The spillover effect on the corporate bond market is more modest but not trivial, since firms' borrowing cost reduction is around 1 billion per quarter. It is worth noting that these numbers should be interpreted as lower bounds for the total fiscal and corporate savings attributed to the central bank's secondary market activity. The reason is the assumption that the asset supply is fixed for both assets and, as a result, we take into account only the effect of liquidity premia on asset prices. Presumably, if the fiscal authority and corporations could manipulate bond issuance and increase asset quantities strategically, they could achieve even larger reductions in their borrowing costs.

6 Conclusions

We develop a general equilibrium model in which two assets (A and B) trade in distinct secondary over-the-counter markets (OTC$_A$ and OTC$_B$). An asset's liquidity is *endogenous* and depends on the terms of trade in the respective secondary market, which in turn are driven by the optimal market entry decisions of investors. Central bank interventions (which, without loss of generality, take place in OTC$_A$) improve sellers' prospects both in case they match with a private buyer, through an improved outside option, and in the event that they sell assets directly to the central bank. Through these channels, more frequent interventions in OTC$_A$ increase the willingness of investors to pay a higher premium for asset A. At the same time, central bank interventions induce asset buyers to find more favorable trading terms in OTC$_B$, realizing that the bank's presence in OTC$_A$ serves as a bargaining chip in the hands of sellers. Naturally, more buyers in OTC$_B$ implies a higher matching probability for sellers in that market manifesting itself as a higher willingness to also pay a premium for asset B, a result we dub the "spillover effect".

Our model can explain qualitatively and quantitatively the yield differential between Treasuries and safe corporate bonds seen in the data and attribute the well-established liquidity advantage of Treasuries to the observed interventions of the Federal Reserve in the secondary market for these securities. Therefore, our analysis highlights an unexplored *link between monetary and fiscal policy*: the Fed's asset purchases in the *secondary* market for Treasury securities raise the resale value of these assets and, through our indirect liquidity mechanism, increase the willingness of investors to pay higher prices in the *primary* market, thus allowing the Treasury to borrow funds at a lower rate. Our counterfactual exercise reveals that the U.S. Treasury saves tens of billion dollars per year due to the increased liquidity that its securities enjoy as a result of the Fed's participation in the secondary market for Treasuries. The calibrated model also allows us to quantify the spillover effect in the market for corporate bonds, which is also substantial.

By explicitly modeling the secondary markets where central bank intervention takes place, our paper offers novel insights on how central bank interventions in specific markets can have beneficial effects throughout the financial system. Our results also carry some cautionary notes for policymakers and empirical researchers. With regard to policy, our spillover effect result suggests that liquidity in a particular market can be improved without direct intervention in that market. On the flip side, our analysis confirms that central bank interventions can crowd out private market interactions, a concern that policymakers have often voiced. Furthermore, our results imply that researchers who aim to tease out the causal effect of central bank interventions by comparing a "treated" with a "control" market should be cautious, as this comparison may be contaminated by the spillover effect, which according to our quantitative analysis is substantial.

Appendix

A Proof of Lemma 2

$$
\begin{aligned}
&\max_{\{\overline{x}_A, \widetilde{\xi}_A\}} \ \overline{S}_{CA}, \text{ s.t. } 0 \le \overline{x}_A \le d_A \text{ and } \widetilde{\xi}_A = \overline{p}\,\overline{x}_A \\
&= \max_{\overline{x}_A} \left\{ u\left(q\left(m + \overline{p}\,\overline{x}_A\right)\right) - u(q(m)) - \varphi \overline{x}_A \right\}, \text{ s.t. } 0 \le \overline{x}_A \le d_A \\
&= \max_{\overline{x}_A} \left\{ u\left(\max\left\{\varphi\left(m + \overline{p}\,\overline{x}_A\right), q^*\right\}\right) - u\left(\max\left\{\varphi m, q^*\right\}\right) - \varphi \overline{x}_A \right\}, \text{ s.t. } 0 \le \overline{x}_A \le d_A
\end{aligned}
$$

Define the objective function $H : [0, \infty) \to \mathbb{R}$ by $H(\overline{x}_A) = u\left(\min\left\{\varphi\left(m + \overline{p}\,\overline{x}_A\right), q^*\right\}\right) - u\left(\min\left\{\varphi m, q^*\right\}\right) - \varphi \overline{x}_A$. It is obvious that H is continuous $\forall \overline{x}_A \ge 0$, strictly increasing in $\left[0, \max\left\{0, \frac{\overline{m}-m}{\overline{p}}\right\}\right]$, and strictly decreasing in $\left[\max\left\{0, \frac{\overline{m}-m}{\overline{p}}\right\}, \infty\right)$. Therefore, the solution $\left(\overline{x}_A, \widetilde{\xi}_A\right)$ is $(0,0)$, if $m \ge \overline{m}$, and $\left(\min\left\{d_A, \frac{\overline{m}-m}{\overline{p}}\right\}, \min\left\{\overline{p} d_A, \overline{m} - m\right\}\right)$, if $m < \overline{m}$.

B Equilibrium with the central bank fixing the size of asset purchases

Suppose that the central bank announces the size of asset purchases in money, $\overline{M}$, instead of the price $\overline{p}$. That is, now the central bank purchases $\frac{\overline{M}}{\overline{p}}$ units of bond at a prevailing price $\overline{p}$. We can define the equilibrium with $\overline{M}$ as follows.

Definition 1. For $\overline{M} < A$, the tuple $\{z_A, z_B, q_{0A}, q_{1A}, q_{0B}, q_{1B}, \overline{q}_{1A}, \widetilde{q}_{1A}, \varphi, p_A, p_B, \overline{p}, e_C, e_N\}$ is an equilibrium if the variables satisfy all the equations described in Section 2 and $\frac{\overline{M}}{\overline{p}} = (e_C\ell - f(e_C\ell, e_N(1-\ell))) \min\{\frac{A}{e_C}, \frac{\overline{q}-q_{0A}}{\varphi\overline{p}}\}$.

Note that since the price at which the central bank purchases the bond is not fixed, we have one more endogenous variable, $\overline{p}$, than in section 2. Accordingly, we add one more equation, $\frac{\overline{M}}{\overline{p}} = (e_C\ell - f(e_C\ell, e_N(1-\ell))) \min\left\{\frac{A}{e_C}, \frac{\overline{q}-q_{0A}}{\varphi\overline{p}}\right\}$, the market clearing condition between the central bank and private agents to pin down the equilibrium. The RHS of the equation is the bond supply from private agents to the central bank: $e_C\ell - f(e_C\ell, e_N(1-\ell))$ is the measure of unmatched C-types in OTC$_A$, the only ones who have the incentive to sell their bonds to the central bank when $\overline{p} < 1$, with each of them selling $\min\left\{\frac{A}{e_C}, \frac{\overline{q}-q_{0A}}{\varphi\overline{p}}\right\}$ units of bond. Note that the condition $\overline{M} < A$ prevents the equilibrium price $\overline{p}$ from being equal to or greater than 1 with one additional trivial requirement, i.e., if we assume that when the total surplus of a match is zero, the N-types do not wish to trade.[21] Then

[21] This could be justified if there exists an infinitesimal transaction cost associated with bargaining.

if $\overline{p} = 1$, there is no deal between N-types and C-types by the assumption because the surplus is zero. All C-types in OTC$_A$ hence try to sell their bonds to the central bank, which makes an excessive bond supply, $\overline{M} < A$. If $\overline{p} > 1$, the bond supply from private agents to the central bank is A because the price is greater than the fundamental value, leading to an excessive supply again, $\frac{\overline{M}}{\overline{p}} < A$. Therefore, for any equilibrium $\{z_A, z_B, q_{0A}, q_{1A}, q_{0B}, q_{1B}, \overline{q}_{1A}, \widetilde{q}_{1A}, \varphi, p_A, p_B, e_C, e_N\}$ with the central bank fixing the price at $\overline{p} < 1$, there exists an equivalent equilibrium with the central bank fixing the size of purchases in money term at $\overline{M} = \overline{p}\,(e_C\ell - f(e_C\ell, e_N(1-\ell)))\min\left\{\frac{A}{e_C}, \frac{\overline{q}-q_{0A}}{\varphi\overline{p}}\right\}$.

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