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Monetary policy consequences of financial stability interventions: assessing the UK LDI crisis and the central bank policy response

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Abstract

We study the macroeconomic implications of non-bank financial institutions (NBFIs) in the context of the 2022 UK gilt crisis and estimate the monetary policy spillovers of financial stability interventions. We make three contributions. First, we develop the first DSGE model featuring liability driven investment (LDI) and pension funds. This novel framework in which LDI activity amplifies the movements in gilt prices allows us to replicate the UK gilt crisis, demonstrating a crucial mechanism through which NBFIs can amplify financial and economic distress. Second, we quantitatively estimate the monetary policy spillovers of the Bank of England financial stability asset purchases. We find that the asset purchases were successful in offsetting LDI-driven gilt market dysfunction. The temporary, targeted nature of these purchases was crucial in avoiding monetary spillovers. Third, we model two counterfactual instruments – an NBFI repo tool and a macroprudential liquidity buffer – and compare their effectiveness as well as monetary spillovers. Our results show that the central bank can successfully address NBFI-driven market stress without loosening monetary policy, avoiding potential tensions between price and financial stability.

Key words: Monetary policy, financial stability, asset purchases, liquidity crisis, liability-driven investors, gilt, DSGE model.

JEL classification: G01, G23, C68, E44, E52, E58.

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"I want to end by drawing on this experience to make the distinction between monetary policy and financial stability interventions. As a central bank we have to be able to do both, and at any time. We cannot decline to do one because it appears to be at odds with the other. For me, the test is whether we can still operate each policy in accordance with its objectives, at all times. And the answer is yes."

Andrew Bailey, Governor of the Bank of England, October 2022

1 Introduction

In late September and early October 2022, UK gilt prices fell at an almost unprecedented pace. Although this turbulence was initially experienced across all sections of the market, it rapidly became apparent that forced selling by certain pension funds and liability driven investment (LDI) funds was amplifying the pressure in certain segments of the gilt market. Yields on index-linked gilts and on the longest-dated nominal gilts began to spiral upwards, with every rise in yields triggering further asset sales by LDIs into an increasingly illiquid market. On September 28th, the Bank of England ('the Bank') launched a novel asset-purchase programme ultimately worth £19.3 billion (0.9% of GDP) to restore market functioning and prevent widespread financial instability (Figure 1). Departing from previous large-scale asset purchases (LSAPs), the scheme was designed to be 'temporary and targeted' (Cunliffe, 2022b) to deliver the maximum impact on financial markets' conditions with the minimum impact on output and inflation. In other words, while past UK LSAPs were executed to make monetary spillovers as *large* as possible (i.e. Quantitative Easing), the 2022 intervention aimed to make them as *small* as possible. The Bank has a twin mandate to maintain both price and financial stability, and this innovative approach to LSAPs enabled the Bank to deliver on both objectives without compromising between them.[1] This paper assesses the macroeconomic implications of NBFIs in the context of the 2022 UK gilt crisis and estimates the monetary policy spillovers of the Bank's financial stability intervention and two counterfactual policies.

We make three contributions. First, we develop the first quantitative DSGE model featuring LDIs and pension funds. This novel framework allows us to replicate the UK gilt crisis and consider the growing role of NBFIs in causing economic fluctuations.[2] Recent evidence not only from the UK in 2022 but also from the '2020 dash for cash' and 2019 spike in US repo

[1]At the time of the intervention, the Bank was tightening monetary policy by raising interest rates and was shrinking its balance sheet via passive run-off (active QT sales were postponed until November 2022).

[2]As of 2023, assets held by NBFIs account for around half of UK and global financial sector assets (FPC, 2023).

markets indicate that NBFIs are an increasing important mechanism through which financial shocks are amplified and transmitted to the real economy (Cappiello et al., 2021).[3] However, in stark contrast with the extensive theoretical literature on banks (Gertler and Kiyotaki, 2010), little is known on NBFIs' financial frictions and their ability to generate a crisis. We contribute to closing this knowledge gap by exploring some specific financial frictions faced by NBFIs (leverage constraints and slow governance).

Second, we assess the monetary policy spillovers of the Bank's financial stability intervention. The literature to date has neglected the possibility that LSAPs designed to tackle financial market distress may have monetary spillovers that complement or counteract the stance of monetary policy; for instance, by increasing asset prices, they may *ease* financial conditions at a time when monetary policy is seeking to *tighten* them. This neglect is likely a consequence of both limited evidence and limited relevance to monetary policy in recent history.[4] The UK gilt crisis showed that these spillovers can potentially create a trade-off between price and financial stability. Ultimately, this trade-off can test the ability of policymakers *'to do both, and at any time'* (Bailey, 2022). To our knowledge, we are the first to quantitively estimate these spillovers and identify the conditions to minimise them, ensuring the central bank's effectiveness in delivering its mandate.

Third, we evaluate counterfactual policies to solve market stress caused by NBFIs. To this end, we model an 'NBFI lending tool' as planned by the Bank (Hauser, 2023). In addition, after the LDI crisis, LDIs are holding greater liquidity than previously and The Pensions Regulator (TPR) has imposed a resilience standard that promotes increased liquidity (The Pensions Regulator, 2023). So we also model the impact of higher liquidity holdings as a percentage of LDI assets on gilt yields during a crisis.[5] Critically, we assess these tools both on their effectiveness at restoring market functioning and on their monetary policy spillovers. Policymakers have long advocated for new tools to provide market liquidity without loosening

[3]See Czech et al. (2021) for a description of the 'dash for cash' in sterling markets and Anbil, Anderson, and Senyuz (2020) on the spike in US repo market.

[4]There are very few Asset Purchases programmes that have been explicitly designed only to address market dysfunction. Amongst these, see the ECB Securities Markets Programme (Eser and Schwaab, 2016). Importantly, they were all implemented when monetary policy was accomodative at the Effective Lower Bound. Consequently, any spillover would have complemented the monetary policy stance; this contrasts sharply with the LDI crisis when monetary policy was instead becoming more contractionary. In addition, the literature has preferred to focus on the impact of monetary policy on financial stability: For a review of the impact of monetary policy on financial stability see Boyarchenko, Favara, and Schularick (2022). For the interactions between macroprudential and monetary policies see Cozzi et al. (2020). In short, the monetary policy consequences of financial stability Asset Purchases programmes remain uncertain.

[5]The TPR resilience standard requires that funds can operate as business as usual even where there are sharp market movements in yield curves of no less than 250bp. Note, there is no direct read across from the level of this buffer in basis points to liquidity holdings as a percentage of assets.

monetary policy.[6] We offer some of the first recommendations.

We build upon previous work by Pinter (2023), Kodres (2023) and others to construct a formal model of LDI behaviour and embed this in a broader financial sector with several actors including pension funds and households. The critical features of our model are i) the separation between pension funds and LDIs (*segmentation*) and ii) the pension funds' inability to recapitalise the LDIs quickly (*adjustment costs*). We simulate a 'risk premium' shock to bond yields by reducing the convenience yields households earn on long-term assets. Our results are driven by an LDIs' leverage constraint, which forces them to respond to a fall in their net worth by either raising additional equity from pension funds or by selling gilts from their portfolio. With pension funds unable to recapitalise the LDIs quickly due to slow decision making and governance concerns, LDIs are forced to sell gilts to households. The effect of these sales differ from 'Quantitative Tightening' (QT) by central banks in two ways. Firstly, LDI sales occur in the span of a single period rather than being staggered over many periods as with QT. Secondly, LDI sales are concentrated in a small segment of the gilt market (in our setup, index-linked gilts) in which households are comparatively small actors, whereas QT sells more types of gilts to a broader range of buyers. These two features combine to generate extremely large 'flow' adjustment costs for households, and consequently extremely large price effects. This further fall in the price of gilts causes the LDIs to lose even more value, necessitating more sales in a fire sales amplification mechanism. In our model, the size of this effect emerges endogenously as the product of three components: the *size of the LDI sector*, the *leverage of the LDI sector*, and the *reciprocal of household's price-elasticity* of demand for index-linked gilts. All three elements are necessary for the price-sale spiral to emerge.

Having replicated the core dynamics of the September 2022 crisis, we turn to modelling potential financial stability interventions. We consider the effect of each intervention on three outcomes of interest: (a) gilt-market functioning (b) monetary policy and (c) the Bank's balance sheet. We find that the implemented strategy (purchasing a large volume of gilts in the most-affected markets) was successful at restoring gilt market functioning and avoiding monetary spillovers, with a trivial increase in the policy rate of interest of 1–5 basis points sufficient to offset any inflationary impact from the intervention.

We also confirm that the 'temporary' aspect of 'temporary and targeted' is crucial in isolating the financial stability intervention and preventing monetary impacts. We model counterfactual scenarios in which asset purchases were unwound more slowly, and find that monetary impacts escalate rapidly the longer purchased assets are held on the balance sheet.

[6] See for instance BIS (2022) and Alexander et al. (2023) for a review.

With a highly persistent 'QE-style' intervention, a rise of 20–40 basis points becomes necessary. This depends on the actual speed the intervention is unwound, rather than public beliefs about the intervention. We examine counterfactual scenarios in which the intervention is believed to be persistent, but is actually unwound quickly. In an extreme scenario where the intervention is mistakenly believed to have QE-style persistence, a rise of 8 basis points is sufficient to control inflation; this contrasts with a rise of 40 points if the intervention is correctly believed to be QE-style. This result suggests that implementation is more important than communication when designing financial stability interventions.

In line with policymakers' choices (Hauser, 2023), we consider two counterfactual tools a central bank might wish to employ in the event of a future episode. We first model an 'NBFI lending tool' which would facilitate direct collateralised loans from the central bank to non-bank financial intermediaries (NBFIs). Providing loans to the LDI sector is ineffective, because the whole crisis dynamic is driven by their attempts to reduce leverage; this is not helped by increasing their liabilities (Alexander et al., 2023). However, we show that providing liquidity to the *pension funds* who purchase LDI products could potentially be effective at resolving the crisis. In our setup, repo loans to pension funds worth 0.23% of GDP have similar market impacts as an asset purchase program worth 0.9% of GDP. This implies it could be possible to resolve future gilt market dysfunction with a reduced impact on the Bank's balance sheet. However, the structure of this tool would need to be carefully designed and integrated into pension fund governance structures to be effective. Secondly, we model a macroprudential 'liquidity buffer' requiring the pension fund/LDI sector to hold liquid assets (money) proportional to total LDI assets. This liquidity buffer is then relaxed during the crisis, allowing LDI losses to manifest as fewer liquid assets rather than gilt sales. This is in line with the increased liquidity promoted by TPR in the aftermath of the 2022 crisis (The Pensions Regulator, 2023). We estimate that requiring pension funds to hold liquid assets worth 2.75% of LDI assets would offset half of the 'LDI effect', reducing but not closing the spread between index-linked and nominal gilts. Imposing a larger liquidity buffer would offset more of the effect, but implies a reduced rate of return on pension fund portfolios during normal times. Finally, we model a further counterfactual scenario in which the UK government debt is persistently less appealing to investors following the change in risk profile. Our policy conclusions with respect to asset purchases and repo tool are unchanged.

The reminder of the paper is organised as follows. After presenting a review of the relevant literature, Section 2 explains the main features of the model, focusing on the sophisticated financial sector. Section 3 describes the mechanisms driving the key effects. Sections 4 shows the calibration of the model. Section 5 replicates the 2022 UK gilts crisis. Section 6 studies the monetary policy implications of the Bank financial stability intervention. For this, it answers two questions: First, did the LSAPs for financial stability affect monetary policy? Second, did the LSAPs intervention need to be temporary to avoid monetary policy spillovers? Section 7 evaluates two alternative tools the Bank could have employed — a repo tool and macro-prudential policy, comparing them with the actual LSAPs intervention — and a counterfactual scenario featuring a persistently less appealing UK government debt. Section 8 concludes.

Figure 1: Yield moves and Bank of England operations

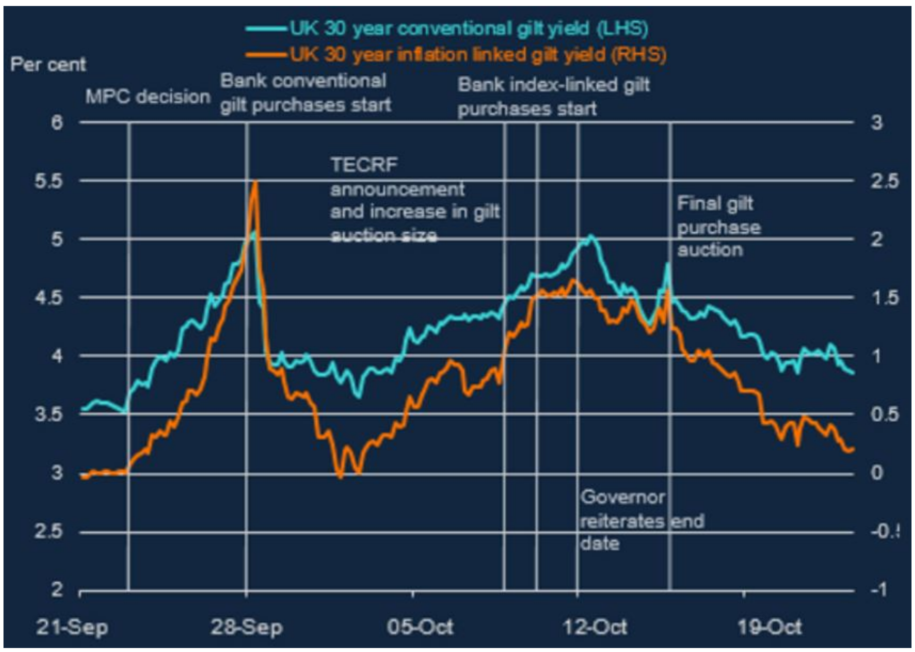


Figure 1 shows the yields of nominal and inflation linked gilts as well as the Bank of England operations during the LDI crisis. This figure is taken from chart 1 in Hauser (2022).

Related Literature This paper relates to three streams of literature: the recent studies on the 2022 UK gilt crisis; the growing body of research applying DSGE models to study non-bank financial institutions and finally the nascent literature on the monetary consequences of financial stability interventions.

Our work builds on existing analysis of the 2022 UK gilt market turbulence. Kodres (2023) provides a narrative overview of events, with a detailed discussion of the conflicting institutional incentives creating a market coordination failure. Pinter (2023) provides an empirical assessment of the crisis using bank-level data to assess changes in LDI balance sheets before during and immediately prior to the market turbulence. In addition to a headline estimate that gilt sales by LDIs and pension funds amounted to £36 billion between the 23/09 and 14/10, he finds that usage of gilt repo agreements was by far the most important factor associated with gilt sales. Although LDIs used a wide array of financial products including OIS swaps to provide pension funds with risk management, Pinter (2023) finds strong evidence in support of the narrative that it was the use of repo to gain leveraged gilt exposure which drove the crisis dynamics (Breeden, 2022; Cunliffe, 2022a). This shapes our novel model and analysis, as we focus on repo and leverage dynamics rather than swaps and margin requirements.

We also connect with a growing literature on non-bank financial institutions (NBFIs) and the increasingly important role they play in financial instability. Recent work in this area includes, though is far from limited to, Aramonte and Avalos (2021), Aramonte, Schrimpf, and Shin (2022), Berre and Sarkar (2023), Cappiello et al. (2021), Cetorelli, Landoni, and Lu (2023), Chari (2023), Claessens and Lewrick (2021), and Hudson, Kurian, and Lewis (2023). Common themes in the literature are the increasing share of NBFIs in asset markets since the global financial crisis, the high degree of interconnection both within the NBFI sector and between NBFIs and traditional banks, and the strong procyclicality of non-bank portfolio choices. There has been a particular recent focus on the 'Dash for Cash' episode in March 2020, which exposed weaknesses both in NBFI liquidity reserves and in policymakers ability to intervene following NBFI disruption (Barone et al., 2022; Eren and Wooldridge, 2021; Hauser, Logan, and Committee, 2022). Although the nature of the 2022 NBFI crisis was quite different to that of 2020, both incidents reveal the increasingly decisive influence of NBFIs on government bond markets.

We also contribute to the literature on the monetary consequences of financial stability interventions. The existing literature has mostly considered the interaction between monetary policy and macroprudential policy, either by considering 'leaning against the wind' policies (using monetary policy to stabilise the credit cycle) or by examining the implications of macroprudential regulations for the monetary transmission mechanism. Examples of the former include Brandão-Marques et al. (2021), Gourio, Kashyap, and Sim (2018), Lupoli (2022), Rieder (2021), Schularick, Steege, and Ward (2021), Svensson (2017), and Coman and Lloyd (2022); examples of the latter include Bussière et al. (2020), Gambacorta and Murcia (2017), Martinez-Miera and Repullo (2019), Svensson (2018), Cozzi et al. (2020), and Bandera (2023). Similarly, papers such as Chavleishvili, Kremer, and Lund-Thomsen (2023) consider the potential threat from sharply contractionary monetary policy to financial stability. However, they not address the converse problem - the risks that financial stability policies pose to monetary stability - beyond stating the need to avoid 'financial dominance' and allowing monetary policy to be steered entirely by financial considerations.

Research on ex-post (as opposed to prudential) interventions of the sort conducted in 2022 is comparatively sparse. Stein (2013) discusses the potential for monetary policy tools to be employed in pursuit of financial stability, arguing that 'gets in all the cracks' and reaches those markets and institutions missed by regulators. Martin, Mendicino, and Ghote (2022) similarly notes that while it is in general inefficient for monetary tools to be employed for financial stability, this relies on comprehensive macroprudential coverage. Since macroprudential tools do not effectively cover NBFIs, they find it is welfare-improving to use interest rate policy ex-post to improve financial stability. However, they do not engage with asset purchases or the question of how best to design an ex-post intervention to sterilise monetary consequences. Duffie and Keane (2023) considers the issue qualitatively, using the UK 2022 crisis as an example of when financial stability operations might in principle conflict with monetary objectives. They provide a discussion of how asset purchase programmes might be designed to minimise monetary impacts, with repeat reference to the UK example and emphasising the need for 'a transparent and timely exit policy'. However, to our knowledge no paper has attempted to formalise this trade-off. We thus contribute to the literature by providing the first quantitative estimate of monetary spillovers from financial stability interventions, as well as the first assessment of how the timing of interventions impacts these spillovers.

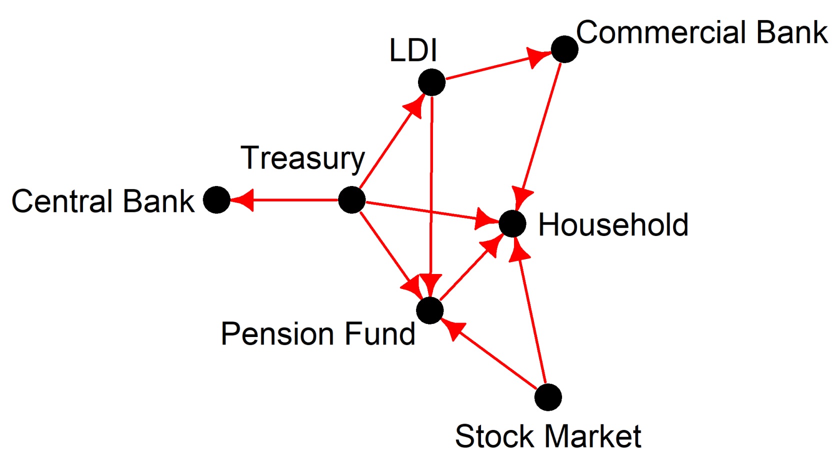
2 Model

2.1 Model Summary

At the core of our model is a sophisticated non-bank financial sector, capturing the key interlinkages between the different actors involved in the 2022 crisis. Critically, pension funds are separated from LDIs and decide their asset holdings - including LDI shares - a period in advance. Deviating from the planned strategy is possible but at increasing marginal costs. This means that while pension funds can inject equity into the LDIs, they cannot do so quickly. This leaves LDIs with only one option for deleveraging in a crisis: selling assets. This potentially generates a price spiral, because when one LDI sells assets it causes a price drop which further increases the leverage of the whole sector, in turn requiring further asset sales and a further price drop. In short, *segmentation* amongst non-bank financial intermediaries and *adjustment costs* are crucial innovations of our model.

The novel non-bank financial sector is then embedded in a medium-scale NK-DSGE model with standard features, including habit persistence, capital investment with adjustment costs, and both price and wage frictions. Households act as the primary bridge between the financial sector and the real economy. In addition to making labour and consumption choices each period, households also face a portfolio allocation decision. This decision is based not only on pecuniary returns, but also 'convenience yields' and 'adjustment costs' capturing household preferences over different asset types and costs from rapidly changing the portfolio composition. These effects allow for financial shocks to transmit through to household behaviour, and hence on to output and inflation.

Figure 2: Financial Interlinkages



Note: Arrows indicate liability holdings, e.g. Treasury → Household implies households own treasury liabilities

Figure 2 shows the interlinkages between the different financial actors in the model.

Figure 2 illustrates the interlinkages between the different financial actors in the model. The most connected agents are households, who hold a wide array of varied financial assets, and the Treasury, which issues three types of 'government bond' which are held by several actors. These three bonds are a liquid short-term asset, a long-term nominal bond, and a long-term index-linked bond. The Treasury itself is passive throughout, acting simply to maintain a constant stock of debt in fixed proportion between the three types. By contrast, the market in treasuries is highly active with interactions between households, liability driven investment funds (LDIs) and the central bank driving our results.

This section proceeds as follows. Section 2.2 sets out our household model, including portfolio balance and adjustment costs; 2.3 lays out our bond market and section 2.4 our stylised commercial bank. The most novel aspects of our model are introduced in sections 2.5 and 2.6, which lay out our pension fund and liability driven investment fund, and section 2.7, which lays out our central bank and three policy options it has for conducting financial stability operations. Section 2.8 briefly explains our Treasury model and 2.9 bond market clearing equations. Our production sector is composed of tiered output firms and labour unions, a brief exposition is provided in section 2.10 but full details are left to appendix B.

2.2 Households

2.2.1 Setup

Households have CRRA utility over adjusted consumption ($\bar{c}_t$) and leisure ($1 - n_t$), and maximise over these variables and the portfolio allocation of assets. We define the following problem:

$$
\begin{aligned}
\max_{c_t, n_t, B_t^{H10}, B_t^P, V_t^M, V_t^{FI}} U_t &= \frac{\bar{c}_t^{1-\sigma}}{1-\sigma} + \phi \frac{(1-n_t)^{1+\psi}}{1+\psi} + \beta U_{t+1} \\
\text{s.t.} c_t + A_t &= w_t^h n_t + \bar{r}_t A_{t-1} + D_t - [\Xi - \xi a_t] - \Psi_t - T_t \\
\bar{c}_t &= c_t - h c_{t-1} \\
A_t &\equiv B_t^H + B_t^{H10} + B_t^{HL} + V_t^H + V_t^{FI} \\
B_t^{HL} &\equiv B_t^{HGL} + B_t^{PL} \\
D_t &\equiv D_t^P + D_t^U
\end{aligned}
$$

With β as the time discount factor, σ and ψ controlling the elasticity of utility with respect to consumption c_t and labour n_t respectively, and ϕ determining steady state labour supply. Households exhibit internal consumption persistence[7] controlled by parameter h; $h = 0$ implies that adjusted consumption $\bar{c}_t = c_t$. Average portfolio returns are denoted $\bar{r}_t - 1$. The term $[\Xi - \xi \log a_t]$ captures household transaction costs, which are mitigated by household liquidity a_t. This is taken from the portfolio balance model of Kabaca et al. (2023) and discussed in more depth below. The term Ψ_t is based on the portfolio adjustment costs in Harrison (2017)

[7]Habit persistence improves our results quantitatively, but appendix A.6 demonstrates that our qualitative conclusions hold even when we remove it from the model.

and is designed to restrict arbitrage in the short term. Conceptually, $[\Xi - \xi \log a_t]$ captures non-financial transaction costs which are alleviated by holding liquid assets, whereas Ψ_t captures transaction costs in those same assets. ξ captures the marginal rate at which liquidity a_t alleviates costs, and Ξ is a fixed-cost parameter which is used to normalise $[\Xi - \xi \log a_t] = 0$ in steady state. A lump sum tax T_t is levied by the fiscal authority. A labour union pays households a wage w_t^h on their labour n_t and also dividends D_t^U.

The model contains several assets which households optimise over. B_t^H refers to household-owned short-term government liabilities, henceforth referred to as "money". This composes both short-term treasury bills and central bank reserves. B_t^{H10} refers to household-owned long-term government bonds ("long bonds"), which are based on Woodford (2001) and calibrated to correspond with a ten-year bond.

B_t^{HGL} is similarly household holdings of a government-issued ten-year Woodford bond, but this bond is indexed-linked to inflation. B_t^{PL} is a precisely analogous asset ("pension bonds") issued by a private-sector defined-benefit pension (DBP) fund. As in Carboni and Ellison (2022) this asset is taken as representative of defined-benefit pensions and fixed-payment insurance products which guarantee households (in the aggregate) a fixed stream of future payments in much the same way as a long bond. Since long bonds and pension bonds are precisely equivalent assets, we solve the household optimisation problem in terms of their sum B_t^{HL}. This composite variable captures household demand for long-term index-linked assets.

The pension fund is entirely bond-financed and makes no profits in steady state, but any unanticipated (net) profits are returned to households each period through the (net) dividend D_t^P. V_t^H refers to household equity in monopolistic final-goods manufacturers which produce output using labour and capital, with capital produced via internal investment. Finally, V_t^{FI} is the equity of a financial intermediary providing finance to Liability Driven Investment (LDI) funds in the form of asset repurchase ("repo") agreements. We will introduce LDIs and their relationship with the rest of the financial sector later.

2.2.2 Discussion

It is worth taking a moment to highlight the novel features of our setup and anticipate how they will drive our core results. The crucial feature is less the index-linking and more the distinction between different types of long-term bond. Instead of an index-linked bond, we could instead introduce a 'very long-term' bond with a duration of (say) 30 years and obtain equivalent results. What matters for our model dynamics is that there exist multiple types of long-term bond, with imperfect arbitrage between the different types and with one having a much smaller market share and consequently lower liquidity. In this sense, our 'linked bond' is best interpreted as representing a broad array of niche assets with a long duration and low market liquidity.

Because of the similarity between this government-issued asset B_t^{GL} and the pension asset B_t^{PL}, the pension fund sector has a strong demand for this niche asset to hedge against price changes (primarily interest rate risk). This is turn means that a relatively small pension/LDI sector controls an outsized share of a shallow market, and hence their decisions have a large impact on prices. This is designed to capture the key fact that on 22/09/2022, at the start of the gilt market dysfunction, LDI funds owned 82% of all long-dated index-linked gilts.[8]

2.2.3 First Order Conditions

We denote by Λ_t the household stochastic discount factor between time t and $t+1$. Solving the household problem yields the following first order conditions:

$$\Lambda_t = \beta \left(\frac{\bar{c}_{t+1}^{-\sigma} - \beta h \bar{c}_{t+2}^{-\sigma}}{\bar{c}_t^{-\sigma} - \beta h \bar{c}_{t+1}^{-\sigma}} \right) \tag{1}$$

$$(1 - n_t)^{\psi} = w_t^h \bar{c}_t^{-\sigma} / \phi \tag{2}$$

We adopt a stylised portfolio balance model based on Kabaca et al. (2023) and Harrison (2017). This algebraically tractable formulation gives households utility (or subtracts it) depending on the composition of their portfolio. This is motivated as capturing financial frictions preventing perfect arbitrage between assets, such as the preferred habitat investors outlined in Vayanos and Vila (2009; 2021) and Ray (2019), credit market frictions such as those in Gertler and Karadi (2011; 2015) and Sims and Wu (2021), and search-match liquidity frictions as in Ferdinandusse, Freier, and Ristiniemi (2020).

We introduce this friction for two reasons. Firstly, it provides a motivation for central bank asset purchases; in their absence asset purchases would have no impact on the real economy (Wallace, 1981). Secondly, it allows us to generate an "equity premium" excess return on V_t^M and V_t^{FI} without requiring us to engage with the complex literature motivating this endogenously. We prefer the pecuniary costs formulation of Kabaca et al. (2023) to the utility-based version of Alpanda and Kabaca (2020) (and others) as this extends more naturally to include portfolio adjustment costs. Adjustment costs are inspired by Harrison (2017) and

[8] Source: SMMD and Bank Calculations

are designed to capture market illiquidity. This plays a role in exacerbating the LDI crisis by making it prohibitively expensive for households to arbitrage away sudden falls in bond prices.

We specify the functional forms:

$$\Psi_t \equiv \frac{\omega_1}{2}\left(\frac{B_t^{H10}}{B_{t-1}^{H10}} - 1\right)^2 + \frac{\omega_2}{2}\left(\frac{B_t^{HL}}{B_{t-1}^{HL}} - 1\right)^2 + \frac{\omega_3}{2}\left(\frac{V_t^{H}}{V_{t-1}^{H}} - 1\right)^2 \tag{3}$$

$$\alpha_t \equiv \left[\zeta_t^{\frac{1}{\kappa_\alpha}}\left(B_t^H\right)^{\frac{\kappa_\alpha - 1}{\kappa_\alpha}} + (1-\zeta_t)^{\frac{1}{\kappa_\alpha}}\left(\hat{B}_t\right)^{\frac{\kappa_\alpha - 1}{\kappa_\alpha}}\right]^{\frac{\kappa_\alpha}{\kappa_\alpha - 1}} \tag{4}$$

$$\hat{B}_t \equiv \left[\hat{\zeta}^{\frac{1}{\kappa_L}}\left(B_t^{HL}\right)^{\frac{\kappa_L - 1}{\kappa_L}} + \left(1-\hat{\zeta}\right)^{\frac{1}{\kappa_L}}\left(B_t^{H10}\right)^{\frac{\kappa_L - 1}{\kappa_L}}\right]^{\frac{\kappa_L}{\kappa_L - 1}} \tag{5}$$

$$\zeta_t = \left(1 - \rho_\zeta\right)\bar{\zeta} + \rho_\zeta \zeta_{t-1} + \epsilon_t^\zeta \tag{6}$$

Where ζ_t is a time-varying weight determining the optimal share of money in the portfolio, $\hat{\zeta}$ a parameter determining the optimal share of linked bonds, κ_α the elasticity of substitution between short- and long-bonds and κ_L the elasticity between linked and non-linked bonds. We allow ζ_t to be time-varying in order that we can apply a 'portfolio shock' ϵ_t^ζ making long-term bonds relatively less attractive and exogenously push up yields on these bonds. Adjustment costs are captured by equation (3); this is adapted from Harrison (2017) to include equity as well as government bonds. Households face a quadratic cost for changing their bond and equity holdings, with the strength of this effect determined by $\omega_1/\omega_2/\omega_3$. We assume that there is no cost to changing money holdings, and abstract from adjustment costs in the FI valuation V_t^{FI} as a minor simplification; this has no impact on our model dynamics.

We define real asset returns between period $t-1$ and t as r_t, r_t^{10},r_t^L, r_t^V and r_t^{FI}. We arrive at a set of asset valuation conditions:

$$E_t\left[\Lambda_t r_{t+1}\right] = 1 - \xi\left[\zeta_t \alpha_t / B_t^H\right]^{\frac{1}{\kappa_\alpha}} \tag{7}$$

$$E_t\left[\Lambda_t r_{t+1}^{10} + \tilde{\Psi}_t^{10}\right] = 1 - \xi\left[\left(1-\zeta_t\right)\alpha_t/\hat{B}_t\right]^{\frac{1}{\kappa_\alpha}}\left[\left(1-\hat{\zeta}\right)\hat{B}_t/B_t^{H10}\right]^{\frac{1}{\kappa_L}} \tag{8}$$

$$E_t\left[\Lambda_t r_{t+1}^{L} + \tilde{\Psi}_t^{L}\right] = 1 - \xi\left[\left(1-\zeta_t\right)\alpha_t/\hat{B}_t\right]^{\frac{1}{\kappa_\alpha}}\left[\hat{\zeta}\hat{B}_t/B_t^{HL}\right]^{\frac{1}{\kappa_L}} \tag{9}$$

$$E_t\left[\Lambda_t r_{t+1}^{V} + \tilde{\Psi}_t^{V}\right] = 1 \tag{10}$$

$$E_t\left[\Lambda_t r_{t+1}^{FI}\right] = 1 \tag{11}$$

Where we have denoted marginal transaction costs as:

$$\tilde{\Psi}_t^{10} \equiv \frac{1}{B_{t-1}^{H10}}\omega_1\left(\frac{B_t^{H10}}{B_{t-1}^{H10}} - 1\right) - \Lambda_t \frac{B_{t+1}^{H10}}{\left(B_t^{H10}\right)^2}\omega_1\left(\frac{B_{t+1}^{H10}}{B_t^{H10}} - 1\right) \tag{12}$$

$$\tilde{\Psi}_t^{L} \equiv \frac{1}{B_{t-1}^{HL}}\omega_2\left(\frac{B_t^{HL}}{B_{t-1}^{HL}} - 1\right) - \Lambda_t \frac{B_{t+1}^{HL}}{\left(B_t^{HL}\right)^2}\omega_1\left(\frac{B_{t+1}^{HL}}{B_t^{HL}} - 1\right) \tag{13}$$

$$\tilde{\Psi}_t^{V} \equiv \frac{1}{V_{t-1}^{H}}\omega_3\left(\frac{V_t^{H}}{V_{t-1}^{H}} - 1\right) - \Lambda_t \frac{V_{t+1}^{H}}{\left(V_t^{H}\right)^2}\omega_2\left(\frac{V_{t+1}^{H}}{V_t^{H}} - 1\right) \tag{14}$$

We close this section by briefly noting the portfolio average return $\bar{r}$:

$$\bar{r} = \frac{r_t B_{t-1}^H + r_t^{10} B_{t-1}^{H10} + r_t^L B_t^L + r_t^V V_{t-1}^{H,M} + r_t^{FI} V_{t-1}^{FI}}{A_{t-1}} \tag{15}$$

2.3 Bonds

We model both government and private long-term bonds using the tractable formulation of Woodford (2001). In this setup, bonds pay coupons indefinitely but the value of the coupon payment declines geometrically at a rate k. This methodology has the crucial advantage that each type $X \in \{10, L\}$ of such bonds can be represented using two variables, a price Q_t^X and a stock value B_t^X. This contrasts with other methods of modelling long-term bonds which require a separate price/stock variable for each vintage of the bond.

The index- and non-linked bonds are similar, but offer a slightly different coupon structure. The non-linked bond offers (nominal) payments of $\mathcal{C}_{10} P_t$ at time $t+1$, $P_t \mathcal{C}_{10} k_1$ at $t+2$, $P_t \mathcal{C}_{10} k_1^2$ at $t+3$ and so on; the real value of payments thus follows $\mathcal{C}_{10}\left(\pi_{t+1}\right)^{-1}$, $\mathcal{C}_{10} k_1 \left(\pi_{t+1}\pi_{t+2}\right)^{-1}$,

$\mathcal{C}_{10}k_1^2 \left(\pi_{t+1}\pi_{t+2}\pi_{t+3}\right)^{-1}$ etc. The linked bond instead offers (nominal) payments of $\mathcal{C}_L P_{t+1}$ at time $t+1$, $\mathcal{C}_L k_2 P_{t+2}$ at $t+2$ and so on; the real value of payments is just $\mathcal{C}_L, \mathcal{C}_L k_2, \mathcal{C}_L k_2^2 \ldots$. We calibrate the coupon parameters $\mathcal{C}_{10}$ and $\mathcal{C}_L$ such that in steady-state $Q_t^{10} = Q_t^L = 100$; this is purely for convenience and has no effect on our results.

In a minor departure from other work, including Carboni and Ellison (2022), we assume that the government- and private-issued bonds have identical properties. This is a simplifying assumption as it allows the pension fund to perfectly hedge liabilities using a single government-issued asset, held indirectly via the LDI. In reality, pension funds would hold a complex mix of liabilities with different durations and a correspondingly complex mix of assets to balance duration risk. The assumption of a single class of asset and liability keeps our framework tractable while capturing the key properties of the LDI market.

We omit the mathematical derivation of the properties of these bonds, referring readers to Woodford (2001) for full details. We instead present the crucial equations linking price to rate of return, denoting by i_t^{10} (r_t^L) the nominal (real) return made on a nominal (linked) bond purchased at time $t-1$ and sold at time t.

$$i_t^{10} = \left(\mathcal{C}_{10} + k_1 Q_t^{10}\right) / Q_{t-1}^{10} \tag{16}$$

$$r_t^L = \left(\mathcal{C}_L + k_1 Q_t^L\right) / Q_{t-1}^L \tag{17}$$

The two types of bond – nominal and index-linked – have extremely similar properties. The difference is that the real price of the bond is linked to either the nominal return (for the non-linked) or the real return (for the linked). We set a coupon decay rate of $k_1 = k_2 = k$ with $k = 1 - 1/40$ such that these correspond roughly to ten-year (forty-quarter) bonds. We set this equal for both linked and non-linked bonds as it facilitates easy analysis between the two; it ensures that Q_t^{10} and Q_t^L react (almost) identically in the absence of the pension/LDI dynamics introduced later and hence divergence in the response can be interpreted as the impact of LDI-driven market dysfunction. However, in appendix A.1 we replicate our core analysis under the alternative case of $k_2 = 1 - 1/80$.

2.4 Commercial Bank

We introduce an extremely stylised commercial bank for the sole purpose of providing repo finance to the non-bank financial sector. While in practice commercial banks provide a much wider array of services to a much broader range of customers, we isolate this specific function of commercial banks since the focus of this paper is on the non-bank sector. Our aim is thus to keep the commercial bank balance sheet as simple as possible.

The commercial bank is capitalised by households, and uses this capital to engage in repo agreements with counterparties. We introduce the relevant counterparty (LDIs) below. Repo finance is provided to the LDIs by buying index-linked bonds from the LDI at a price $\tilde{Q}_t^{Rep}$, with a binding agreement from the LDI to repurchase the bond next period at a (real) price Q_t^{Rep}. We assume for analytic convenience that all coupons paid on the bonds accrue to the LDI and not to the commercial bank; this could be arranged through careful timing of the repo agreement or by appropriate adjustment of the repurchase price and has no impact on any results. The bank makes a return based on the ratio of sale price to purchase price, $r_t^{Rep} \equiv Q_t^{Rep}/\tilde{Q}_t^{Rep}$. This return is guaranteed since the repurchase price is fixed at time of sale and we assume no counterparty risk (the LDI is always able to repay). A full and detailed balance sheet for the commercial bank would include index-linked bonds, since they are technically owned by the bank for the duration of the repo agreement. However, the bank is in no way exposed to the rate of return of these bonds courtesy of the strict repo agreement with the LDI. We can thus omit index-linked bonds from the commercial bank balance sheet, and instead treat them as if they were still part of the LDI balance sheet. This is possible due to the minimalist modelling of the banking sector; in reality the bonds do indeed lie on the commercial bank balance sheet for the purposes of accountancy, regulation and stress-testing. A more sophisticated model considering interactions and complementarities between banks and non-banks would need to place an appropriate volume of linkers on the commercial bank balance sheet for the duration of the repo loan.

Bonds are initially purchased at a price $\tilde{Q}_t^{Rep}$ and resold at a price Q_t^{Rep}. The choice of a purchase price $\tilde{Q}_t^{Rep} < 1$ implies a haircut is levied on the bonds, i.e. a price $\tilde{Q}_t^{Rep} = 0.8$ implies the bank has applied a 20% haircut and provided a loan equal to only 80% of the bond's market value. We assume throughout that no haircut is required and $\tilde{Q}_t^{Rep} = 1\ \forall t$. This has no impact on results, since in practice any plausibly sized haircut is dominated by the leverage constraint we introduce in section 2.6. The size of haircut would also control the volume of bonds placed onto the commercial bank balance sheet we we to model this.

We assume that commercial banks are owned by households and inherit their discount factor Λ_t, and that the repo price Q_{t-1}^{Rep} is index-linked. Since are focus is on the non-banking financial intermediation rather than the banking sector, we abstract from frictions and assume the commercial bank can provide (collateralised) finance flexibly. This allows us to assume that banks are entirely equity financed without further loss of generality, abstracting from deposits[9].

The commercial bank problem can be defined as a Bellman in two equations over bank valuation V_t^{FI} and dividends D_t^{FI}:

$$\max_{X_t} V_t^{FI} = D_t^{FI} + \Lambda_t V_{t+1}^{FI} \tag{18}$$

$$D_t^{FI} \equiv Q_{t-1}^{Rep} X_{t-1} - X_t \tag{19}$$

We abstract from any constraints on commercial bank lending since our focus is on the LDI sector, and instead assume that the bank simply chooses the volume X_t of repo lending it wishes to conduct. We assume repo lending is for a single quarter and then requires refinancing, i.e. bonds purchased at time t will be repurchased by the LDI at a price Q_t^{Rep} in period $t+1$. The choice of short-term repo is consistent with the evidence in Pinter (2023) that the vast majority of repo borrowing by LDIs is for two quarters or less.

The commercial bank has a single first-order condition linking Q_t^{Rep} with the discount factor Λ_t:

$$Q_t^{Rep} = \frac{1}{\Lambda_t} \tag{20}$$

Intuitively, the price of a repo loan is pinned down by the household discount factor. In the absence of uncertainty and convenience yields, Q_t^{Rep} is simply the expected real interest rate.

2.5 Pension Fund

We motivate the existence of Liability Driven Investment funds (LDIs) by appeal to the household portfolio allocation problem. In the literature on preferred habitats and the portfolio balance channel of QE, households exhibit preferences over the asset structure of their portfolio. For example, Harrison (2017) assume that households have a target ratio of short- to long-term government debt, and experience either pecuniary or utility costs when they deviate from this ratio. We motivate LDIs by extending these preferences to capture private-sector assets as well as government bonds. In particular, we assume that households wish to hold a long-term private sector asset B_t^{PL} in addition to government bonds. While we follow Carboni and Ellison (2022) in modelling this as a long-term liability exactly equivalent to a long-term

[9] In other frameworks, such as Gertler and Karadi (2011), the distinction between bank deposits and bank equity is crucial since they restrict the flow of net dividends between bank and household using a stochastic entry/exit mechanism. Absent this friction, the two are precisely equivalent (Modigliani and Miller, 1958).

government bond, this should not be interpreted as a literal bond. The term B_t^{PL} is instead intended to capture defined-benefit pensions and fixed-return life insurance products which offer households (taken together) a guaranteed future payment.

This has implications for model dynamics, in that we assume the quantity (but not the value) of these liabilities is fixed across the time period of the model. This reflects the fact that the process of buying households out of a pension scheme or life-insurance product which they have already paid for is exceptionally complex, and conversely that households typically do not join such schemes by means of a lump-sum payment but instead build up a stake gradually via incremental monthly payments. For our application of a liquidity shock, the crucial detail is that the pension fund is unable to raise liquidity by increasing the supply of B_t^{PL}.

Following the structure of the financial intermediary (FI) in Gertler and Karadi (2011), we model pension funds as a fixed mass indexed $i \in [0,1]$, which die stochastically with probability $1 - \varsigma$ and are replaced immediately by an equal number of new firms. As argued by Sims and Wu (2021), this is best interpreted as representing financial frictions preventing smooth transition of dividends and equity issuance between FIs and households. For our purposes, this assumption ensures that pension funds cannot painlessly resolve liquidity crises by issuing more equity.

The pension fund has a straightforward balance sheet, with a single liability and a choice between "growth assets" $V_{i,t}^{PF}$, money B_t^{PF} and equity in an LDI pool $V_{i,t}^{LDI}$. We also introduce convex portfolio adjustment costs $\Psi_{i,t}^{PF}$, which increase quadratically when the pension fund buys or sells growth assets. This is designed to capture the fact that pension funds typically operate over long time horizons, and are not well placed to change their portfolio composition at short notice. The cost term $\Psi_{i,t}^{PF}$ is thus designed to reflect both direct transactional costs involved in trading in highly illiquid assets, and also more abstract difficulties with institutional sluggishness and coordination difficulties. For example, a pension fund may require time to consult with clients before radically reducing or increasing growth assets. This will play a crucial role in our crisis dynamics, since the pension fund will be reluctant to inject equity into the LDI if this requires an expensive firesale of illiquid growth assets. We abstract from other assets the pension fund may hold, such as gilts, since these are not relevant to the crisis dynamics we are interested in. The pension fund problem is further simplified by our earlier assumption that the LDI maintains a fixed volume of liabilities.

Pension fund holdings of money are constrained by a regulatory minimum $\mathcal{M}_{i,t}$; they may exceed this level but cannot fall below it. This is an occasionally binding constraint; it will always bind in steady state so long as the return on money is lower than that on equity, i.e. $r_t < r_t^V$. We introduce money and the threshold $\mathcal{M}_{i,t}$ to allow for macroprudential policy.

By setting a high value for $\mathcal{M}_t$ in normal times, policymakers can lower $\mathcal{M}_{i,t}$ during a crisis to allow pension funds to use this liquidity and recapitalise LDIs. We discuss $\mathcal{M}_{i,t}$ further in section 2.7.

We also introduce at this stage a central bank loan X_t^{CB}. This is a loan that may be provided by the central bank to the pension fund at the discretion of policymakers, designed to represent an array of potential non-bank liquidity tools which could be used to provide direct support to non-banks, analogous to liquidity tools already employed to support the banking sector. We abstract from operational details such as institutional eligibility, collateral eligibility and loan pricing; we assume for simplicity that the loan is provided at market rate Q_t^{Rep} and that the pension funds we model have sufficient high-grade collateral in their portfolio to satisfy any eligibility requirements. Importantly, we also assume that accessing this loan does not incur the same type of adjustment costs and governance concerns associated with adjusting other aspects of the pension fund portfolio, i.e. we assume $d\Psi_{i,t}^{PF}/dX_t^{CB} = 0$. The extent to which this is plausible depends entirely on the design of the tool and the relationship between the pension fund and the central bank. For example, institutional eligibility could be linked to a governance structure providing fund managers with a high degree of flexibility to accept and spend central bank liquidity.

Taken together, we can characterise the pension fund problem across five equations:

$$
\begin{aligned}
&\max_{V_{i,t}^{LDI},\tilde{V}_{i,t},B_{i,t}^{PF}} E_t\left[\mathcal{V}_{i,t+1}\right] - \frac{\gamma}{2}\left(\ell_t VLDI_{i,t} - \chi B_{i,t}^{PL}\right)^2 / B_{i,t}^{PL} \\
&\quad \text{s.t.} B_{i,t}^{PF} \geq \mathcal{M}_{i,t} \\
&\quad \mathcal{V}_{i,t} = r_{i,t}^{LDI} V_{i,t-1}^{LDI} + r_t^M V_{i,t-1}^{PF} + r_t B_{i,t-1}^{PF} - r_t^L B_{i,t-1}^{PL} - Q_{t-1}^{Rep} X_{i,t-1}^{CB} && \text{(Asset return)} \\
&\quad \mathcal{V}_{i,t} = V_{i,t}^{LDI} + V_{i,t}^{PF} + B_{i,t}^{PF} + \Psi_{i,t}^{PF} - B_{i,t}^{PL} - X_{it}^{CB} && \text{(Balance Sheet)} \\
&\quad B_{i,t}^{PL} = Q_{i,t}^{L} \times \bar{B}^P && \text{(Defined-benefit pensions)} \\
&\quad \Psi_{i,t}^{PF} \equiv \frac{\omega_P}{2}\left(V_{i,t}^{PF} - \tilde{V}_{i,t-1}\right)^2 / B_{i,t}^{PL} && \text{(Portfolio adjustment costs)}
\end{aligned}
$$

Transaction costs are a function of both *planned assets* $\tilde{V}_{t-1}$ and *actual assets* V_t^{PF}. The key here is to introduce a lag in the pension fund planning process. Each period t, they decide in advance on target asset holdings for next period $\tilde{V}_t$. These purchases are then executed in the subsequent period as V_t^{PF}. In the absence of uncertainty, the pension fund will always choose $\tilde{V}_t = V_{t+1}^{PF}$ and incur zero costs. In a world of uncertainty however, the pension fund may wish to deviate from the planned level in response to shocks and buy more or less than it originally intended. However, doing so will impose increasing marginal costs. In our application, this has the property that pension funds can readily recapitalise LDIs in the medium term, but doing so immediately is prohibitively expensive. Marginal transaction costs are controlled by the parameter ω_P, and are scaled by pension liabilities $B^{PL}_{i,t}$ to keep costs relevant at all portfolio sizes. Throughout the paper, we set ω_P to be arbitrarily large ($\omega_P = 500$) to effectively prevent deviations from the plan ($V^{PF}_{i,t} \approx \tilde{V}_{i,t-1}$).

We motivate the objective function by arguing that the pension fund is set a hedging target χ by pension scheme members or the pensions regulator; whereby a fraction χ of total liabilities should be backed by government bonds (held indirectly via the LDI). This is designed as an abstract representation of risk-management by the pension fund, and specifically management of the interest-rate risk associated with long-term liabilities. γ can be thought of as a 'risk aversion' parameter capturing the strength of the pension funds hedging motive.

Solving the pension fund problem yields the following first-order conditions for equity and planned equity:

$$E_t \left[r^M_{t+1} - \left[1 + \omega_P \left(V^{PF}_{i,t} - \tilde{V}_{i,t-1} \right) / B^{PL}_{i,t} \right] r^{LDI}_{t+1} \right] = \gamma \left(\chi B^{PL}_{i,t} - \ell_t VLDI_{i,t} \right) / B^{PL}_{i,t}$$

$$\tilde{V}_{i,t} = E_t \left[\left(V^{PF}_{i,t+1} \right) \right]$$

These first order conditions provide an arbitrage condition between LDI shares and growth assets. The key property is that the pension fund will accept a spread between LDI returns and equity returns if this facilitates risk management. As γ approaches zero the pension fund cares more about expected returns and spreads shrink; with high γ the fund is willing to accept almost any spread and prioritises hedging.

We also obtain a first-order condition with respect to money as well as the shadow value of the liquidity constraint $\lambda^{\mathcal{M}}_{i,t}$:

$$E_t \left[r_{t+1} - r^{LDI}_{t+1} \right] = \gamma \left(\chi B^{PL}_{i,t} - \ell_t VLDI_{i,t} \right) / B^{PL}_{i,t} - \lambda^{\mathcal{M}}_{i,t}$$

$$\lambda^{\mathcal{M}}_{i,t} = 0 \quad \vee \quad B^{PF}_{i,t} = \mathcal{M}_{i,t}$$

In steady state, the liquidity constraint will bind and pension funds hold the minimum liquidity permitted under regulation ($B^{PF}_{i,t} = \mathcal{M}_{i,t}$). The constraint multiplier $\lambda^{\mathcal{M}}_{i,t}$ adjusts to clear the spread between short-term bonds and LDI shares, i.e. the pension fund would like to hold less liquidity and more LDI shares (and equities) but cannot due to the liquidity constraint. Throughout most of our results, the threshold $\mathcal{M}_{i,t} = 0$ at all times. In this context, the liquidity constraint can be interpreted as a no-borrowing constraint, i.e. the pension fund is not permitted to borrow liquid assets in order to buy LDI shares or equities. However, if bond prices rise sharply and the expected return on LDI funds falls, the pension fund can choose to hold excess cash and the constraint is slack ($\lambda^{\mathcal{M}}_{i,t} = 0$). The key reason we introduce this mechanism is to prevent an unrealistic 'positive feedback loop' on bond prices. Since pension funds are unable to quickly adjust equity holdings, any unanticipated profits must be kept as either cash or LDI shares. If we assumed $B^{PF}_{i,t} = \mathcal{M}_{i,t}$ at all times and did not allow for the occasionally binding constraint, pension funds would be forced to invest all unanticipated returns into LDI funds and drive up bond prices long past the point where they are a financially sensible investment. The occasionally binding constraint allows them the option of increasing exposure to LDIs and index-linked bonds without forcing them to do so.

2.5.1 Aggregation

As in Gertler and Karadi (2011), we aggregate pension funds symmetrically. Each period a fraction $1 - \varsigma$ of pension funds are liquidated, and an equal number of new funds are born with starting capital v. We assume that the equity plans of the old funds are inherited by their replacements, i.e. $\tilde{V}_{i,t}/V_t$ is the same across all funds. This means that the equations governing the aggregate behaviour of pension funds follows:

$$\mathcal{V}_t = \varsigma \left(r_t^{LDI} V_{t-1}^{LDI} + r_t^M V_{t-1}^{PF} - r_t^L B_{t-1}^{PL} - Q_{t-1}^{Rep} X_{t-1}^{CB} \right) + (1-\varsigma)\, v \tag{21}$$

$$\mathcal{V}_t - \Psi_t^{PF} = V_t^{LDI} + V_t^{PF} - B_t^{PL} - X_t^{CB} \tag{22}$$

$$\gamma \left(\chi - \ell_t VLDI_t / B_t^{PL} \right) = E_t \left[r_{t+1}^M - \left[1 + \omega_P \left(V_t^{PF} - \tilde{V}_{t-1} \right) / B_{i,t}^{PL} \right] r_{t+1}^{LDI} \right] \tag{23}$$

$$\tilde{V}_t = E_t \left[V_{t+1}^{PF} \right] \tag{24}$$

$$D_t^{LDI} = (1-\varsigma) \left(r_t^{LDI} V_{t-1}^{LDI} + r_t^M V_{t-1}^{PF} - r_t^L B_{t-1}^{PL} - v - \Psi_t^{PF} - Q_{t-1}^{Rep} X_{t-1}^{CB} \right) \tag{25}$$

$$\Psi_t^{PF} \equiv \frac{\omega_P}{2} B_{i,t}^{PL} \left(V_t^{PF} - \tilde{V}_{t-1} \right)^2 \tag{26}$$

$$B_t^{PL} = Q_t^L \times \bar{B}^P \tag{27}$$

$$E_t \left[r_{t+1} - r_{t+1}^{LDI} \right] = \gamma \left(\chi B_{i,t}^{PL} - \ell_t VLDI_{i,t} \right) / B_{i,t}^{PL} - \lambda_t^{\mathcal{M}} \tag{28}$$

$$\lambda_t^{\mathcal{M}} = 0 \quad \vee \quad B_t^{PF} = \mathcal{M}_t \tag{29}$$

Note that just as in Gertler and Karadi (2011), new pension funds are capitalised with valuation v. Diverging from Gertler and Karadi (2011) however, we calibrate $v < 0$ to give pension funds a negative valuation. This is consistent with the evidence in Pinter (2023) and many others that the majority of defined-benefit pension funds are underfunded, and the overwhelming majority of those engaged in LDI. This does not strongly affect market dynamics, but implies that pension funds hold fewer assets and hence are a somewhat smaller actor in asset markets than they would be otherwise.

2.6 Liability Driven Investment

The liability driven investment firm has a stylised balance sheet. It takes on a single asset class, index-linked government bonds; we denote LDI holdings of these bonds as B_t^{LDI}. This is financed using a combination of net worth V_t^{LDI} and asset-repurchase (repo) loans from an FI counterparty denoted X_t. In practice, LDIs are likely to use a combination of repo agreements and other hedging instruments such as interest-rate swaps. However, Pinter (2023) finds that exposure to repo was the dominant factor driving bond sales during the crisis we are interested in; a regression analysis found that the swap exposure of an LDI had no significant effect on its bond sales once repo exposure was controlled for. We thus focus on repo as the key financial instrument driving crisis dynamics.

Defining the net dividend to the pension fund as ϖ_t^L, we characterise the balance sheet across three equations:

$$V_t^{LDI} = B_t^{LDI} - X_t \tag{30}$$

$$V_t^{LDI} = r_t^L B_{t-1}^{LDI} - Q_{t-1}^{Rep} X_{t-1} - \varpi_t^L \tag{31}$$

$$\ell_t \equiv \frac{V_t^{LDI} + X_t}{V_t^{LDI}} \tag{32}$$

Note that the net dividend ϖ_t^L is set implicitly by the pension fund as it maximises over V_t^{LDI}. The last equation defines the leverage ratio of assets to liabilities. We can use this to rewrite the asset returns equation and define r_t^{LDI}:

$$r_t^{LDI} = \ell_{t-1} r_t^L - Q_{t-1}^{Rep} \left(\ell_{t-1} - 1\right) \tag{33}$$

Since Q_{t-1}^{Rep} and ℓ_{t-1} are predetermined, this makes it clear that the return r_{t+1}^{LDI} is exactly ℓ_t times as volatile as r_{t+1}^L. Similarly, it is trivially the case that $\text{cov}\left(r_{t+1}^A, r_{t+1}^{LDI}\right) = \ell_t \text{cov}\left(r_{t+1}^A, r_{t+1}^L\right)$ for all asset types A.

Rather than optimising the leverage ratio to satisfy an objection function, we assert that LDIs are required to maintain a constant leverage ratio under the terms of their agreement with the pension fund. This is based on the stylised fact that each LDI pool has leverage targets and limits. The specific implementation of these targets and limits varies across funds, but a typical fund might have a target leverage ratio of 2-4 and an upper limit of 7-10. For example, the BMO LDI pool used by the Volkswagen defined-benefit pension scheme has a target leverage of 'c. 2.5x to 3.5x' and a 'stop-loss trigger' of 'c. 7.5x' (Volkswagen Group Pension Scheme, 2020). During normal times, LDI fund managers can absorb a small rise in the leverage ratio so long as it remains below the upper limit, and adjust gradually back to the target rate via asset sales or an equity injection from participating pension funds. However, when LDI leverage breaches the upper limit, they are obliged to take immediate action to shrink the balance sheet with the aim of either returning leverage to target or preparing for insolvency. In the case of the Volkswagen policy, the LDI pool is contractually obligated to reduce leverage to below that ratio within one business day (Volkswagen Group Pension Scheme, 2020).

For our purposes, the assumption that the LDI must maintain a constant leverage ratio amounts to an assumption that *by the end of the period* (quarter) they must have reduced their leverage, although they may potentially be deviating from target within that period.

Specifically, we impose:

$$\ell_t = \ell \tag{34}$$

This means that if V_t^{LDI} falls due to a decline in asset prices, the LDI is obliged to reduce X_t by $(\ell - 1)$ units for each unit of value lost. This must be funded by selling $(\ell - 1)$ units of B_t^{LDI}. This creates the fire sales dynamic that drives our results: a fall in Q_t^L reduces V_t^{LDI}, which forces the LDI to reduce X_t and B_t^{LDI}, which puts further pressure on Q_t^L in a self-reinforcing spiral. Subsection 3.2 explores the components driving the fire sales.

2.7 Central bank

We assume the central bank sets the short-term nominal interest rate i_{t+1} as a function of inflation π_t and net output $\tilde{y}_t$ according to a standard Taylor rule. This leads to the simple equation:

$$\log(i_{t+1}) = \rho_r \log(i_t) + (1 - \rho_r)\left[\log(\bar{i}) + \varrho_y \log(y_t/\bar{y}) + \varrho_\pi \log(\pi_t/\bar{\pi})\right] \tag{35}$$

$$\tilde{y}_t \equiv c_t + \hat{I}_t \tag{36}$$

Where ρ_r captures interest rate smoothing, $\bar{\pi}$ is the target rate of inflation, $\bar{i}$ ($\bar{y}$) is steady-state nominal interest on money (output) and ϱ_y (ϱ_π) is the weight placed on output (inflation) in the central bank reaction function. Net investment $\hat{I}_t$ is defined in appendix B. Our timing convention implies that the nominal rate of return on money is predetermined each period, in contrast to the time-varying period returns on bonds.

The central bank is also capable of conducting financial stability interventions. We model two types of intervention, asset purchases of linked (nominal) bonds B_t^{CBL} (B_t^{CB10}) and repo loans X_t^{CB}. Repo loans X_t^{CB} have already been discussed in section 2.5; the idea is to provide liquidity to *pension funds* which they can then inject as equity into the LDI sector. Asset purchases can be conducted for either monetary policy (MP) or financial stability. We assume for simplicity that interventions are always a surprise and follow autoregressive processes with persistence ρ_{FS} and ρ_X for asset and repo interventions respectively:

$$B_t^{CB10} = \rho_{FS} B_{t-1}^{CB10} + \epsilon_t^{CB10} \tag{37}$$
$$B_t^{CBL} = \rho_{FS} B_{t-1}^{CBL} + \epsilon_t^{CBL} \tag{38}$$
$$X_t^{CB} = \rho_X X_{t-1}^{CB} + \epsilon_t^{CBL} \tag{39}$$

Asset purchases in our model are structured somewhat differently to the actual intervention conducted by the Bank in September-October 2022, which instead operated as a 'backstop pricing' model setting a floor on bond prices and committing to purchase bonds at this price[10]. This would be more properly modelled as an occasionally binding constraint, with the Bank committing to a policy rule of the form:

$$\begin{array}{ll} \text{if } Q_t^L \geq \bar{Q} & B_t^{CBL} = 0 \\ \text{else} & Q_t^L = \bar{Q} \end{array}$$

In our application with a transient shock, using backstop pricing gives identical results while introducing unnecessary computational complexity. In other applications the two can meaningfully diverge. With a persistent shock or an extended period of volatility, backstop pricing becomes more effective because agents anticipate that the Bank will stabilise future prices as well as contemporaneous ones. This reduces uncertainty about future asset prices and hence increases their value in the present, which in turn means the Bank can maintain the backstop with fewer asset purchases. In our context, asset prices stabilise rapidly once the shock vanishes and so there is no practical difference between asset purchases and backstop pricing.

The key difference between asset purchases conducted for financial stability (FS) and monetary policy (MP) purposes is the duration bonds are held for. When ρ_{FS} is close to one, bond purchases suppress bond returns persistently and hence transmit to the real economy through consumption and investment behaviour. When ρ_{FS} is close to zero, bond returns are only temporarily suppressed and the response by households and firms is consequently weaker. However, what should be clear from this is that the distinction is not absolute - in our setup, FS operations will have monetary consequences and MP operations will have financial ones. The extent to which there will be entanglement between FS and MP will depend both on the choice of ρ_{FS} and the context in which operations are conducted. In section 6.2, we consider

[10] A limit of £5 billion of purchases each day was set, but never reached.

counterfactual scenarios across a range of ρ_{FS}.

The central bank pays for asset purchases by issuing money. We denote by B_t^{CB} central bank net holdings of money. The central bank maintains a net worth of zero by returning any (net) profits CBS_t to the treasury; in steady state these are zero. We hence write the following equations to characterise the central bank balance sheet and asset returns:

$$0 = B_t^{CB} + B_t^{CB10} + B_t^{CBL} + X_t^{CB} \tag{40}$$

$$CBS_t = r_t B_{t-1}^{CB} + r_t^{10} B_{t-1}^{CB10} + r_t^L B_{t-1}^{CBL} + Q_{t-1}^{Rep} X_{t-1}^{CB} \tag{41}$$

We also introduce at this stage a rule for macroprudential policy. We assume the central bank sets the liquidity buffer to be a fraction of LDI liabilities m according to the process:

$$\mathcal{M}_t = \left(1 - \epsilon_t^{\mathcal{M}}\right) m B_t^{LDI} \tag{42}$$

With m controlling the steady-state liquidity ratio and $\epsilon_t^{\mathcal{M}}$ a shock with expected value $E_t\left[\epsilon_{t+1}^{\mathcal{M}}\right] = 0$. By setting $\epsilon_t^{\mathcal{M}} > 0$ during a crisis period, we can implement a reduced liquidity buffer and allow the pension fund to inject liquidity into the LDI. Note that since we assume zero money adjustment costs, applying the liquidity buffer directly to the LDI would yield equivalent results.

2.8 Treasury

The treasury applies a lump sum tax T_t to fund and interest payments on a stock of debt. It acts to maintain a constant debt/GDP ratio of $\bar{b}$ and a constant ratio ϑ of short- to long-term bonds. The budget identity is standard. Letting B_t denote money liabilities, B_t^{10} nominal long bonds, and B_t^L linked long bonds, we have:

$$B_t + B_t^{10} + B_t^L + T_t = s y_t + r_t B_{t-1} + r_t^{10} B_{t-1}^{10} + r_t^L B_{t-1}^L \tag{43}$$

$$B_t + B_t^{10} + B_t^L = \bar{b} y \tag{44}$$

$$B_t = \vartheta \left(B_t + B_t^{10} + B_t^L\right) \tag{45}$$

$$B_t^L = \vartheta_L \left(B_t + B_t^{10} + B_t^L\right) \tag{46}$$

2.9 Clearing

Bond market clearing implies the following relationships:

$$B_t = B_t^H + B_t^{CB} + B_t^{PF} \tag{47}$$

$$B_t^{10} = B_t^{H10} + B_t^{CB10} \tag{48}$$

$$B_t^{HL} = B_t^L + B_t^{PL} \tag{49}$$

Equities are held by households and pension funds, and hence clearing requires:

$$V_t = V_t^H + V_t^{PF} \tag{50}$$

2.10 Firms and unions

There are four types of firms interacting in the model: i) a capital goods producer that creates physical capital $\hat{I}$; ii) a representative wholesale firm that transforms capital and labour into wholesale output; iii) wholesale output is purchased and repackaged by a continuum of retail firms that sell (retail) output to a final good firm; iv) the final goods firm creates a final good combining retail outputs. All firms are owned by a stock broker with value V_t, which pays net profits ϖ_t each period to households and pension funds proportionally to their owning share. This is analytically convenient as it simplifies the household portfolio and pension fund problems; they choose their exposure to a single variable V_t capturing the entire equity market rather than optimising over each type of firm.

There are also two actors in the labour market: i) trade unions which buys household labour and sells heterogeneous labour output and ii) a competitive labour packager which buys unions out and sells packaged labour to the wholesale firms. Union profits are returned directly to households; labour packagers make zero profits in equilibrium.

The firm and union models are adapted from that in Sims and Wu (2021), with the difference that we use nominal price frictions based on Rotemberg (1982) rather than Calvo (1983). The using of Rotemburg pricing is analytically and computationally convenient as it yields an explicit expression for firm profits without requiring the definition of extensive auxiliary variables as with Calvo pricing. The two models are identical up to first order, and at higher order Rotemburg pricing is better supported by the data (Richter and Throckmorton, 2016). Full details of the firm and union setup can be found in appendix B.

3 Discussion

This section explains the mechanisms driving three key effects: the crisis, the fire sales and the central bank's asset purchases.

3.1 From the 'portfolio shock' to the crisis

We simulate the 2022 UK gilt crisis using an exogenous 'portfolio shock' ϵ_t^{ζ}, which we interpret as a reduced convenience yield on long-dated UK government bonds (capturing the same effects as an increase in default risk). In other words, the 'portfolio shock' makes long-term bonds relatively less attractive for households and exogenously pushes up yields on these bonds. The presence of leverage-constrained LDIs amplifies the shock. The initial fall in bond prices causes losses for LDIs, increasing their leverage. However, LDIs are required to keep a constant leverage ratio under the terms of their agreement with the pension fund. By the end of the period they must reduce their leverage ratio back to their target, which can be achieved either by issuing new equity or by selling assets. However, due to a combination of transaction costs and slow governance arrangements, the pension fund is extremely reluctant to inject additional equity into the LDI at short notice. The LDI must therefore reduce leverage by selling gilts, but this liquidation pushes down prices even further. This additional price drop causes further losses and higher leverage for the LDI sector as a whole, generating further cycles of asset sales and price drops. The initial shock is therefore amplified by these fire sales, explained in more details in the subsection below. These dynamics center on the market for index-linked government bonds, with high market segmentation ensuring relatively low pass-through to non-financial firms and the real economy.

3.2 Components driving the fire sales

Subesection 2.6 showed that a fall in bond price Q_t^L reduces LDI net worth V_t^{LDI}, which (due to the leverage constraint) forces the LDI to reduce repo loans X_t and bond holdings B_t^{LDI}, which puts further pressure on Q_t^L in a self-reinforcing spiral. Although we do not solve the model analytically to derive an explicit expression for how bond price Q_t^L responds to shocks as a function of parameters, it is helpful to consider the 'feedback loop' following a stylised shock to asset values. Suppose that the bond price Q_t^L falls unexpectedly by $d\epsilon_t^Q$ due to an exogenous shock. We can crudely characterise the strength of this loop as a product of derivatives:

$$\frac{dQ_t^L}{d\epsilon_t^Q} = 1 + \frac{\partial V_t^{LDI}}{\partial Q_t^L} \frac{\partial X_t}{\partial V_t^{LDI}} \frac{\partial Q_t^L}{\partial B_t^{LDI}} \frac{dQ_t^L}{d\epsilon_t^Q}$$

Which, rearranged, yields:

$$\frac{dQ_t^L}{d\epsilon_t^Q} = 1/\left(1 - \mathcal{D}_t\right) \tag{51}$$

$$\mathcal{D}_t \equiv \frac{\partial V_t^{LDI}}{\partial Q_t^L} \frac{\partial X_t}{\partial V_t^{LDI}} \frac{\partial Q_t^L}{\partial B_t^{LDI}} \tag{52}$$

Where we have defined the 'feedback ratio' $\mathcal{D}_t$ which captures the additional pressure on Q_t^L generated by the LDI. This has three components:

(a) How much does V_t^{LDI} respond to a fall in asset values?

(b) How much do X_t and B_t^{LDI} need to be reduced following a fall in V_t^{LDI}?

(c) How much further do prices fall as a result of these asset sales?

The first of these is straightforwardly $\partial V_t^{LDI} / \partial Q_t^L = k_2 B_{t-1}^{LDI}$[11]; losses are the change in bond price multiplied by the bonds held at the start of the period. Similarly, the second term is simply $\partial X_t / \partial V_t^{LDI} = (\ell - 1)$ with a larger leverage ratio implying that a larger reduction in the balance sheet will be necessary to restore balance. The third term is more complex, and depends on household capacity to arbitrage between different assets. If households faced no adjustment costs or convenience concerns, then they are perfect arbitrageurs and the LDI balance sheet reduction would only a limited effect on prices; $\partial Q_t^L / \partial B_t^{LDI} \approx 0$. If households do face adjustment or convenience costs to buying linked bonds, then $\partial Q_t^L / \partial B_t^{LDI} > 0$ and bond sales put further pressure on prices. Taken together, we can write:

$$\mathcal{D}_t = B_{t-1}^{LDI} \left(\ell - 1\right) \frac{\partial Q_t^L}{\partial B_t^{LDI}} \tag{53}$$

While stylised, equation (53) clearly communicates that the fire sales are the product of three factors: *LDI size*, *LDI leverage*, and *financial frictions*. If any of these elements is small or zero,

[11] Assuming no change in the net dividend ω_t^{LDI}; this holds so long as ω_3 is arbitrarily large and the pension fund does not adjust.

then $\mathcal{D}_t = 0$ and there is no gilt market dysfunction beyond the original shock to asset prices. Conversely, as $\mathcal{D}_t$ approaches 1 asset prices become increasingly unstable; if $\mathcal{D}_t \geq 1$ then the market is entirely unstable and prices collapse in response to the slightest shock. In reality there are restraints on the feedback spiral not captured by our simple framework. One such mechanism is limited liability; LDI valuation is constrained at zero and hence the relationship $\partial V_t^{LDI}/\partial Q_t^L = B_{t-1}^{LDI}$ eventually breaks down. Similarly, the price effect $\partial Q_t^L/\partial B_t^{LDI}$ will not be constant and second-order effects will ensure that real-world prices eventually stabilise.

3.3 Asset purchases' transmission mechanism

The asset purchases by the central bank operate through households' preferences and costs. These are modelled as 'portfolio balance' stock effects and 'adjustment cost' flow (liquidity) effects, as described in subsection 2.2. When LDIs are forced to sell gilts (because of their binding leverage constraint), households must buy them very quickly, typically in the space of a few weeks. However, this imposes high marginal adjustment costs on households, pushing down gilt prices, causing further losses for LDIs and triggering other rounds of sales. These fire sales can be mitigated by central bank asset purchases: by buying gilts and creating anticipation of future purchases, the central bank ensures fewer or no adjustment costs at all for households and hence little or no impact on gilt prices. Note that 'portfolio balance' stock effects are small if the asset purchases are temporary, but they become important if the central bank intervention persists, changing savings and investment behaviour by agents (subsection 6.2). Finally, the significant inertia we assume in the model plays a role in the transmission mechanism of asset purchases and their monetary policy spillovers: households and firms only gradually increase spending with the result that there is a meaningful lag between policy implementation and real economic effects. Appendix A.6 and A.7 remove households' habit persistance and reduce firms' investment costs, respectively: the results demonstrate that our qualitative conclusions hold even when we reduce inertia in the model.

4 Parameters and calibration

Most of our parameter values are standard and taken directly from the literature; we discuss only those which are novel, unusual or calibrated.

On 30/06/2022, shortly before the crisis, linked bonds were 30.4% of outstanding UK government debt by market value (UK Debt Management Office, 2023). This gives us $\vartheta_L = 0.304$. Deriving the share of nominal bonds and money is more complex. On a naive estimate, nominal bonds form 68.0% of UK government debt by market value on the same date (UK Debt Management Office, 2023), with short bonds (money) only 1.6%. However, this misses the fact that a huge quantity of nominal bonds are owned by the Bank of England, which in turn has issued a huge quantity of money to the private sector. It follows that if we consider the consolidated balance sheet of the Treasury and Bank together[12], the share of nominal bonds will be lower and the share of money higher.

Accounting for this can be done in two ways. One strategy is to subtract nominal bonds held by the Bank from the total nominal bonds issued by the Treasury and hence infer money as residual debt. The alternative is to use the outstanding cash and reserve liabilities of the Bank to obtain the quantity of money, and hence infer nominal bonds as the residual. In practice, the Bank has more reserve liabilities than it has nominal bonds because it holds other assets[13]; the two methods consequently produce slightly different results. Using the former strategy, we find that the Bank held 35.7% of government bonds (on 30/06/2022, UK Debt Management Office 2023). This implies that nominal bonds are 34.7% of net liabilities and money is 39.1%. The latter, based on Bank of England (2023a), instead gives shares of 25.7% and 48.1% respectively. We use the former numbers throughout and set $\vartheta = 0.391$, but our results are not sensitive to this.

On the household side, we set $\bar{\zeta} = \vartheta$ to give a term premium of zero (no excess return on bonds over money). This is consistent with the yield curve data for 30/06/2022 (Bank of England, 2023b), which shows that the 10-year rate is (almost) identical whether calculated via 10-year bonds or OIS rates; the existence of a positive (negative) term premium would imply that OIS rates should be below (above) the yield on a 10-year bond. We then calibrate ξ to be consistent with an equity premium of 1.82%. This is significantly lower than the empirical equity premium, which includes risk premia in addition to convenience yields. Investment-grade corporate bonds are fixed-return safe assets, and hence any remaining difference in yield compared with government bonds can be reasonably be ascribed to convenience effects (Vissing-Jørgensen, 2023). The value of 1.82%[14] is based on the mean difference over January 2022[15] and June 2023 between the 10-year OIS rate and the average return on a 10-year investment-grade corporate bond (taken from S&P Dow Jones Indices,

[12] We could instead extend our model to allow a non-zero steady state balance sheet for the central bank. This introduces additional complexity without any impact on results.

[13] These include foreign currency, direct loans to the private sector and outstanding indemnity payments owed from the Treasury(Bank of England, 2023a).

[14] This estimated convenience yield is substantially higher than the estimate of 0.66% Vissing-Jørgensen (2023) obtains in the US using a similar methodology; this is likely attributable to a smaller and hence less liquid market for UK corporate bonds.

[15] The Bank of England began publishing 10-year OIS information in 2022.

2023). This gap fluctuated between 1.06% and 2.32% across the time period, in appendix A.3 we replicate our main results using these alternative values. Given this equity premium, we set β such that the real return on money is 1% (annualised). This is approximately consistent with the advanced-economy estimates for R^* in Holston, Laubach, and Williams (2017) and Federal Reserve Bank of New York (2023), and implies $\beta = 0.993$. Our results are not sensitive to alternative choices for β. The labour weight ϕ is calibrated to give $n = 0.5$ in steady state.

For the financial frictions, we calibrate κ_α such that when the central bank buys nominal bonds worth 1% of annual GDP, it has a peak impact on GDP of 0.24% (Fabo et al., 2021). The resulting value of $\kappa_\alpha = 0.12$ is very close to the value of $\kappa_\alpha = 0.1$ chosen by Kabaca et al. (2023), and is based on the assumption of zero adjustment costs ($\omega_1 = 0$) and a strong degree of persistence for QE ($\rho_{QE} = 0.99$). We then choose a value $\kappa_L = 0.9$ for linked bonds, implying a high degree of substitutability between linked and unlinked bonds. This is based on the experience of QE in the UK, with purchases of nominal bonds transmitting strongly to yields on linked bonds. Section A.4 explores a lower value $\kappa_L = \kappa_\alpha$ and finds that this does not substantially impact our results. Ξ is calibrated to clear $\Xi = \xi\alpha$ in steady state. The adjustment cost on linkers ω_2 is calibrated to match the LDI shock dynamics; this process is discussed in detail in section 5. We set the remaining adjustment costs at $\omega_1 = \omega_3 = 0$ throughout our main results, this is best interpreted as an assumption that these are locally zero across the range of scenarios we explore and our results are not sensitive to alternative choices.

For the pension fund and LDI parameters, we set $\ell = 4$ based on the evidence of Pinter (2023) and SMMD data about the leverage of LDI funds in early September 2022. The Gertler-Karadi friction for pension funds is set at $\varsigma = 0.95$, this has no impact on our results and is simply present to prevent households directly recapitalising pension funds and hence indirectly LDIs. The pension fund hedging motive γ is calibrated such that $BLDI/BP = 0.85$, i.e. that pension fund liabilities are 85% backed by linked bonds. This is again approximately consistent with Pinter (2023) and SMMD data on the hedging ratio of affected pension funds shortly before the crisis. We calibrate $\bar{B}^P$ such that $BP = 0.1\bar{Y}$. This does not match the overall share of defined-benefit pensions in the economy, but approximately matches the share most affected by the LDI crisis based on the three most impacted LDIs holding assets worth 9% of GDP at the start of the crisis (Pinter, 2023; Breeden, 2022).

Table 1: Parameters

Parameter	Value	Description	Source
β	0.985	Time Discount Factor	Standard
h	0.5	Habit persistence	Standard
σ	1.587	Household CRRA	Estimates in Groom and Maddison (2019)
ψ	-0.400	Inverse Frisch Elasticity	Standard
ϕ	0.0861	Utility weight on labour	Calibrated s.t. $\bar{n} = 0.5$
κ_α	0.12	ELS Money and Long	See discussion
$\kappa_Ł$	0.100	ELS Linked and Nominal	As in Kabaca et al. (2023)
ξ	0.013	Marginal Value of Convenience	See discussion
Ξ	4.435	Fixed Convenience Costs	See discussion
$\bar{\zeta}$	0.333	Weight on Money	See discussion
$\hat{\zeta}$	0.156	Weight on Linkers	See discussion
ω_1	1.616	Household Adjustment Cost (Bond)	Calibrated
ω_2	1.616	Household Adjustment Cost (Bond)	Calibrated
ω_3	1.616	Household Adjustment Cost (Equity)	Calibrated
ω_P	500.0	Pension Fund Adjustment Cost	Assumed
k	0.975	Woodford Survival Rate	Corresponds to ten-year bond
ς	0.800	Pension Fund Survival Rate	Assumed, arbitrary
v	-0.0068	Pension Fund Startup Value	See discussion
γ	0.359	Pension Fund Hedging Motive	See discussion
$\bar{B}^P$	0.100	Pension Bond Quantity	See discussion
ℓ	4.000	LDI Leverage	See discussion
$\bar{\pi}$	1.005	Steady-State Inflation	Standard
ϱ_Y	0.500	Taylor Rule (Output)	Standard
ϱ_π	1.500	Taylor Rule (Inflation)	Standard
ρ_R	0.800	Taylor Rule (Persistence)	Standard
$\bar{B}$	3.200	Steady-State Debt/GDP	Consistent with 80% debt/GDP
ϑ	0.333	Steady-State Money/Debt	See discussion
ϑ_L	0.304	Steady-State Linkers/Debt	See discussion
θ	0.330	Capital Share of Income	Standard
δ_0	0.026	Capital Depreciation (u=1)	Standard
δ_1	0.002	Capital Depreciation (u′)	Calibrated to give $\bar{\delta} = \delta_0$
δ_2	0.010	Capital Depreciation (u″)	Standard
S′	2.500	Investment Adjustment Costs	Christiano, Eichenbaum, and Evans (2005)
η	11.00	ELS Retailers	Standard
η_w	11.00	ELS Unions	Standard
φ	114.7	Rotemburg (Prices)	Calibrated to Calvo=0.75
φ_w	114.7	Rotemburg (Wages)	Calibrated to Calvo=0.75
ρ_ζ	0.900	Persistence Yield Shock	Assumed
ρ_{FS}	0.500	Persistence Asset Purchases	Implied duration 6 months

5 Replication of a crisis

On September 23rd 2022, the UK Government announced to Parliament a new 'Growth Plan', also referred to as a 'Mini Budget'. This plan had many components, but a core principle was an acceptance that the UK national debt would rise sharply over the medium term to fund measures intended to increase economics growth. While there was no formal review of the impact on national debt by the Office for Budget Responsibility, the Treasury announced that an additional £72 billion (3.27% of GDP) of borrowing would be required over the last three months of 2022 alone.

The effect of this announcement was to sharply increase yields on UK gilts, and reduce market prices of UK government debt. Figure 3 shows the change in price for all UK gilts between the 20th of September and the 27th of September. We choose the 20th as our base date because some details of the 'Growth Plan' were reported in the press over the 21st and 22nd, making the 20th the cleanest choice of a 'pre-crisis' market. Results are not sensitive to the choice of an alternative base date. We choose the 27th as our comparison as this is when gilt prices reached their nadir; the Bank of England gilt market intervention was announced on the 28th.

Figure 3 shows that the price impact of the 'growth plan' was greatest for index-linked gilts and for longer-dated gilts; the longest-dated linkers lost more than half their value in the span of seven days. At every time-to-maturity beyond 4-5 years, the price impact was greater for linkers than nominal gilts. This could be explained through normal pricing mechanisms if inflation was expected to decline sharply, but if anything inflation expectations were increasing over this period. It is therefore clear that the sharp divergence between nominal bonds and linkers was a consequence of financial frictions, and in particular by LDI forced sale dynamics (Breeden, 2022; Pinter, 2023).

We simulate the crisis in our model using a yield shock ϵ_t^{ζ}, which we interpret as a reduced convenience yield on long-dated UK government bonds (or equivalently, a higher risk premium). This is modelled as a transient shock, but one which agents believe to be persistent. That is, agents anticipate the shock will persistent with $\rho_{\zeta} = 0.9$, but in reality ζ returns to steady state at $t+1$. In terms of implementation, the economy receives an unanticipated shock ϵ_t^{ζ}, followed by another unanticipated shock $\epsilon_{t+1}^{\zeta} = -\rho_{\zeta}\epsilon_t^{\zeta}$. This is designed to reflect the uncertainty surrounding the 'growth plan', agents uncertain as to whether the government will persist with the change in tax policy or instead reverse many of the measures; ultimately a change in government caused yields to return to previous levels. The choice of the shock persistence parameter $\rho_{\zeta} = 0.9$ is arbitrary but has little impact on results; our findings are

Figure 3: UK Gilt Prices after the 'Growth plan'

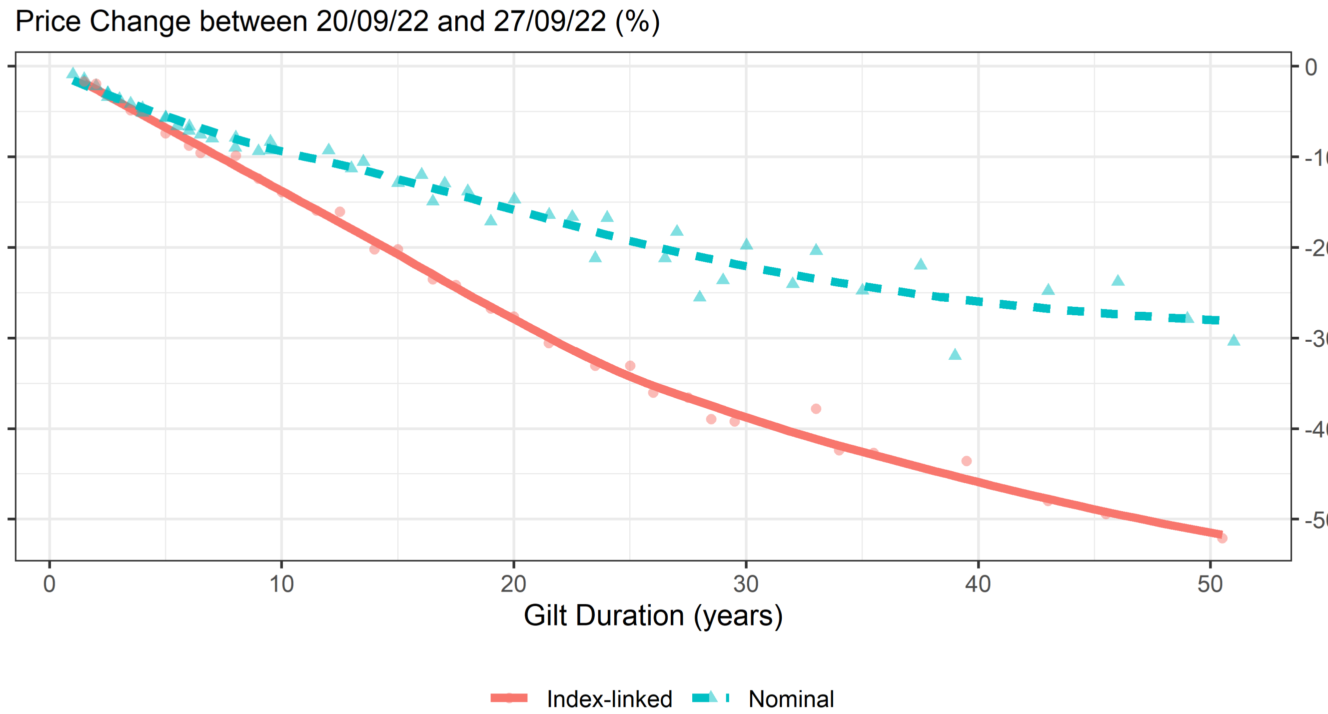


Figure 3 shows the change in price for all UK gilts between the 20th of September and the 27th of September 2022. Source: Bloomberg Finance L.P., Tradeweb and Bank calculations.

much the same for lower values $\rho_\zeta \in \{0, 0.5, 0.8\}$ but require a correspondingly higher value for ϵ_t^ζ.

Conditional on ρ_ζ, we calibrate ϵ_t^ζ such that the price of nominal bonds falls by 14.7%, matching the decline in price for twenty-year bonds. The choice to match the price decline 20/09-27/09 is not an innocent one, and could lead to either an over- or under-estimate of the eventual price impact. It could be a conservative estimate, because in the absence of intervention several LDIs would have been declared insolvent (Cunliffe, 2022b). This would have led to the remainder of their bond portfolios being seized and sold by creditors, depressing prices still further in the following weeks (Cunliffe, 2022b). On the other hand, it is possible that over the time horizon of a quarter, as in the model, more arbitrageurs would have intervened and stabilised the market such that prices recovered somewhat from the trough observed on 27/09. We use the observed decline in price as a compromise which keeps our results rooted in data. The results of the central bank intervention in section 6.1 further support this choice as it replicates the empirical intervention well without additional calibration.

We choose twenty-year bonds because longer-term nominal bonds which were themselves strongly affected by LDI dynamics (Breeden, 2022). This is because in reality LDIs held a mixture of very-long (30+ year) nominal bonds and linkers (Pinter, 2023), and the 'linked bonds' in our model are best interpreted as representing all types of gilt dominated by LDIs. We then calibrate the household adjustment cost parameter ω_2 such that the price of linked bonds falls by 27.6%, matching the decline in the twenty-year linked price[16]. ω_2 drives this effect because it controls household capacity to absorb linked bonds from the LDI sector. If ω_2 is small, households can readily buy the linked bonds the LDI wishes to sell and the impact on Q_t^L is minimal. If ω_2 is large, households demand a large discount to compensate them for the adjustment costs and hence LDI sales lead to a large impact on bond prices.

All simulations are carried out in Dynare 5.4 (Adjemian et al., 2022) using the Occbin package originally developed by Guerrieri and Iacoviello (2015). We use Occbin to capture the occasionally-binding liquidity constraint affecting the pension fund. This constraint is binding[17] in almost every period (pension funds keep the minimum required level of liquidity), but it relaxes when expected returns on linked bonds fall far below expected returns on money $\left(E_t\left[r_{t+1}^L\right] << E_t\left[r_t\right]\right)$; pension funds and LDIs are happy to acquire money rather than over-invest in low return linkers. This creates an asymmetry between yields shocks. LDI activity amplifies the impact of a positive yield shock (pension funds are unable to inject money to cover large LDI losses) but not a negative yield shock (pension funds are happy to save large LDI profits as money).

The use of Dynare and Occbin does imply some loss of accuracy, since this entails taking a first-order approximation of the model and solving this linearised version. The primary cost of this in our context is that we are unable to consider second- and third-order effects which may change quantitative results away from steady state. All results should thus be considered an approximation of the true impacts of fiancial stability interventions on asset prices and the economy. For example, asset purchases may have a somewhat larger effect when output is below steady state, and in this context our results may somewhat understate the impact of intervention. With that said, this distortion is unlikely to be large and is mitigated by careful calibration of the portfolio friction parameters.

Figure 4 shows the effect of this risk-premium shock on bonds prices in an economy both with and without liability driven investment. We model an economy without LDIs by setting

[16]In appendix A.5, we consider 30-year bonds as an alternative reference group with price declines of 19.8% (nominal) and 39.2% (linked).

[17]For technical reasons, Occbin requires constraints to be relaxed in steady state and during 'normal times'. We therefore implement the equivalent constraint $\lambda_{i,t}^{\mathcal{M}} \leq 0$. This always binds when the liquidity constraint would be relaxed and vice versa.

the size of the pension sector $BP = 0$ such that neither pension funds or LDIs have any effect on asset markets. This illustrates the fact that the shock is designed in such a way that in the absence of LDI activity, the prices of nominal bonds and linkers react almost identically and fall by approximately 14.7% as in the data. With a substantial LDI sector however, the model replicates the sharp additional decline in linker prices due to deleveraging by LDIs. This manifests as a single period of heavy disruption, with LDIs selling a large volume of gilts into a highly illiquid market and making huge losses.

Figure 4: Impact of a Risk Premium Shock on Bond Prices

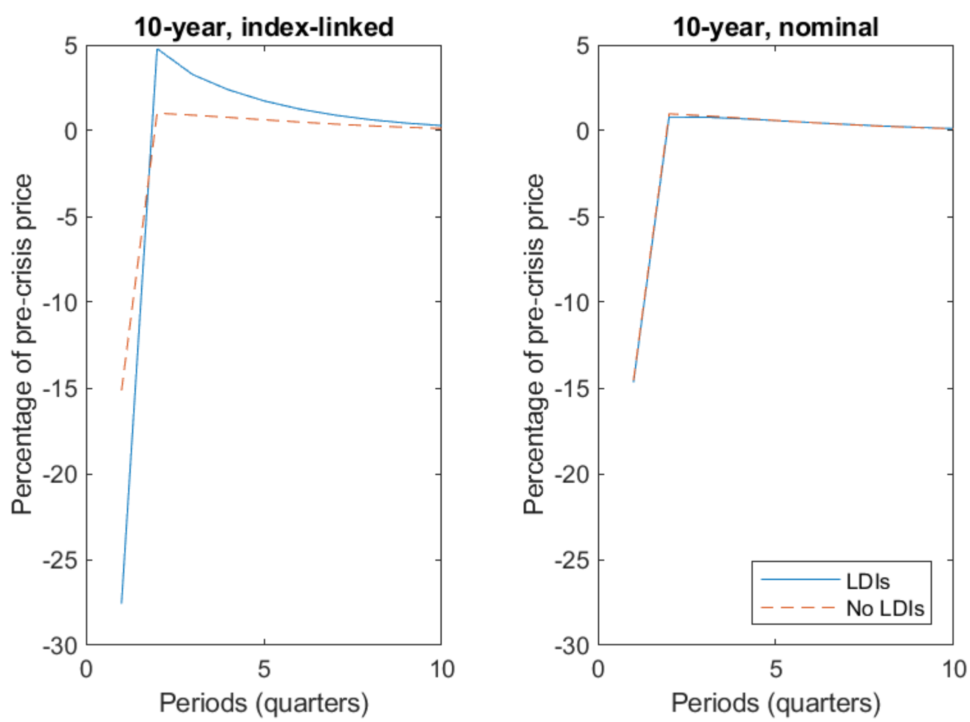


Figure 4 shows the effect of a risk-premium shock on bonds prices in an economy with (blue line) and without (red dashed line) LDIs.

However, in our setup the market recovers relatively quickly once the transient shock fades in period two. This arises because pension funds have two strong incentives to recapitalise LDIs as quickly as possible. Firstly, sharply lower V_t^{LDI} and B_t^{LDI} means that pension funds are no longer hedged against further yield shocks; they are completely exposed to any increase in gilt prices and wish to recapitalise LDIs to regain their hedge. Secondly, a sharp increase in bond yields gives pension funds a direct pecuniary incentive to invest in LDIs and increase their exposure to linked bonds and their high returns. In the first period, high adjustment costs ω_P prevent pension funds from marshalling their resources. In subsequent periods however, pension funds gradually recapitalise LDIs which in turn gradually reacquire linkers and increase B_t^{LDI}.

In our setup, there is a persistent overcorrection in linker prices driven by household adjustment costs. In period one, LDIs are obliged to sell a very large quantity of linked bonds to households. Adjustment costs ω_2 make it extremely expensive for households to rapidly acquire these linked bonds. LDIs must compensate them for these costs by selling the bonds at a steep discount, generating the sharp decline in prices in the model. However, having acquired these bonds households face equivalent adjustment costs for selling them back to the LDI. This means that not only do LDIs have to sell at a steep discount during the crisis period, they are obliged to buy at a premium over subsequent periods as they buy the linked bonds back and rebuild their portfolio. In crude terms, LDI and pension fund activity generates additional demand for linkers once the shock fades, pushing their prices up relative to nominal bonds without this additional demand. In reality, the effects may have been somewhat different. In particular, many LDIs might have been pushed into insolvency during the initial shock (Breeden, 2022). Pension funds would not have been able to recapitalise insolvent LDIs as quickly and easily as they do in our model. Consequently, although the (indirect) demand for linked bonds from pension funds would be just as strong, their ability to actually buy them would be severely limited if LDIs actually went insolvent, reducing the overcorrection.

6 Monetary Policy Implications of Financial Stability Interventions

6.1 Factual: Asset Purchases

On September 28th, the Bank of England announced an asset purchase programme ultimately worth £19.3 billion,[18] or roughly 0.9% of GDP (Breeden, 2022). This was targeted at specific segments of the gilt market experiencing the most distress, and in particular those inhabited primarily by LDIs (Cunliffe, 2022b). This was the first time the Bank had conducted a major purchase programme of index-linked assets, previously asset purchases for the purpose of monetary stability were composed of either nominal government bonds or high-grade corporate bonds (Cunliffe, 2022a). This was announced as a strictly time-limited intervention with 'minimum yield pricing', with the bank purchasing only high-yield (low price) gilts up to a threshold (Cunliffe, 2022a). As discussed in section 2.7, minimum pricing is identical to

[18]This compares with approximately £36 billion in gilt sales by LDIs over the same time horizon (Pinter, 2023), with the remainder absorbed by household and other financial firms.

direct asset purchases in our setup due to the transient nature of the shock.

We model this intervention as unanticipated purchases of linked gilts worth 0.9% of GDP ($\epsilon_t^{FSL} = 0.009\bar{Y}$), the eventual size of the program. In reality, this number was composed of long-dated nominal gilts as well as index-linked ones, we appeal again to our broad interpretation of 'index-linked' gilts in our model as capturing a wider array of niche assets for which LDIs were the dominant market actor. We set program persistence at $\rho_{FS} = 0.5$, implying that the central bank rapidly unwinds purchases over 3-6 months once the shock has passed to avoid lasting changes to its balance sheet and to minimise potential consequences for monetary policy. We return to ρ_{FS} in section 6.2 to examine the consequences of a more persistent intervention.

Figure 5: Financial Stability Intervention: Asset Purchases worth 0.9% of GDP

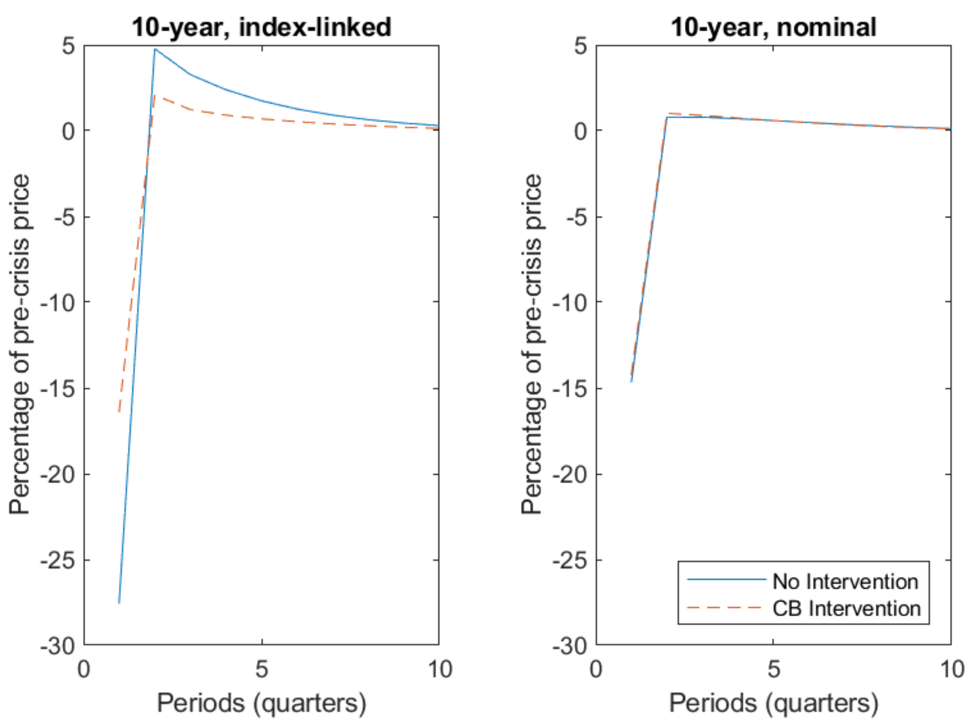


Figure 5 shows the effect of a risk-premium shock on bonds prices in an economy with (red dashed line) and without (blue line) asset purchases worth 0.9% of GDP (the eventual size of the Bank programme).

Figure 5 shows the effect of this intervention on the price of linkers and nominal bonds. The first thing to note is that the intervention is remarkably successful: the spread between linked and nominal bonds almost completely closes. This provides supporting evidence for our calibration and modelling choices, since it suggests that an intervention of equivalent size has a roughly equivalent effect on asset markets. We also find that the intervention only impacted the target market, with very little spillover into 10-year nominal gilts.

Figure 6: Financial Stability Intervention: Asset Purchases worth 0.9% of GDP

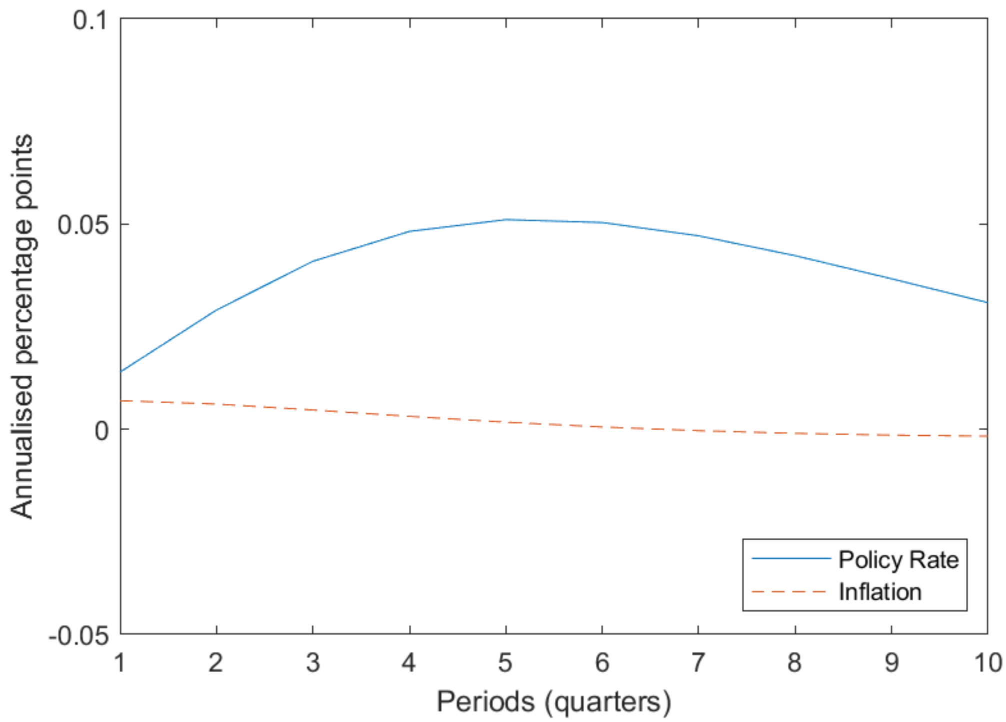


Figure 6 shows the impact of asset purchases worth 0.9% of GDP on the policy rate (blue line) and inflation (red dashed line). These are the monetary policy spillovers of the financial stability asset purchases.

Figure 6 shows the impact of these asset purchases on the policy rate of interest (which we interpret as monetary policy) and inflation. We find that the asset purchase intervention was well-designed and has minimal monetary consequences. This was one of the key design intentions of the policy response due to inflationary concerns at the time (Cunliffe, 2022b) and our results strongly support the idea that this design was effective. Despite large-scale asset purchases worth 0.9% of GDP, a small increase in the policy rate of 1–5 basis points is sufficient to accommodate the intervention and almost completely eliminate inflationary effects. As we shall see in section 6.2, the key determinant of monetary spillovers is the time-limited nature of the asset purchases. With assets acquired and held for only a short period, there is no persistent decline in bond yields and hence little change in saving and investment behaviour by households and firms.

6.2 Do asset purchases need to be temporary to avoid monetary policy spillovers?

Alongside the use of backstop pricing, asset purchases were designed to be 'temporary and targeted' to prevent monetary consequences (Cunliffe, 2022b). Our results in section 6.1 show that this was successful, and the intervention had no substantial implications for monetary policy. However, this leaves open the question of precisely how temporary and targeted the intervention needed to be to avoid spillovers. For operational reasons and in other contexts, it might be necessary or desirable for financial stability operations to be unwound more slowly.

6.2.1 Transparent, Time-Limited Interventions

We initially assume that the timing of the intervention is decided in advance, and transparently announced to the public who have full knowledge of the duration of asset purchases. This forms the basis of figure 7, which shows how the impacts of the asset purchases change depending on the announced (and implemented) unwind speed. We then consider an alternative in which public *beliefs* about the unwind speed vary, even as the actual speed of unwinding is held constant at 3-6 months.

Figure 7 shows the monetary spillovers of the asset purchase intervention conditional on ρ_{FS}. In each case, the intervention is calibrated such that $Q_1^L = Q_1^{10}$ i.e. the central bank only buys the assets necessary to close the gap between nominal gilts and linkers. We find that the central bank needs to purchase fewer assets if the intervention is more persistent. With a $\rho_{FS} = 0$, completely closing the price gap requires asset purchases worth 1.05% of GDP; with $\rho_{FS} = 0.99$ this falls to 0.88% of GDP. This is because more persistent interventions imply that linker prices will be higher for longer; agents anticipate this and hence there is a greater price effect in the present.

Despite the intervention being smaller, the monetary spillovers increase rapidly as the intervention becomes more persistent. While the inflationary effect is small in our model, this is only the case because the central bank is increasing the policy rate to offset the impact. With the most persistent interventions ($\rho_{FS} = 0.95$ and and $\rho_{FS} = 0.99$), we estimate that the policy rate would need to rise by 30-40 basis points for a prolonged period.

These results support the intuitive idea that financial stability interventions must be temporary as well as targeted if they are to avoid monetary spillovers. With that said, they also indicate that for the specific episode we are considering there was scope to slow unwinding somewhat. The monetary impacts are small and similar for $\rho_{FS} \in \{0, 0.5, 0.75\}$, which

Figure 7: Monetary Consequences of Transparent Time-Limited Interventions

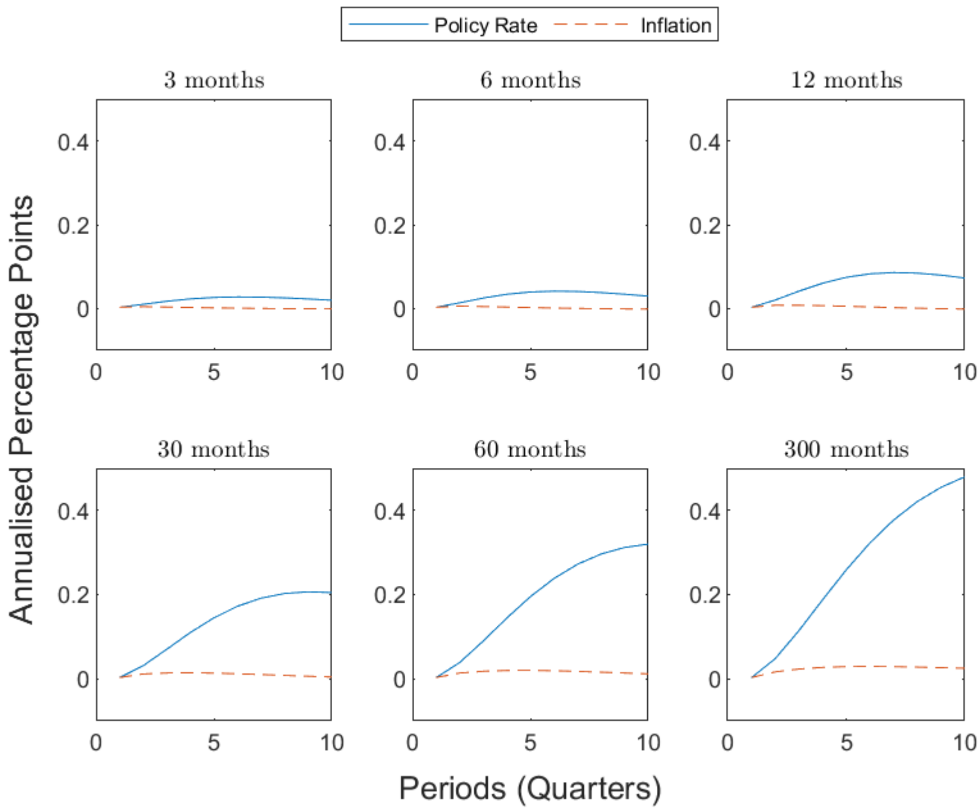


Figure 7 shows the impact on the policy rate (blue line) and inflation (red dashed line) of the asset purchases conditional on the persistence of the intervention. These are the monetary policy spillovers of financial stability asset purchases with different degrees of persistency.

correspond roughly with unwinding times of a quarter, six months and a year respectively. Monetary spillovers only begin to escalate rapidly from this point onwards. This suggests that asset purchases could reasonably be unwound over the course of six months to a year. It is also worth highlighting that in section 7.1 we found no such consequences for using the repo tool; this intervention could be deployed persistently without significant consequences. This is because use of the repo tool does not involve removing scarce assets from the market.

6.2.2 Uncertain, Time-Limited Interventions

Figure 8 instead shows the impact of public *beliefs* about the unwind speed. In each panel, the central bank unwinds the FS intervention at the same speed ($\rho_{FS} = 0$, or exactly three months). However, at the time of the intervention the public believes the intervention will be persistent

($\rho_{FS} \neq 0$). This is designed to capture a scenario in which the central bank is intending to conduct a time-limited intervention, but either this has not been effectively communicated to the public or the public does not believe the communication. This is implemented as a two-stage process. In period one, at the time of the intervention, we set ρ_{FS} in the same way as for figure 7. However, in period two we apply an unanticipated shock which sets $\rho_{FS} = 0$, and hence the intervention is entirely unwound.

Figure 8: Monetary Consequences of Uncertain Time-Limited Interventions

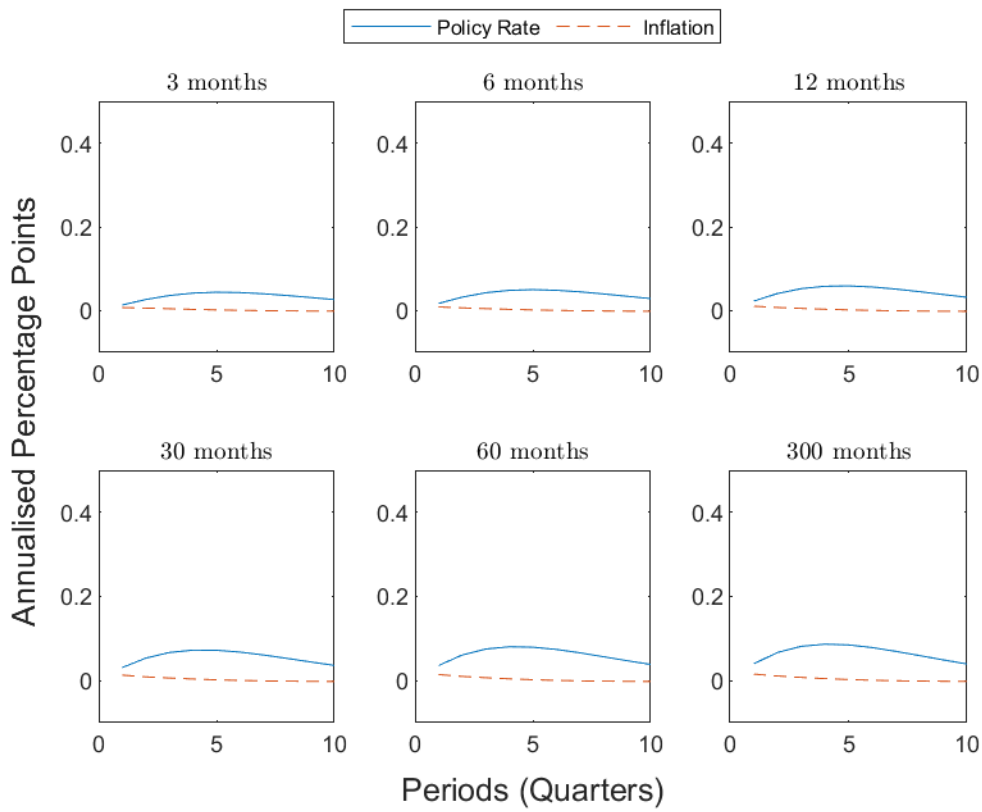


Figure 8 shows the impact on the policy rate (blue line) and inflation (red dashed line) of public beliefs about the asset purchases unwind speed.

The results sharply contrast with figure 7, and should be reassuring for central banks worrying about the communication challenge of differentiating between financial stability interventions and monetary policy ones. Comparing the extreme scenarios of $\rho_{FS} = 0$ (3 months) and $\rho_{FS} = 0.99$ (300 months), it is clear that public perceptions do matter: there are greater monetary spillovers when the public believes the intervention will have QE-like persistence compared with when they (correctly) believe it to be temporary. However, this differences are extremely small. If the high-persistence beliefs prevail, an interest rate rise of 8 basis points (at peak) is necessary to control inflation. If low persistence ones do, then a rise of 4 points is sufficient. This difference is trivial, particularly when compared to the more stark implications of a genuinely persistent intervention as in figure 7. The reason why high-persistence beliefs do not have large monetary policy spillover is because we assume significant inertia in households and firms' behaviour. Households have consumption 'habit persistence' and only gradually increase spending. Firms face investment 'adjustment costs', and only gradually increase investment. Over time, households and firms do gradually increase spending, driving inflation higher. However, one quarter (the first period in our simulation) is not long enough for real activity to respond significantly. Appendix A.6 and A.7 remove habit persistance and reduce investment costs, respectively: the results demonstrate that our qualitative conclusions hold even when we reduce inertia in the model.

7 Alternative Central Bank Tools and Shock Dynamics

7.1 Counterfactual: Repo Tool

We explore two counterfactual policies the Bank could have adopted instead of asset purchases. The first of these is a *repo tool*, modelled as the variable X_t^{CB}. As discussed in section 2.5, there is no point in providing repo finance to the LDIs: they are obliged to reduce their leverage, so each unit of finance from the central bank simply reduces finance from the commercial bank by a unit, without affecting B_t^{LDI} or Q_t^L. Our repo tool instead targets pension funds, with the idea that they are provided with liquidity on condition they inject it into the LDIs as equity. We set the persistence parameter $\rho_X = 0.5$ for consistency with the QE intervention.

Figure 9 shows the effect of a repo loan to pension funds worth 0.23% of GDP, a quarter of the size of the asset purchase program. The first panel shows the effect on linker prices, the second the effect on monetary policy; we omit the impact on nominal gilt prices since they follow the same path shown in previous graphics. The most important aspect to note here is the striking similarity of the repo intervention to the asset purchase intervention, despite the fact that the intervention is a fraction the size. This turns out to be highly intuitive, and a direct consequence of LDI leverage. The extent to which LDIs amplify the initial fall in prices depends directly on how many linkers households are forced to purchase and consequently how large a price cut is required to induce households to make these purchases. Each unit of asset purchases takes one unit of linkers off the market, reducing household adjustment costs and stabilising prices. However, each unit of *repo* takes ℓ units of gilts off the market. By increasing $VLDI_t$ by 1, the

Figure 9: Financial Stability Intervention: Repo Loan worth 0.23% GDP

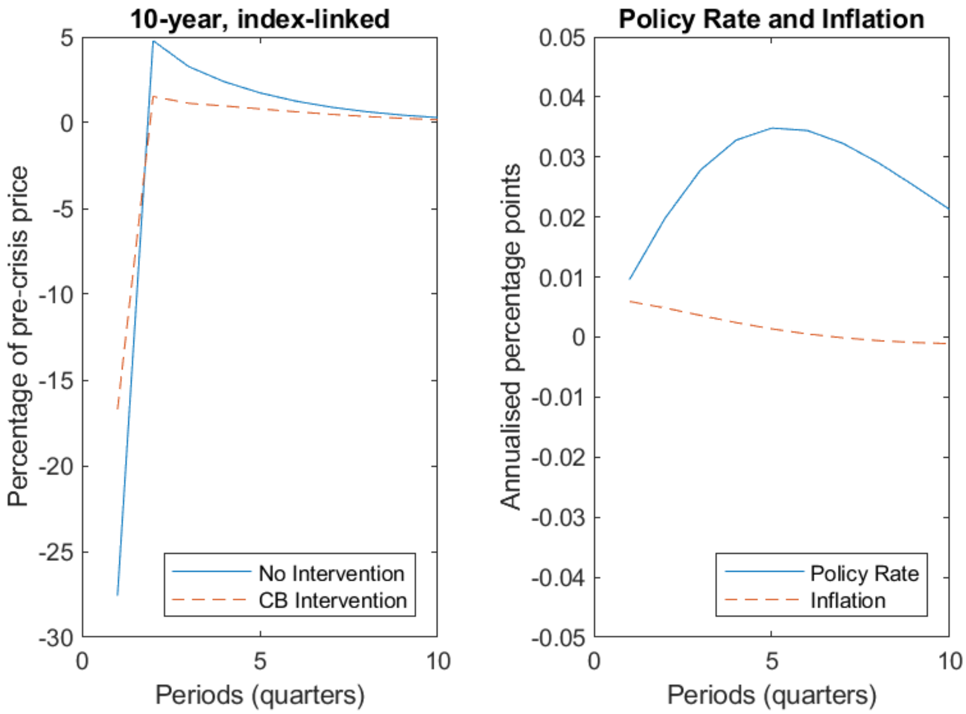


Figure 9 shows the effect of a repo loan to pension funds worth 0.23% of GDP, a quarter of the size of the asset purchase program. The LHS panel shows the effect on linker prices while the RHS panel shows the effect on policy rate and inflation (monetary policy spillovers). We omit the impact on nominal gilt prices since they follow the same path shown in previous graphics.

LDI can take on an additional ℓ units of gilts - or in this context, can avoid selling an additional ℓ units.

This makes recapitalising LDIs (indirectly) a highly efficient intervention, since it achieves the same market stabilisation objective with a smaller 'footprint' on the Bank's balance sheet. The second panel suggests that it also has lower spillovers into the policy rate and inflation; this is a consequence of setting $\rho_{FS} = \rho_X = 0.5$. The monetary consequences of the two tools are almost identical when we instead set $\rho_{FS} = \rho_X = 0.5$, and significantly larger if we set $\rho_{FS} = \rho_X = 0.9$. This difference arises because persistent asset purchases imply that there are fewer linkers available to households and pension funds in the medium term; this scarcity pushes down on yields. Conversely, persistent repo has no such implication for asset supply and hence there is no medium term effect on yields from using the repo tool persistently. Insofar as the central bank wishes to unwind interventions slowly for operational reasons, the repo tool can be prolonged safely.

7.2 Counterfactual: Macroprudential Policy

The second alternative tool we use is a macroprudential liquidity buffer, requiring pension funds and/or LDIs to hold a minimum amount of money during normal times. This can then be exploited by setting this minimum to zero during the crisis period, which either enables the LDI to run down money holdings instead of selling linkers or enables the pension fund to recapitalise the LDI. In section 2.5, we implemented this buffer at pension fund level to simplify the LDI balance sheet; in the absence of money adjustment costs this has exactly the same effect as introducing a buffer at LDI level. Recall that we defined macroprudential policy using equation 42, repeated here:

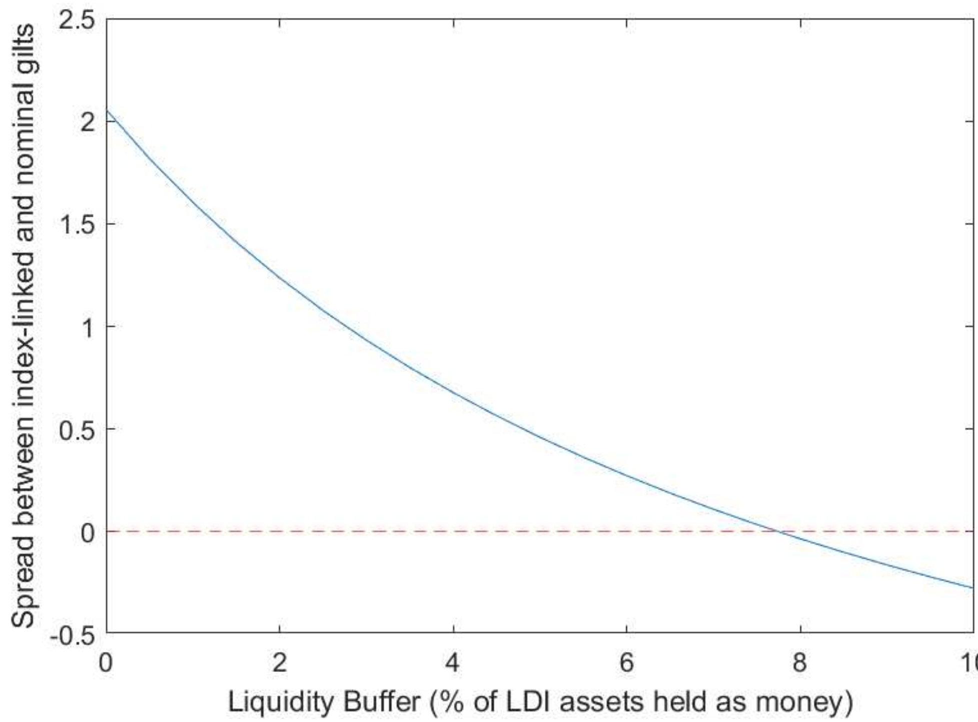
$$\mathcal{M}_t = \left(1 - \epsilon_t^{\mathcal{M}}\right) m B_t^P$$

We set the shock value $\epsilon_t^{\mathcal{M}} = 1$ throughout this section, implying that the liquidity buffer is completely removed during the crisis period. We then explore a range of values for the normal-times fraction m, which directly determines how effective this is. With $m = 0$, funds keep no liquidity during normal times and so removing the threshold has no impact. With higher values $m > 0$, removing the threshold enables the pension fund to inject equity into the LDI and halt linker sales. Note that due to the way we calibrate our parameters, increasing m means that in steady state pension funds hold additional money and less equity; the size of the LDI sector is unchanged. We would otherwise observe an additional channel whereby forcing pension funds to hold more liquidity 'crowds out' investment in LDIs and linkers, reducing steady-state LDI assets and thus mechanically reducing their impact on gilt markets. We choose this strategy as our interest here is active macroprudential policy, rather than passive policy via steady-state portfolio choice.

Figure 10 shows the period one spread between (nominal) yields on index-linked and nominal gilts. A spread of zero implies that both types of gilt offer the same expected return, as is the case in the baseline scenario with LDIs or pension funds. A spread of 2.16% corresponds to the no-intervention scenario displayed in figure 4. The x-axis shows a range of possible steady-state liquidity buffers, which are then relaxed using $\epsilon_t^{\mathcal{M}} = 1$ during period 1.

The key message of figure 10 is that a high liquidity buffer combines with active macroprudential policy does indeed present an alternative to asset purchases or a repo tool. We estimate that a liquidity buffer worth roughly 7.7% of LDI assets is sufficient to close the spread between linkers and nominal gilts. To be concrete, consider a liquidity buffer worth 2.75% of LDI assets. Our results in figure 10 suggest that combined with an active policy to relax the buffer during the crisis, this would have been sufficient to close the spread between

Figure 10: Financial Stability Intervention: Active Macroprudential Policy



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linkers and nominal gilts by half. Even if this level of liquidity is not sufficient to resolve the market dysfunction, the problem would have been partly alleviated and any asset purchases or repo would have been significantly smaller.

However, imposing a larger buffer in steady state does carry costs. In particular, forcing the pension fund (or LDI) to hold additional low-return money reduces their asset returns and potentially threatens their ability to fulfil their obligations. In our stylised model, changing the share of liquid assets from 0% to 7.7% reduces the steady-state real return on the pension fund portfolio by about 10% (from 1.28% to 1.16%). While this number should not be taken literally (the pension fund portfolio problem has been greatly simplified to isolate LDI-related dynamics), it is indicative of the potential costs that would be imposed on pension funds if regulators impose overly-strict liquidity buffers. It is beyond the scope of this paper to derive an optimal liquidity buffer which strikes the perfect balance between steady-state costs and financial stability; we simply note that a meaningful trade-off exists and contribute our finding that the liquidity buffer worth 2.75% would have sharply reduced the need for intervention.

7.3 Counterfactual: what if the portfolio shock was not reversed?

Figure 11 runs through our scenarios again, but this time in a context where the initial preference shock (lowering the value of long-term bonds) is not unexpectedly reversed in the second period. Instead, the household preference shock persists into the medium term with a decay rate $\rho_\zeta = 0.9$. This is designed to reflect a situation in which the UK government debt is persistently less appealing to investors following the change in risk profile. Our main results assume that underlying conditions return to normal in the second period and long-term gilts once again offer the same non-pecuniary returns to investors as they did pre-crisis. In figure 11, there is no such reversal and gilt prices take a long time to recover.

The top panels correspond to figure 4, showing the path of gilt prices with and without LDI activity. By construction, in the absence of LDI activity both nominal and linker prices gradually recover. With LDI amplification however, we observe both a sharper initial drop in prices - the same period one collapse as in our main results - but also a faster recovery, with linker prices substantially higher in period two than their conventional counterparts. This is driven by the same mechanism as the overcorrection observed in figure 5: pension funds (through LDIs) take advantage of the lower prices to buy more linkers, acting to stabilise prices in the medium term. They cannot do this initially due to the leverage constraint and portfolio frictions, but given time they are able to sell equity from their portfolio to acquire more linkers. Note that this finding relies on two assumptions embedded in our model. First, we implicitly assume the LDI-pension sector survives the initial shock without any insolvencies, and is thus able to capitalise in the second period. In reality, it is likely that many institutions would have collapsed during the initial period in the absence of intervention. It is thus unclear that the sector as a whole would have been in a position to expand linker holdings in the second period due to firm exit, even if individual surviving firms acted to buy more. Second, we assume that the preference shock applies only to households and not to the pension funds or LDIs; i.e. they are not concerned by the change in risk profile. This latter assumption is plausible so long as pension fund demand for linkers is driven by regulation, since linkers would continue offering the same regulatory advantages of a 'safe' asset regardess of the underlying asset properties.

The four lower panels replicate figures 5,6 and 9 in the new context, showing the hypothetical impact of central bank intervention in the context of persistently lower bond prices. The general picture and conclusion is much the same when the shock is reversed: both asset purchases and repo are successful in stabilising linker prices with minimal consequences

Figure 11: Projected impacts with a persistent preference shock

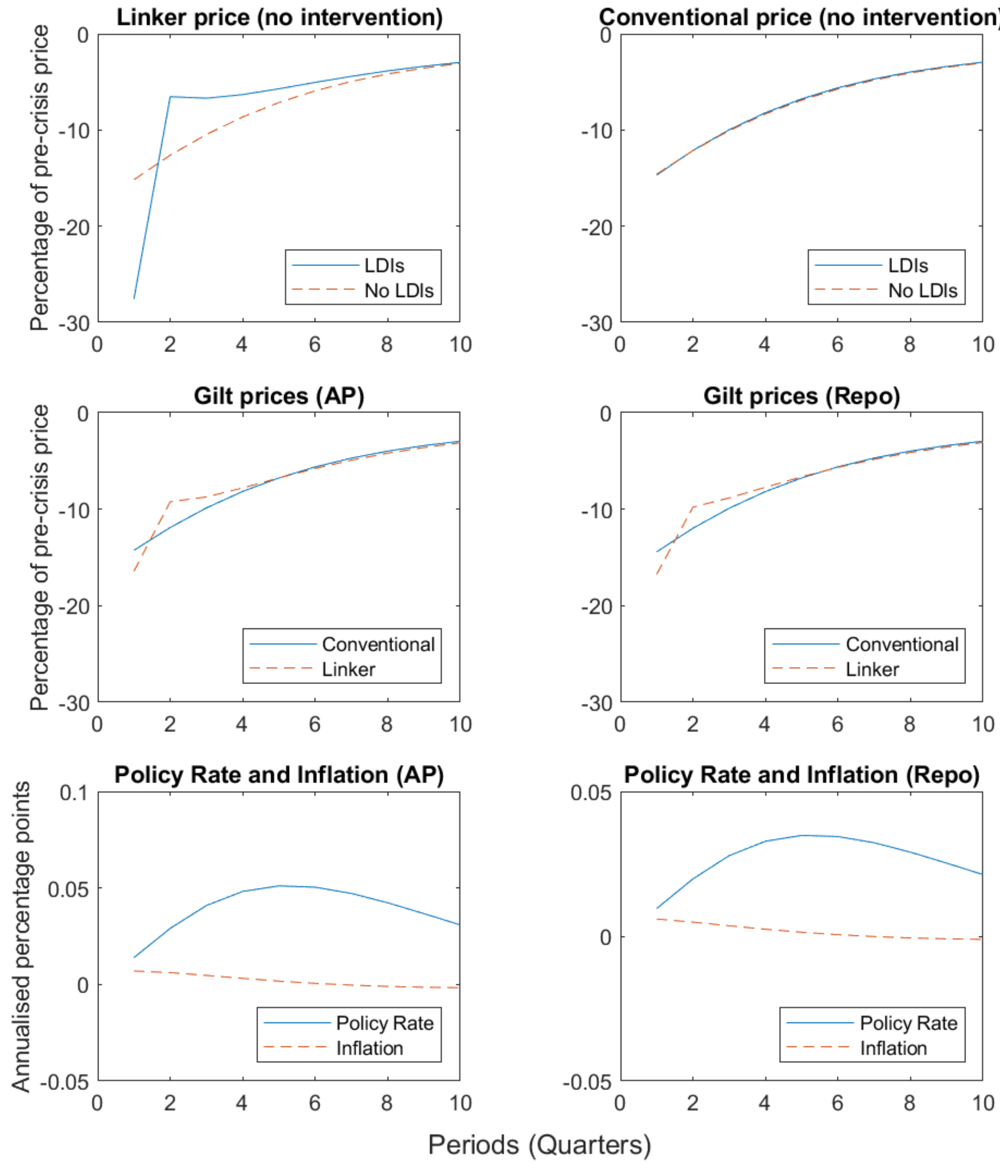

Figure 11 runs through the scenarios of Figures 4, 5, 6 and 9 but, differently from previous simulations, the initial preference shock is not unexpectedly reversed in the second period. Instead, the household preference shock persists into the medium term with a decay rate $\rho_{\zeta} = 0.9$. The top panels show the effect of the risk-premium shock on gilt prices in an economy with and without LDIs; the middle panels show the impact of asset purchases (LHS) and repo loan (RHS) on gilt prices; and the bottom panels shows the monetary policy spillovers (impacts on policy rate and inflation) of asset purchases (LHS) and repo loan (RHS).

for monetary policy. This is partly an artifact of our model implementation: since the model is solved to first order, the impacts of a policy response will look similar regardless of the macroeconomic context. A small difference arises since the pension fund liquidity constraint (equation 29) does not bind when the shock is reversed, but binds when it is not. The explanation for this is that by period two, the pension fund has sold equities with the intention of increasing exposure to index-linked bonds due to the higher returns now on offer. When the shock is not reversed, they proceed as planned and inject equity into LDIs who then buy index-linked bonds. When the shock *is* reversed, index-linked bonds returns are no longer underpriced; the fund does not invest as much into the LDIs and holds the remainder as cash until it can re-invest in equity. This has minor economic implications - in period two of figure 11, the pension fund holds less (no) money compared with previous results, and hence households hold more money. This has a small effect on consumption and investment, but our policy conclusions with respect to asset purchases and repo are unchanged.

8 Conclusion and future research

We have constructed a novel DSGE framework capable of replicating the fire-sale dynamics observed in the LDI sector during the 2022 UK gilt market crisis. We have used this framework to assess the impact of central bank asset purchases, a repo tool providing liquidity to pension funds, and a macroprudential tool mandating a large liquidity buffer. We find that all of these interventions have the potential to resolve the market dysfunction, but all involve trade-offs. Asset purchases are effective, but require the central bank to take volatile assets directly onto its balance sheet. Repo loans are equally effective with a smaller footprint on the balance sheet, but must be carefully constructed with reference to pension fund governance arrangements to ensure the liquidity can actually be deployed where it is most needed. The macroprudential tool stabilises the gilt market without any effect on the Bank's balance sheet, but imposes costs on defined-benefit pension funds during normal times that may threaten their long-term financial health.

We have also shown that rapidly unwinding an asset purchase intervention is crucial in limiting the impact and ensuring there are no monetary spillovers. We find that so long as the intervention is mostly wound up within a year, the effect on inflation and the policy rate is minimal. Once the intervention is prolonged much beyond a year however, the intervention generates substantial inflationary pressure which must be offset with an increase in the policy rate of interest of $0.2 - 0.4\%$ over the medium term. This effect is driven by the actual persistence of the intervention, rather than public beliefs. Even if the public initially believe the financial intervention to be 'QE-style', there are no significant monetary spillovers so long as it is unwound promptly.

Our findings open up several avenues for future research. Firstly, there is clearly scope to develop a broader framework in which to examine the monetary consequences of these financial stability interventions when placed in other contexts. Our paper has kept a narrow focus on liability driven investment and replicating the particular dynamics at play during the 2022 gilt market crisis. This leaves open the question of whether asset purchases conducted for financial stability might have larger monetary consequences in other contexts. While we are confident our broad finding — that keeping asset purchases 'temporary and targeted' is crucial to minimising monetary spillovers — will generalise to other contexts, further research should explore more channels of transmission and other types of financial crisis to see if our quantitative findings translate smoothly.

Secondly, we have not considered the long-term implications of these policies. In particular, it is reasonable to expect that if any of these policy options became embedded in the central bank toolkit then financial institutions in general — and LDIs in particular — might respond by increasing their leverage and reducing their own internal efforts to forecast and avert future episodes. This extends to potential arbitrageurs such as hedge funds, who were unable to conduct a timely intervention in this particular episode but have the incentive to do so in future. Future research should properly account for the long term, including an assessment of how central bank policy rules impact portfolio choices during normal times as well as during crisis periods.

Thirdly and relatedly, we have not engaged in a full discussion of optimal policy. All three of our policy tools have drawbacks, manifesting as monetary spillovers for asset purchases and the repo tool and as lower steady-state returns for pension funds in the case of the macroprudential tool. There is clearly scope for further work to go beyond our qualitative discussion of these limitations and solve for the policy mix which maximises expected household utility.

A Sensitivity analysis

All figures in this section contain panels replicating figures 4, 5 and 6 for the impact of the yield shock and of temporary asset purchases worth 0.9% of GDP. The last panel is an adaptation of figure 7 showing the maximum increase in inflation and the policy rate resulting from these asset purchases across different values of ρ_{FS}. For each set of results, we recalibrate all other parameters as described in section 4, and the shock value ϵ_t^{ζ} as described in section 5.

A.1 Changing k

Figure A.1: Sensitivity Analysis: $k = 1 - 1/120$

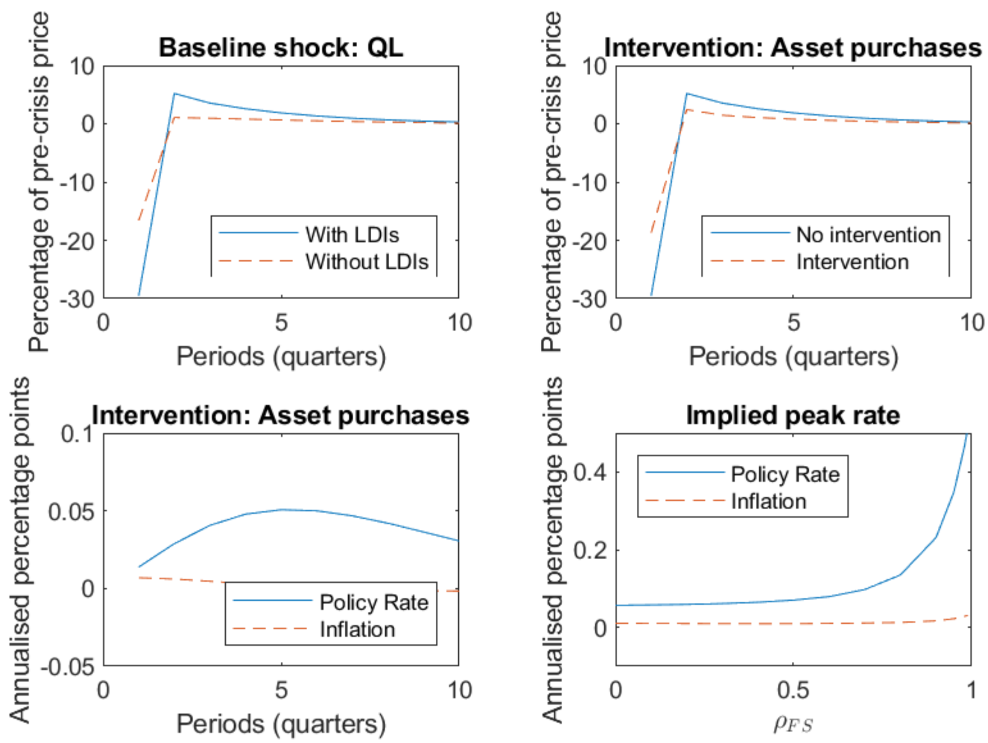

Figure A.1 shows our results if we change Q_t^L from a ten-year bond to a thirty-year bond. There are no changes to any of our results, analysis or policy implications.

A.2 Lower equity premium

Figure A.2: Sensitivity Analysis: Convenience Yields of 1.06%

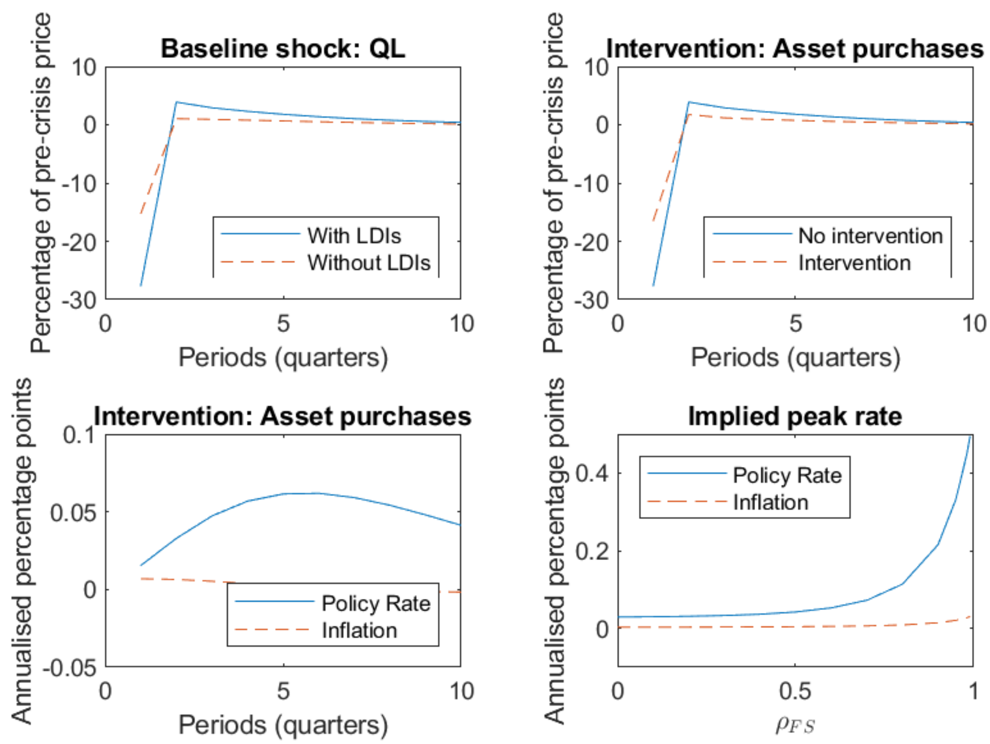

Figure A.2 shows our results if we use a lower estimate of steady-state convenience yields, 1.06% instead of 1.86%. There are no changes to any of our results, analysis or policy implications.

A.3 Higher equity premium

Figure A.3: Sensitivity Analysis: Convenience Yields of 2.32%

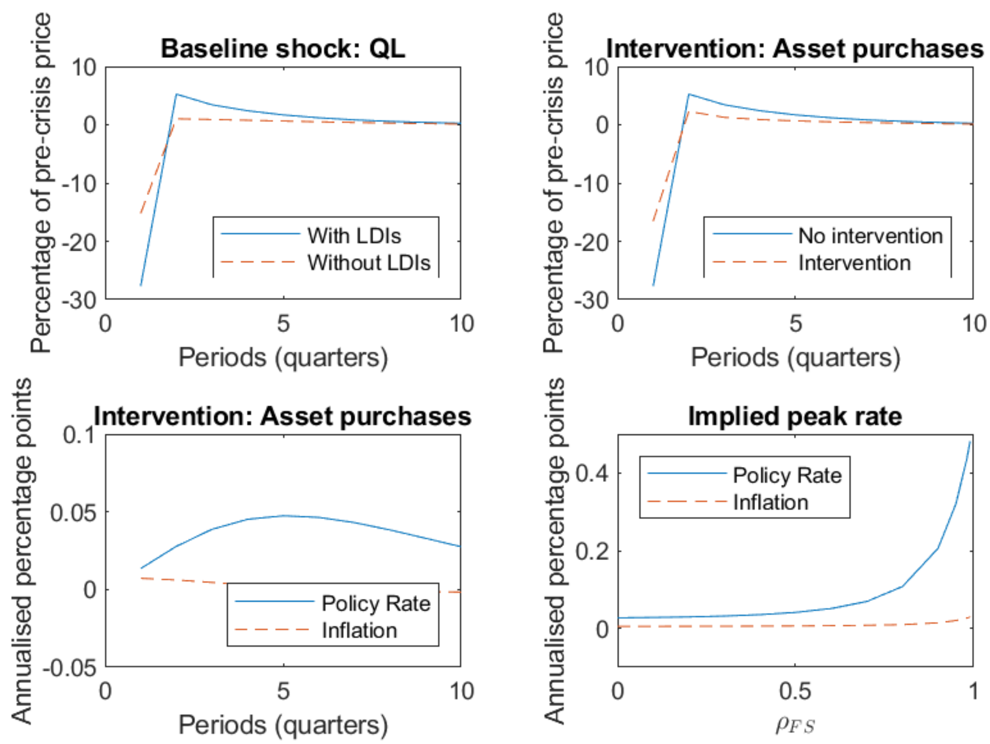

Figure A.3 shows our results if we use a higher estimate of steady-state convenience yields, 2.32% instead of 1.86%. There are no changes to any of our results, analysis or policy implications.

A.4 Lower κ_L

Figure A.4: Sensitivity Analysis: $\kappa_L = 0.12$

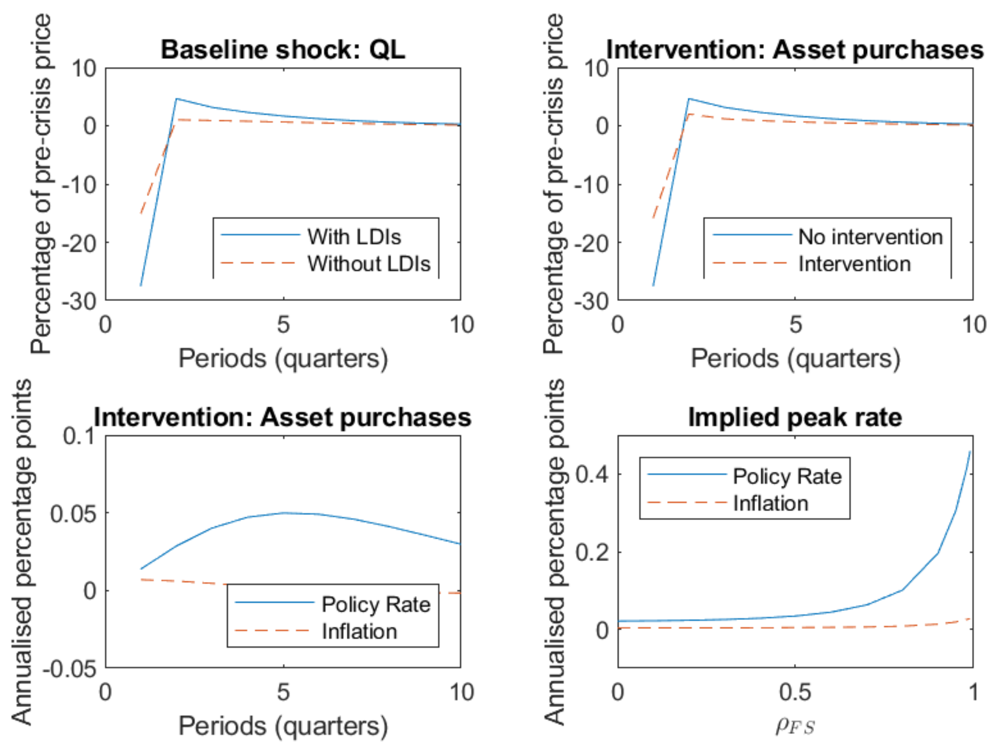

Figure A.4 shows our results if we assume that linkers and nominal bonds are extremely bad substitutes, rather than relatively close ones (CES elasticity $\kappa_L = 0.12$ instead of $\kappa_L = 0.9$). This does not change our core results, but does suggest there would fewer monetary spillovers from prolonged interventions (section 7). This arises because if demand for linkers and nominal bonds is highly inelastic, buying and holding linked gilts has less of an impact on other asset markets.

A.5 30-year reference group

Figure A.5: Sensitivity Analysis: Thirty-Year Bonds as Reference

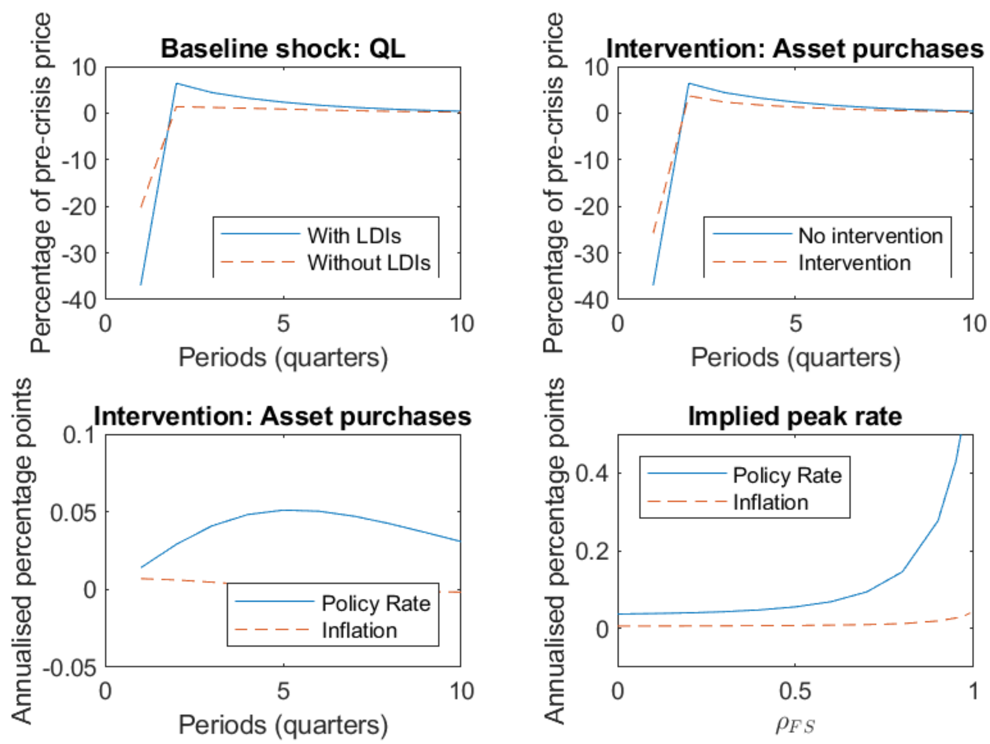

Figure A.5 shows our results if we calibrate the shock and ω_2 to the price drop of thirty-year nominal and index-linked bonds (19.8% and 39.2%), rather than twenty-year (14.7% and 27.6%). Results are broadly similar, with two basic differences. The first is that asset purchases of 0.9% of GDP are not sufficient to completely offset the LDI effect (panel 2); further asset purchases would have been required (over the quarter) to resolve the gilt market dysfunction. The monetary spillovers of purchases worth 0.9% of GDP are essentially the same (panel 3), and so as a direct consequence the monetary spillovers of 'sufficient intervention' are larger across all levels of intervention persistence (panel 4).

A.6 No Habit Persistence

Figure A.6: Sensitivity Analysis: No Habit Persistence

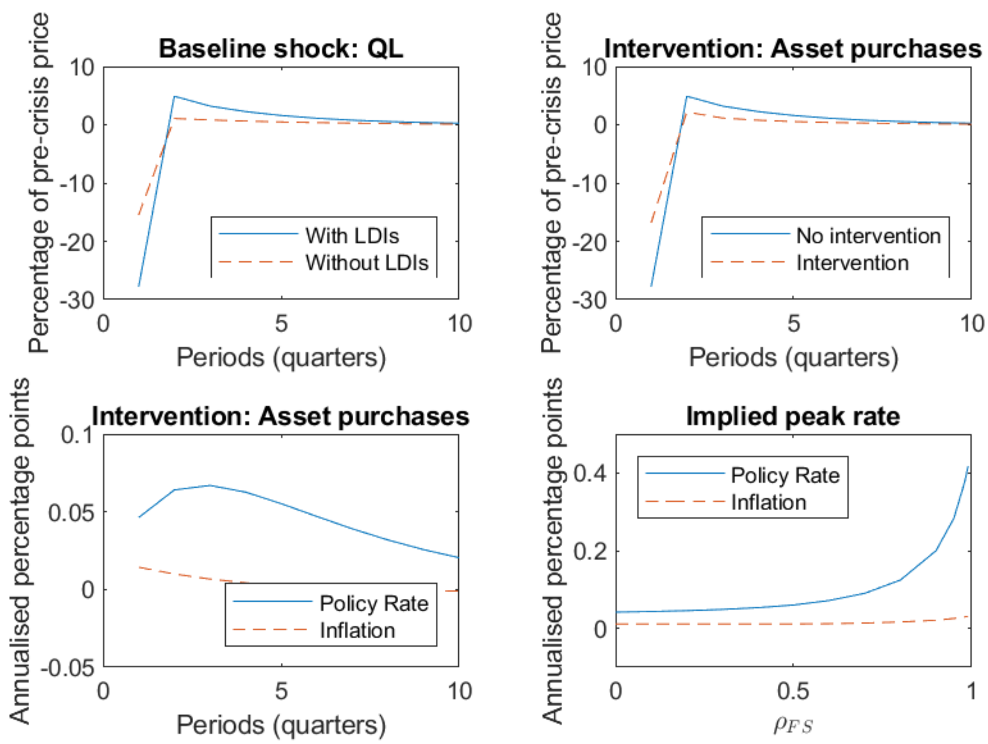

Figure A.6 shows our results if we remove habit persistence from the model ($h = 0$). Results are broadly similar, but monetary spillovers are somewhat larger - a rate rise of 6-7bps is needed, and is more front-loaded than the increase in our main results. This is because the asset purchases increase consumption significantly more on impact, rather than gradually over time. This is not consistent with the empirical evidence that the economy responds to monetary policy with a significant lag (see e.g. Cesa-Bianchi, Thwaites, and Vicondoa (2020)).

A.7 Lower Investment Adjustment Costs

Figure A.7: Sensitivity Analysis: Lower Investment Adjustment Costs

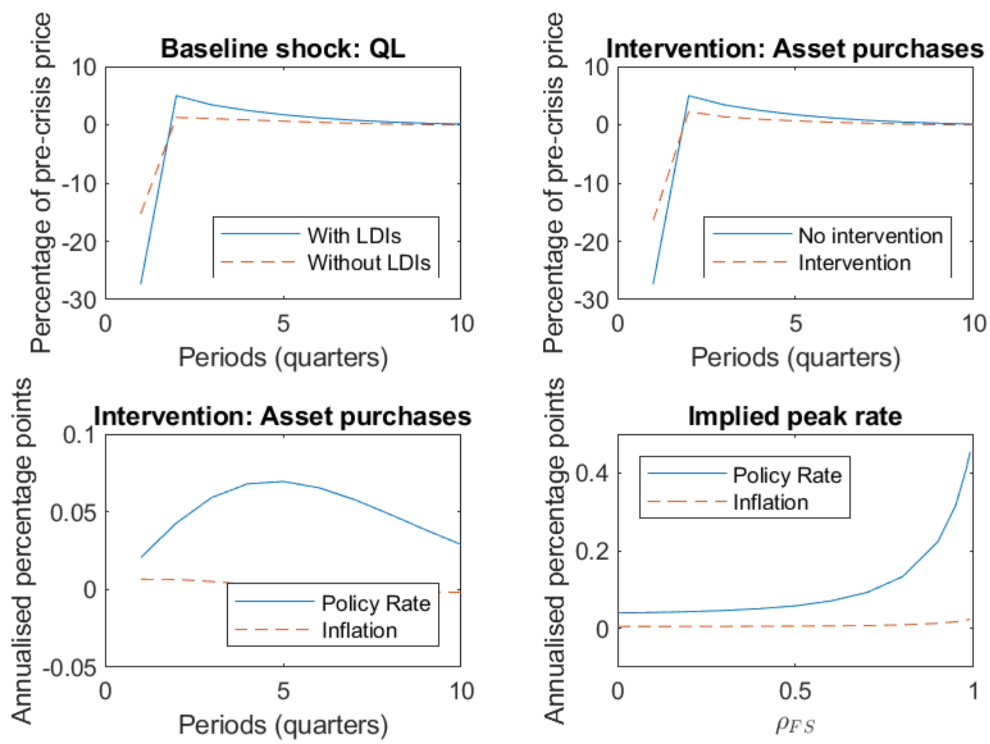

Figure A.7 shows our results if we reduce the investment adjustment cost parameter ($S' = 1$ instead of $S' = 2.5$). Results are broadly similar, but as with removing habit persistence this scenario necessitates a stronger monetary policy response -of 6-7bps. This is because investment responds more strongly to the asset purchases when it is easier to adjust. Note that removing investment adjustment costs entirely ($S' = 0$) greatly alters our results and a large rise of > 0.15 bps would be required. Our broad conclusions hold across all realistic values for S'.

B Firm and Union details

B.1 Stock brokers

The stock broker makes profits ϖ_t equal to the sum of firm profits, implicitly defining a real rate of return:

$$\varpi_t = \varpi_t^R + \varpi_t^W + \varpi_t^K \tag{54}$$

$$r_t^V \equiv (\varpi_t + V_t) / V_{t-1} \tag{55}$$

With ϖ_t^R as retailer profits, ϖ_t^W wholesaler profits and ϖ_t^K profits of capital-makers. In steady state and in general, $\varpi_t^W > \varpi_t^R > \varpi_t^K$. Wholesalers are the dominant component since they own the capital stock and hence their profits include the return to capital; retailer profits are pure rents which arise from the markup between wholesaler and retailer output. Capital makers make zero profits in steady state, but make (net) profits dynamically due to adjustment costs. Final goods firms make zero profit at all times as they are perfectly competitive and own no assets.

B.1.1 Final Goods Firm

A competitive final goods firm buys retail outputs $Y_t(f)$ from heterogeneous retailers indexed $f \in [0, 1]$ at nominal prices $P_t(f)$ and combines them into an aggregate output Y_t which it sells at nominal price P_t. For the production of Y_t, the final goods firm uses a CES technology with elasticity of substitution $\eta > 1$, creating:

$$Y_t = \left(\int_0^1 Y_t(f)^{\frac{\eta-1}{\eta}} df \right)^{\frac{\eta}{\eta-1}} \tag{56}$$

The maximisation problem of the final goods firm is the following:

$$\max_{Y_t(f)} P_t \left(\int_0^1 Y_t(f)^{\frac{\eta-1}{\eta}} dh \right)^{\frac{\eta}{\eta-1}} - P_t(f) Y_t(f) \tag{57}$$

The FOC with respect to $Y_t(f)$ is the below standard retail output demand function:

$$Y_t(f) = \left(\frac{P_t(f)}{P_t} \right)^{-\eta} Y_t \tag{58}$$

While the aggregate price (price of the final output good) P_t is:

$$P_t^{1-\eta} = \int_0^1 P_t(f)^{1-\eta} df \tag{59}$$

B.1.2 Retail firms

Monopolistic retail firms indexed by $f \in [0, 1]$ buy wholesale output $Y_{m,t}$ at a nominal price $P_{m,t}$ and repackage it for sale to a final goods firm at nominal price $P_t(f)$. Retail firms are subject to a Rotemberg (1982) style price rigidity, with price adjustment cost z_t^p. We use Rotemburg pricing as it gives identical results to Calvo at first order, while offering greater algebraic simplicity and a closed-form expression for firm profits. This is important for our use case since we wish to keep track of equity valuations and returns; in other settings this is not important as profits are left implicit. The nominal profit of a retail firm follows:

$$P_t \varpi_t^R(f) = P_t(f) Y_t(f) - P_{m,t} Y_{m,t}(f) - P_t Y_t z_t^p(f) \tag{60}$$

$$z_t^P(f) = \frac{\varphi}{2}\left(\frac{P_t(f)}{\bar{\pi} P_{t-1}(f)} - 1\right)^2 \tag{61}$$

Since in equilibrium $Y_{m,t}(f) = Y_t(f)$, we use (58) to obtain:

$$P_t \varpi_t^R(f) = Y_t \left[P_t(f)^{1-\eta} P_t^{-\eta} - P_{m,t}\left(P_t(f)/P_t\right)^{-\eta} - P_t z_t^p(f)\right] \tag{62}$$

Firms face a quadratic cost of adjusting prices, which is controlled by a parameter φ and scaled by aggregate output Y_t. When setting prices, they thus consider last-period prices, current demand, and the anticipated next-period price. We write the maximisation problem as a Bellman, with the discount factor Λ_t inherited from households:

$$\max_{P_t(f)} V_t^R(f) = Y_t \left[P_t(f)^{1-\eta} P_t^{-\eta} - P_{m,t}\left(P_t(f)/P_t\right)^{-\eta} - P_t z_t^p(f)\right] + \Lambda_t V_{t+1}^R(f)/\pi_{t+1} \tag{63}$$

The FOC with respect to $P_t(f)$ is:

$$0 = Y_t \left[(1-\eta) P_t(f)^{-\eta} P_t^{-\eta} + \eta P_{m,t} P_t(f)^{-\eta-1} P_t^{\eta} - P_t \frac{\partial z_t^p(f)}{\partial P_t(f)}\right] - \Lambda_t Y_{t+1} P_t \frac{\partial z_{t+1}^p(f)}{dP_t(f)} \tag{64}$$

We use that in symmetric equilibrium $P_t = P_t(f)$ for all firms $f \in [0, 1]$. Hence:

$$0 = Y_t \left[(1-\eta) + \eta \frac{P_{m,t}}{P_t} - \varphi \frac{P_t}{\bar{\pi} P_{t-1}} \left(\frac{P_t}{\bar{\pi} P_{t-1}} - 1 \right) \right] - \Lambda_t Y_{t+1} \varphi \frac{P_{t+1}}{\bar{\pi} P_t} \left(\frac{P_{t+1}}{\bar{\pi} P_t} - 1 \right) \tag{65}$$

We note the identity $P_t/P_{t-1} \equiv \pi_t$ and let $p_{m,t} \equiv P_{m,t}/P_t$ be the real price of wholesale goods. Hence we can rearrange and write this as a compact expression:

$$(1-\eta) + \eta p_{m,t} = \nu_t + \Lambda_t \left(Y_{t+1}/Y_t \right) \nu_{t+1} \tag{66}$$

$$\nu_t \equiv \varphi \left(\frac{\pi_t}{\bar{\pi}} \right) \left(\frac{\pi_t}{\bar{\pi}} - 1 \right) \tag{67}$$

Finally, it is now trivial to derive firm profits in equilibrium. We apply $P_t(f) = P_t$ in symmetric equilibrium and obtain:

$$\varpi_t^R = Y_t \left[1 - p_{m,t} - z_t^p \right] \tag{68}$$

$$z_t^p = \frac{\varphi}{2} \left(\frac{\pi_t}{\bar{\pi}} - 1 \right)^2 \tag{69}$$

Note that $z_t^p \approx 0$ to a first order approximation around the steady state.

B.1.3 Wholesale firms

The representative wholesale firm follows a Cobb-Douglas production function:

$$Y_{m,t} = Z(u_t K_t)^{\theta} n_{d,t}^{1-\theta} \tag{70}$$

Where Y_m is output, $n_{d,t}$ is the labour factor of production, Z is a productivity parameter, K_t is the stock of firm capital that is multiplied by the capital utilisation rate u_t. K_t is accumulated following the standard law of motion:

$$K_{t+1} = \hat{I}_t + (1 - \delta(u_t))K_t \tag{71}$$

Where δ is the depreciation rate and $\hat{I}_t$ investment net of adjustment costs. Finally, the wholesale firm's profit (dividend) in real terms is:

$$\varpi_t^W = p_{m,t} Z(u_t K_t)^{\theta} n_{d,t}^{1-\theta} - w_t n_{d,t} - p_t^k \hat{I}_t \tag{72}$$

With P_t^k being the price of new capital. The wholesale firm maximises equation (72) subject to (71). Taking the first order conditions with respect to $n_{d,t}$, $\hat{I}_t$, u_t, and K_{t+1} and rearranging, we obtain:

$$w_t = (1-\theta) p_{m,t} Z (u_t K_t)^{\theta} n_{d,t}^{-\theta} \tag{73}$$

$$p_t^k \delta'(u_t) = \theta p_{m,t} (u_t K_t)^{(\theta-1)} n_{d,t}^{1-\theta} \tag{74}$$

$$p_t^k = E_t \Lambda_{t,t+1} [\theta p_{m,t+1} Z (u_{t+1} K_{t+1})^{\theta-1} u_{t+1} n_{d,t+1}^{1-\theta} + (1-\delta(u_{t+1})) p_{t+1}^k] \tag{75}$$

Where w_t is the real wage, $p_{m,t}$ is the price of wholesale output and p_t^k is the price of new capital.

B.1.4 Capital producer

Unconsumed final output I_t is used by a capital producer to create new physical capital $\hat{I}_t$:

$$\hat{I}_t = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t \tag{76}$$

Where $S()$ is an adjustment cost function with standard properties. The new capital is sold to firm at nominal priceP_t^k (real price $p_t^k \equiv P_t^k / P_t$). This implies capital producer real profits follow:

$$\varpi_t^K = p_t^k \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t - I_t \tag{77}$$

The maximisation problem then is:

$$\max_{I_t} \mathbb{E} \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left\{ p_{t+j}^k \left[1 - S\left(\frac{I_{t+j}}{I_{t+j-1}}\right)\right] I_{t+j} - I_{t+j} \right\} \tag{78}$$

And the FOC with respect to I_t is the following:

$$1 = p_t^k \left[1 - S\left(\frac{I_t}{I_{t-1}}\right) - S'\left(\frac{I_t}{I_{t-1}}\right) \frac{I_t}{I_{t-1}}\right] + \mathbb{E} \Lambda_t p_{t+1}^k S\left(\frac{I_{t+1}}{I_t}\right) \left(\frac{I_{t+1}}{I_t}\right)^2 \tag{79}$$

We note briefly that $S(.) \approx 0$ to a first order approximation around steady state and hence $I_t \approx \hat{I}_t$ and profits follow:

$$\varpi_t^K \approx \left(p_t^k - 1\right) I_t \tag{80}$$

B.2 Labour Market

The labour market has two tiers: a labour packer and labour unions.

B.2.1 Labour packer

A competitive labour packer buys union labour $n_{d,t}(h)$ at nominal price $W_t(h)$ and converts it into the labour ready for production, $n_{d,t}$, using a CES technology with elasticity of substitution $\eta_w > 1$:

$$n_{d,t} = \left(\int_0^1 n_{d,t}(h)^{\frac{\eta_w - 1}{\eta_w}} dh \right)^{\frac{\eta_w}{\eta_w - 1}} \tag{81}$$

The labour packer sells $n_{d,t}$ to production firms at w_t, the aggregate wage. The maximisation problem of the labour packer is the following:

$$\max_{n_{d,t}(h) \forall h \in [0,1]} P_t \varpi_t^{LP} = W_t \left(\int_0^1 n_{d,t}(h)^{\frac{\eta_w - 1}{\eta_w}} dh \right)^{\frac{\eta_w}{\eta_w - 1}} - W_t(h) n_{d,t}(h) \tag{82}$$

The FOC with respect to $n_{d,t}(h)$ yields a standard labour demand function:

$$n_{d,t}(h) = \left(\frac{W_t(h)}{W_t} \right)^{-\eta_w} n_{d,t} \tag{83}$$

The labour packer sells $n_{d,t}$ to production firms at w_t, the aggregate wage, according to:

$$W_t^{1-\eta_w} = \int_0^1 W_t(h)^{1-\eta_w} dh \tag{84}$$

B.2.2 Labour Union

Labour unions — indexed by h and subject to a Rotemburg wage rigidity — buy labour from households at a nominal wage $W_{h,t}$ and sell it to the labour packer at a nominal price W_t. Rotemburg costs are controlled by the parameter φ_w and scaled by total labour demand. The nominal profit of a labour union is:

$$P_t\varpi_t^U(h) = W_t(h)n_{d,t}(h) - W_{h,t}n_t(h) - n_tW_tz_t^w(h) \tag{85}$$

$$z_t^w(h) = \frac{\varphi_w}{2}\left(\frac{W_t(h)}{\bar{\pi}W_{t-1}(h)} - 1\right)^2 \tag{86}$$

Using $n_t(h) = n_{d,t}(h)$ in equilibrium and applying (83):

$$P_t\varpi_t^U(h) = n_t\left[W_t(h)^{1-\eta_w}W_t^{-\eta_w} - W_{h,t}W_t(h)^{-\eta_w}W_t^{\eta} - P_tz_t^w(h)\right] \tag{87}$$

Firms face a quadratic cost of adjusting prices, which is controlled by a parameter φ and scaled by aggregate output Y_t. When setting prices, they thus consider last-period prices, current demand, and the anticipated next-period price. We write the maximisation problem as a Bellman, with the discount factor Λ_t inherited from households:

$$\max_{W_t(h)} V_t^U = n_t\left[W_t(h)^{1-\eta_w}W_t^{-\eta_w} - W_{h,t}W_t(h)^{-\eta_w}W_t^{\eta} - W_tz_t^w(h)\right] + \Lambda_tV_{t+1}^U/\pi_{t+1} \tag{88}$$

The FOC with respect to $W_t(f)$ is:

$$0 = n_t\left[(1-\eta_w)W_t(h)^{-\eta_w}W_t^{-\eta_w} + \eta W_{h,t}W_t(h)^{-\eta_w-1}W_t^{\eta} - W_t\frac{\partial z_t^w(h)}{\partial W_t(h)}\right] - \Lambda_tn_{t+1}W_t\frac{\partial z_{t+1}^w(h)}{dW_t(h)} \tag{89}$$

We use that in symmetric equilibrium $W_t = W_t(h)$ for all unions $h \in [0,1]$. Hence:

$$0 = n_t\left[(1-\eta_w) + \eta_w\frac{W_{h,t}}{W_t} - \varphi_w\frac{W_t}{\bar{\pi}W_{t-1}}\left(\frac{W_t}{\bar{\pi}W_{t-1}} - 1\right)\right] - \Lambda_tn_{t+1}\varphi_w\frac{W_{t+1}}{\bar{\pi}W_t}\left(\frac{W_{t+1}}{\bar{\pi}W_t} - 1\right) \tag{90}$$

We let $W_t/P_t \equiv w_t$ and let $w_{h,t} \equiv W_{h,t}/P_t$ be real wages paid to the union and to households respectively. Hence we can rearrange and write this as a compact expression:

$$(1-\eta_w) + \eta\left(w_{h,t}/w_t\right) = \nu_{w,t} + \Lambda_t\left(n_{t+1}/n_t\right)\nu_{t+1} \tag{91}$$

$$\nu_{w,t} \equiv \varphi_w\left(\frac{\pi_tw_t}{\bar{\pi}w_{t-1}}\right)\left(\frac{\pi_tw_t}{\bar{\pi}w_{t-1}} - 1\right) \tag{92}$$

Finally, it is now trivial to derive union profits in equilibrium. We apply $W_t(h) = W_t$ in symmetric equilibrium and obtain:

$$\varpi_t^U = n_t \left[w_t - w_{h,t} - z_t^w \right] \tag{93}$$

$$z_t^w = \frac{\varphi_w}{2} \left(\frac{\pi_t w_t}{\bar{\pi} w_{t-1}} - 1 \right)^2 \tag{94}$$

Note that $z_t^w \approx 0$ to a first order approximation around the steady state.

C Equilibrium conditions

Real-return definitions:

$$r_t \equiv i_t / \pi_t \tag{E.1}$$

$$r_t^{10} \equiv i_t^{10} / \pi_t \tag{E.2}$$

$$r_t^L \equiv i_t^L / \pi_t \tag{E.3}$$

$$r_t^V \equiv \left(V_t + \varpi_t \right) / V_{t-1} \tag{E.4}$$

$$r_t^{FI} \equiv \left(V_t^{FI} + \varpi_t^{FI} \right) / V_{t-1}^{FI} \tag{E.5}$$

$$r_t^{LDI} = \ell_{t-1} r_t^L - Q_{t-1}^{Rep} \left(\ell_{t-1} - 1 \right) \tag{E.6}$$

Household:

$$\Lambda_t = \beta \frac{\bar{c}_{t+1}^{-\sigma} - h\beta \bar{c}_{t+2}^{-\sigma}}{\bar{c}_t^{-\sigma} - h\beta \bar{c}_{t+1}^{-\sigma}} \tag{E.7}$$

$$\bar{c}_t = c_t - hc_{t-1} \tag{E.8}$$

$$(1 - n_t)^{\psi} = w_t^h c_t^{-\sigma} / \phi \tag{E.9}$$

Portfolio:

$$\Psi_t \equiv \frac{\omega_1}{2}\left(\frac{B_t^{H10}}{B_{t-1}^{H10}} - 1\right)^2 + \frac{\omega_2}{2}\left(\frac{B_t^{HL}}{B_{t-1}^{HL}} - 1\right)^2 + \frac{\omega_3}{2}\left(\frac{V_t^{H}}{V_{t-1}^{H}} - 1\right)^2 \tag{E.10}$$

$$\alpha_t \equiv \left[\zeta_t^{\frac{1}{\kappa_\alpha}}\left(B_t^H\right)^{\frac{\kappa_\alpha - 1}{\kappa_\alpha}} + (1-\zeta_t)^{\frac{1}{\kappa_\alpha}}\left(\hat{B}_t\right)^{\frac{\kappa_\alpha - 1}{\kappa_\alpha}}\right]^{\frac{\kappa_\alpha}{\kappa_\alpha - 1}} \tag{E.11}$$

$$\hat{B}_t \equiv \left[\hat{\zeta}^{\frac{1}{\kappa_L}}\left(B_t^{HL}\right)^{\frac{\kappa_L - 1}{\kappa_L}} + (1-\hat{\zeta})^{\frac{1}{\kappa_L}}\left(B_t^{H10}\right)^{\frac{\kappa_L - 1}{\kappa_L}}\right]^{\frac{\kappa_L}{\kappa_L - 1}} \tag{E.12}$$

$$E_t\left[\Lambda_t r_t\right] = 1 - \xi\left[\zeta_t \alpha_t / B_t^H\right]^{\frac{1}{\kappa_\alpha}} \tag{E.13}$$

$$E_t\left[\Lambda_t r_t^{10} + \tilde{\Psi}_t^{10}\right] = 1 - \xi\left[(1-\zeta_t)\,\alpha_t/\hat{B}_t\right]^{\frac{1}{\kappa_\alpha}}\left[\left(1-\hat{\zeta}\right)\hat{B}_t/B_t^{H10}\right]^{\frac{1}{\kappa_L}} \tag{E.14}$$

$$E_t\left[\Lambda_t r_t^{L} + \tilde{\Psi}_t^{L}\right] = 1 - \xi\left[(1-\zeta_t)\,\alpha_t/\hat{B}_t\right]^{\frac{1}{\kappa_\alpha}}\left[\hat{\zeta}\hat{B}_t/B_t^{HL}\right]^{\frac{1}{\kappa_L}} \tag{E.15}$$

$$E_t\left[\Lambda_t r_t^{V} + \tilde{\Psi}_t^{V}\right] = 1 \tag{E.16}$$

$$E_t\left[\Lambda_t r_t^{FI}\right] = 1 \tag{E.17}$$

$$\tilde{\Psi}_t^{LR} \equiv \frac{1}{B_{t-1}^{H10}}\omega_1\left(\frac{B_t^{H10}}{B_{t-1}^{H10}} - 1\right) - \Lambda_t\frac{B_{t+1}^{H10}}{\left(B_t^{H10}\right)^2}\omega_1\left(\frac{B_{t+1}^{H10}}{B_t^{H10}} - 1\right) \tag{E.18}$$

$$\tilde{\Psi}_t^{LR} \equiv \frac{1}{B_{t-1}^{HL}}\omega_2\left(\frac{B_t^{HL}}{B_{t-1}^{HL}} - 1\right) - \Lambda_t\frac{B_{t+1}^{HL}}{\left(B_t^{HL}\right)^2}\omega_1\left(\frac{B_{t+1}^{HL}}{B_t^{HL}} - 1\right) \tag{E.19}$$

$$\tilde{\Psi}_t^{V} \equiv \frac{1}{V_{t-1}^{H}}\omega_3\left(\frac{V_t^{H}}{V_{t-1}^{H}} - 1\right) - \Lambda_t\frac{V_{t+1}^{H}}{\left(V_t^{H}\right)^2}\omega_2\left(\frac{V_{t+1}^{H}}{V_t^{H}} - 1\right) \tag{E.20}$$

Bonds:

$$i_t^{10} = \left(\mathcal{C}_{10} + k_1 Q_t^{10}\right)/Q_{t-1}^{10} \tag{E.21}$$

$$i_t^{L} = \pi_t\left(\mathcal{C}_{L} + k_1 Q_t^{L}\right)/Q_{t-1}^{L} \tag{E.22}$$

Commercial Bank:

$$Q_t^{Rep} = \frac{1}{\Lambda_t} \tag{E.23}$$

$$\varpi_t^{FI} = Q_{t-1}^{Rep} X_{t-1} - X_t \tag{E.24}$$

Pension fund:

$$V_t^{PF} = \varsigma \left(r_t^{LDI} V_{t-1}^{LDI} + r_t^{V} V_{t-1}^{PF,M} + r_t B_t^{PF} - r_t^{10} B_{t-1}^{P10} - Q_{t-1}^{Rep} X_{t-1}^{CB} \right) + (1-\varsigma)\, v \tag{E.25}$$

$$V_t^{PF} - \Psi_t^{PF} = V_t^{LDI} + V_t^{PF} - B_t^{P10} - X_t^{CB} \tag{E.26}$$

$$\gamma \left(\chi - \ell_t VLDI_t / B_t^{PL} \right) = E_t \left[r_{t+1}^{M} - \left[1 + \omega_P \left(V_t^{PF,M} - \tilde{V}_{t-1} \right) / B_{i,t}^{PL} \right] r_{t+1}^{LDI} \right] \tag{E.27}$$

$$\tilde{V}_t = E_t \left[V_{t+1}^{PF} \right] \tag{E.28}$$

$$D_t^{LDI} = (1-\varsigma) \left(r_t^{LDI} V_{t-1}^{LDI} + r_t^{M} V_{t-1}^{PF,M} - r_t^{10} B_{t-1}^{10} - v - \Psi_t^{PF} - Q_{t-1}^{Rep} X_{t-1}^{CB} \right) \tag{E.29}$$

$$\Psi_t^{PF} \equiv \frac{\omega_P}{2} B_{i,t}^{PL} \left(V_t^{PF,M} - \tilde{V}_{t-1} \right)^2 \tag{E.30}$$

$$B_t^{PL} = Q_t^{L} \times \bar{B}^{P} \tag{E.31}$$

$$E_t \left[r_{t+1} - r_{t+1}^{LDI} \right] = \gamma \left(\chi B_{i,t}^{PL} - \ell_t VLDI_{i,t} \right) / B_{i,t}^{PL} - \lambda_t^{\mathcal{M}} \tag{E.32}$$

$$\lambda_t^{\mathcal{M}} = 0 \quad \vee \quad B_t^{PF} = \mathcal{M}_t \tag{E.33}$$

LDI:

$$V_t^{LDI} = B_t^{LDI} - X_t \tag{E.34}$$

$$V_t^{LDI} = r_t^{L} B_{t-1}^{LDI} - Q_{t-1}^{Rep} X_{t-1} - \varpi_t^{L} \tag{E.35}$$

$$\ell = \frac{V_t^{LDI} + X_t}{V_t^{LDI}} \tag{E.36}$$

Central Bank:

$$\log\left(i_{t+1}\right) = \rho_r \log\left(i_t\right) + \left(1-\rho_r\right)\left[\log\left(\bar{i}\right) + \varrho_y \log\left(\tilde{y}_t/\bar{y}\right) + \varrho_\pi\left(\pi_t - \bar{\pi}\right)\right] \tag{E.37}$$

$$\tilde{y}_t \equiv c_t + \hat{I}_t \tag{E.38}$$

$$B_t^{CB10} = \rho_{FS} B_{t-1}^{CB10} + \epsilon_t^{CB10} \tag{E.39}$$

$$B_t^{CBL} = \rho_{FS} B_{t-1}^{CBL} + \epsilon_t^{CBL} \tag{E.40}$$

$$X_t^{CB} = \rho_X X_{t-1}^{CB} + \epsilon_t^{CBL} \tag{E.41}$$

$$0 = B_t^{CB} + B_t^{CB10} + B_t^{CBL} + X_t^{CB} \tag{E.42}$$

$$CBS_t = r_t B_{t-1}^{CB} + r_t^{10} B_{t-1}^{CB10} + r_t^L B_{t-1}^{CBL} + Q_{t-1}^{Rep} X_{t-1}^{CB} \tag{E.43}$$

$$\mathcal{M}_t = \left(1 - \epsilon_t^{\mathcal{M}}\right) m B_t^{LDI} \tag{E.44}$$

Treasury:

$$B_t + B_t^{10} + B_t^L + T_t = s y_t + r_t B_{t-1} + r_t^{10} B_{t-1}^{10} + r_t^L B_{t-1}^L \tag{E.45}$$

$$B_t + B_t^{10} + B_t^L = \bar{b} y \tag{E.46}$$

$$B_t = \vartheta\left(B_t + B_t^{10} + B_t^L\right) \tag{E.47}$$

$$B_t^L = \vartheta_L\left(B_t + B_t^{10} + B_t^L\right) \tag{E.48}$$

Bond market clearing:

$$B_t = B_t^H + B_t^{CB} + B_t^{PF} \tag{E.49}$$

$$B_t^{10} = B_t^{H10} + B_t^{CB10} \tag{E.50}$$

$$B_t^{HL} = B_t^L + B_t^{PL} \tag{E.51}$$

Capital producer:

$$\hat{I}_t = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t \tag{E.52}$$

$$1 \approx p_t^k \left[1 - S'\left(\frac{I_t}{I_{t-1}}\right) \frac{I_t}{I_{t-1}}\right] \tag{E.53}$$

Wholesale firm:

$$w_t = (1-\theta) p_{m,t} Z (u_t K_t)^{\theta} n_t^{-\theta} \tag{E.54}$$

$$p_t^k \delta'(u_t) = \theta p_{m,t} (u_t K_t)^{(\theta-1)} n_t^{1-\theta} \tag{E.55}$$

$$p_t^k = E_t \Lambda_{t,t+1} [\theta p_{m,t+1} Z (u_{t+1} K_{t+1})^{\theta-1} u_{t+1} n_{t+1}^{1-\theta} + (1 - \delta(u_{t+1})) p_{t+1}^k] \tag{E.56}$$

$$Y_t = Z (u_t K_t)^{\theta} n_t^{1-\theta} \tag{E.57}$$

$$K_{t+1} = \hat{I}_t + (1 - \delta(u_t)) K_t \tag{E.58}$$

Retail firm:

$$(1-\eta) + \eta p_{m,t} = \nu_t + \Lambda_t \left(Y_{t+1}/Y_t\right) \nu_{t+1} \tag{E.59}$$

$$\nu_t \equiv \varphi \left(\frac{\pi_t}{\bar{\pi}}\right) \left(\frac{\pi_t}{\bar{\pi}} - 1\right) \tag{E.60}$$

Stock broker:

$$\varpi_t \approx Y_t - w_t n_t - I_t \tag{E.61}$$

Labour union:

$$(1-\eta_w) + \eta \left(w_{h,t}/w_t\right) = \nu_{w,t} + \Lambda_t \left(n_{t+1}/n_t\right) \nu_{t+1} \tag{E.62}$$

$$\nu_{w,t} \equiv \varphi_w \left(\frac{\pi_t w_t}{\bar{\pi} w_{t-1}}\right) \left(\frac{\pi_t w_t}{\bar{\pi} w_{t-1}} - 1\right) \tag{E.63}$$

$$\varpi_t^U = n_t \left[w_t - w_{h,t} \right] \tag{E.64}$$

Shocks:

$$\zeta_t = \rho_\zeta \zeta_{t-1} + (1 - \rho_Z)\, \bar{\zeta} + \epsilon_t^\zeta \tag{E.65}$$

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