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System-wide stress simulation

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Abstract

We present a model for assessing how the UK's system of market-based finance — an increasingly important source of credit to the real economy since the financial crisis — might behave under stress. The core of this model is a set of representative agents, which correspond to key sectors of the UK's financial system. These agents interact in asset, funding (repo), and derivatives markets and face a range of solvency and liquidity constraints on their behaviour. Our model generates 'tipping points' such that, if shocks are large, or if headroom relative to constraints is small, lower asset prices can cause solvency/liquidity constraints to bind, resulting in forced deleveraging and large endogenous illiquidity premia. We illustrate such an outcome via a stress scenario in which a deteriorating corporate sector outlook coincides with tighter leverage limits at key intermediaries. Our findings highlight the key role played by broker-dealers, commercial banks, investment funds and life insurers in shaping these dynamics.

Key words: Systemic risk, market-based finance, fire sales, stress testing.

JEL classification: G18, G21, G22, G23.

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1. Introduction

Market-based finance – the provision of finance to the real economy by non-bank financial institutions, including via financial markets – has grown considerably over the past decade. In the United Kingdom, nearly all net finance raised by private companies since the crisis has been through the issuance of equities and bonds. Globally, the assets of non-bank financial institutions reached US$160 trillion in 2016, an increase of over 50% since 2008 (FSB (2017)). The growth of market-based finance has had numerous benefits for society. It has helped mitigate the damaging effects of reduced credit provision by banks following the global financial crisis, providing households and businesses with an alternative source of funding. It may have provided risk-sharing benefits of diversity for individual investors. And as market-based finance typically involves lower leverage than in a bank-centric system, some argue systemic risk has been reduced.

But we do not yet know how market-based finance will respond under a severe stress. In particular, the rapid growth of non-bank credit provision since the global financial crisis means that the system's behaviour during previous periods of stress may not be a good guide to future behaviour. A particular concern is how core participants in the system – dealers, open-ended investment funds, hedge funds, and long-term investors (like insurance companies and pension funds) – might interact in periods of stress. Behaviour that might be individually rational, such as reducing risk-exposure when asset prices decline and volatility increases, might generate instability at the system-level, including via fire-sales (Cunliffe (2017), Brazier (2018)).

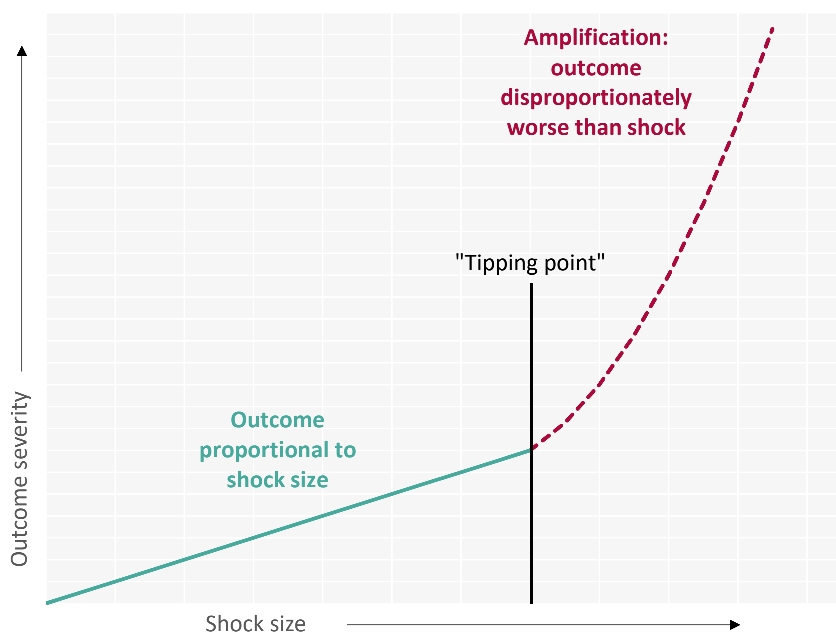
In this paper, we develop a general equilibrium model that can be used to simulate how the UK's system of market-based finance might behave under stress. The core of this model is a set of representative agents, which correspond to key sectors of the UK's financial system. These agents interact in asset, funding (repo) and derivatives markets. We articulate the occasionally-binding solvency and liquidity constraints some of these agents face – including those imposed by regulators, such as risk-based capital and leverage constraints, those imposed by by market-participants, such as the need to post initial and variation margin in repo and derivative markets, and those imposed by procyclical investor behaviour. And we posit decision rules for how these agents adjust their balance sheets when these constraints bind. A key feature of our model is that liquidity in secondary asset markets and funding markets is endogenous, determined by the portfolio choices and constraints faced by long-term investors and funding providers.[1] Using these assumptions,

[1] We therefore avoid appealing to fixed estimates of the 'price impact' of asset sales obtained from historical data, as is the case in some other approaches, e.g. Greenwood et al. (2015). This is particularly valuable given the material changes to the size and composition of the market-based finance system, including to its regulation, since the financial crisis.

we analyse how the system responds to various fundamental shocks depending upon its initial state.

In general, given the nonlinear structure of our model, we find 'tipping points' beyond which the effect of shocks is amplified substantially. Figure 1 provides a stylised illustration of this property of the model. If agents have substantial headroom relative to their constraints such that the system is in the left-hand region of this figure, our model predict that shocks will have relatively proportional effects on asset prices – and that endogenous illiquidity premia will be small. But if shocks are especially large, or if there is little headroom relative to constraints such that the system moves to the right-hand region of this figure, the model can generate an adverse feedback loop in which lower asset prices cause solvency/liquidity constraints to bind, pushing asset prices lower still and generating large endogenous illiquidity premia. We use our model to explore both the determinants of these tipping points, and the constraints and shocks that matter most in terms of the resulting amplification.

Figure 1: *Tipping points in the impact of shocks*



Our model features several key contagion channels that are emphasised in the literature. The first arises from the interaction between agents' solvency and liquidity constraints and their common holdings of assets. This can give rise to 'fire sale' externalities in which forced asset sales by one agent can prompt falls in market prices, reducing the net worth of other agents, which in turn forces them to also sell (Shleifer and Vishny (2011)). A second contagion channel, which interacts with the first, centres on the repo market and the possibility that cash-providers either pull short-term funding or increase haircuts, forcing those reliant on repo funding to deleverage, including by reducing their own provision of repo (Gai, Haldane and Kapadia (2011)). A similar type of contagion in the model can also take place via derivatives markets via margin calls. As in Brunnermeier and Pedersen (2008), these channels are mutually reinforcing.

We parameterise the model using a new dataset that draws on a variety of sources of information on UK financial markets and institutions. These data document the assets and liability positions of key sectors of the UK's financial system, sourced from a range of regulatory and public sources, including the Bank of England and UK Office for National Statistics, reports to prudential and conduct regulators, as well as information from commercial data providers. In total, we account for £16.8tn of assets across the sectors in this dataset. We also identify holdings of almost £2.2tn of UK government bonds, corporate bonds and equities, covering around 50% of the stock of government bonds, and around 40% of the stock of outstanding corporate bonds and equities. The largest data gaps we face relate to the hedge fund sector.

We analyse the properties of the model through the lens of a stress scenario in which the outlook for corporate profitability deteriorates sharply, leading to higher expected defaults and lower income growth. While the focus in a typical banking system stress test would be assessing the impact of such loss rates for banks' capital adequacy, our interest is in how the feedback and interaction effects in our model affect the risk-bearing capacity of the wider financial system. Our baseline calibration predicts a relatively orderly adjustment in response to this shock, with selling pressure from fast-moving investors (hedge fund and investment fund sectors) partly offset by insurers' and pension funds' countercyclical behaviour. However, if this initial shock occurs when broker-dealers and commercial banks are close to leverage and risk-based capital limits, its impact is amplified greatly. Broker-dealers in this case pull reverse repo provision to 'downstream' investors, including the hedge fund sector, limiting these agents' capacity to stabilise the market. Similarly, we find that asset sales by capital-constrained commercial banks significantly amplify the impact on asset prices.

Our model predicts a substantial decline in asset prices and funding market activity in this scenario, with the pure liquidity component of corporate bond spreads jumping by around 35 basis points, an outcome that could have significant adverse effects on the wider macroeconomy. We find that a social planner facing this scenario would have the biggest 'bang for her buck' by first alleviating the capital constraints facing the dealer and commercial bank, and then by providing liquidity to the investment fund sector, alleviating its need to fire-sell assets. Our results also highlight the solvency position of the life-insurance sector as a key tipping point for the system: we find qualitatively different dynamics when the insurer switches from being a marginal buyer supporting asset prices to being a forced seller.

Just as all models are necessarily abstractions of reality, there are several caveats to bear in mind when interpreting our results. First, while our of choice to use representative agents to model key financial sectors provides parsimony and tractability, it comes at a significant cost – namely, we are forced to abstract from within-sector heterogeneity. The same is true for asset classes: we do not distinguish between investment-grade and high-yield corporate bonds, for instance. This is likely to be an important impediment for understanding how some risks can propagate throughout the system. We are not able to model the role of central counterparties (CCPs), for instance. Nor can we capture the possibility of classic bank runs. Moreover, by focusing on sectoral averages, our model is likely to overstate the resilience of the system in situations where sectors are only as strong as their weakest institutions. Second, while the coverage of our model is comprehensive relative to existing models in the literature, there are nevertheless important markets and sectors missing, including securities lending, credit derivatives and key foreign asset classes, as well as interactions with rest-of-the-world agents via asset and funding markets. For these reasons, the main utility of our model is as a high-level organising framework for assessing the resilience of market-based finance – and in particular, as a device for identifying sectors and markets that require greater in-depth study given their contribution to tipping points and amplification – rather than a tool for generating precise point predictions.

Related literature:–

This work builds upon a number of strands of the existing literature. The first examines how the sales of assets by one financial institution acting in its own interest can encourage, or even force, other market participants into sudden asset sales. Such 'fire sales' can be prompted by funding shortages and/or falls in institutions' net worth, both of which can be caused by an initial fall in asset prices (see Shleifer and Vishny (1992)). For example, Greenwood et al. (2015) and Cont and Schanning (2017) examine how, after an initial fall in asset prices, leverage constraints on banks can trigger sales of assets, generating additional falls in asset prices. Given that other banks also hold these assets, there is contagion across the banking sector via common asset holdings. Similar dynamics have also been observed between sectors. Brunnermeier and Pedersen (2009) model margin-price spirals in which collateral calls in securitised funding markets cause fire sales by different leveraged investors, pushing down market prices and causing further sales

A second strand of literature focuses on how financial institutions respond to changes in asset prices, and how such responses vary with their business models and balance sheet structures. Braouezec et al. (2016) show that, as a result of capital and liquidity constraints, banks may choose to deleverage in response to certain shocks. Douglas et al. (2017, 2018) model the response of UK life insurance companies and pension funds to changes in asset prices, highlighting the potential for pro-cyclical behaviour. Other papers outline the channels through which investors in open-ended investment funds might act pro-cyclically, causing asset management firms to initiate sales of assets as their prices fall (see, for example, Chevalier and Ellison (1997) and Goldstein et al. (2017)).

A third strand of literature seeks to combine these insights to simulate stress across the financial system. Baranova et al. (2017) build a representative agent model in which broker-dealers and hedge funds supply liquidity in corporate bond markets. They assess the degree to which redemptions – and subsequent sales of assets – by open-ended investment funds could have a destabilising effect on market prices. They find that redemptions from European open-ended corporate bond funds of a magnitude similar to that witnessed during the crisis could – in tandem with constraints on the leverage of intermediaries – lead to material falls in the value of asset prices. Halaj (2017) apply an agent-based set up to assess how shocks to the funding of banks can amplify sales of assets by asset managers. And Bookstabber et al. (2017) develop a more granular agent-based framework at the level of individual investors, rather than sectors. They show how stress can propagate via common asset holdings and funding-based contagion channels occurring within a stylised system of cash providers, dealers and investors. Like Baranova et al, however, these approaches consist only of partial equilibria in which the role of longer-term investors in buying securities sold by the asset manager is not explicitly modelled; rather the price impact of such asset sales on prices is estimated using historical data.

As described above, the framework offered here combines the richness of the literature on individual agents' behaviours and the scope for these to cause contagion, with a general equilibrium framework. Such a general equilibrium method has also been employed in a similar context elsewhere in the literature – for example Calimani et al. (2017), who model contagion between asset managers and banks in a general equilibrium model with a single traded security. The distinguishing feature of our paper, however, is the broader range of modelled financial sectors and instruments.

The paper is structured as follows. The next section describes characteristics of the market-based finance sector in the United Kingdom. Details of the model are given in Section 3. The data we use to parameterise the model is described in Section 4. Section 5 documents results from the model, where we analyse price determination, the effects of single shocks and also a multi-layered stress scenario. Key figures and tables documenting our results are presented in Annex A; Annex B sets out details of the parameterisation.

2. Characteristics of the market-based finance sector

This section describes characteristics of the market-based finance sector, summarises recent trends, and presents a stylised birds-eye view of the main institutions and systemic risk channels, which subsequently form the building blocks of the model we present in Section 3.

Most credit is channelled to both financial and non-financial firms via two routes: the banking system or market-based finance. By 'market-based finance' we mean the system of markets, non-bank financial institutions and infrastructure that (alongside banks) provides financial services to support the real economy. These services include intermediating between saving and investment, and the transfer of risks. In practice real economy firms access credit through the market-based finance system by issuing bonds and equities. The importance of the market-based finance system has grown considerably since the financial crisis, both in the UK and globally. The total assets of firms involved in the provision of market-based finance now account for almost half of total financial system assets in the United Kingdom and globally. The total assets of sectors involved in market-based finance globally were $160 trillion at the end of 2016 (Figure A.1).

Some sectors have grown particularly rapidly since the crisis – the total net assets of open-ended investment funds have more than doubled in the UK and globally. And the share of corporate bonds held in open-ended investment funds in the United Kingdom and the euro area has increased by more than 70% since the financial crisis. The total volume of corporate bonds and equities in issuance has grown commensurately, with UK corporate bonds in issuance growing by 75% since the crisis. Market-based finance has also been important in flows terms – since 2007, nearly three quarters of net finance raised publicly by UK private non-financial corporations in the UK has been through the issuance of tradable securities, and most of this through corporate bond issuance (Figure A.2).

Figure A.3 presents a stylised representation of the market-based finance system.[2] Panel (a) shows that the real economy gets access to credit via the traditional bank-based route and via market-based finance. We can also see that, unlike the banking system, the provision of market-based finance relies on the functioning of secondary asset markets. Secondary asset markets are where a wide range of investors trade securities and where the market price of these securities is determined. Going from left to right, panel (b) shows the workings of the secondary asset markets. Cash flows from the real economy to a range of sectors. These sectors invest the real economy's cash in the capital markets that are intermediated by dealers (e.g. corporate bonds) or exchanges (e.g. equities). Institutional investors and open-ended funds generally invest on a long-only basis, while hedge funds

[2] We thank Niki Anderson for providing us with this figure.

also engage in short-selling, illustrated by the bi-directional flows.

The functioning of secondary asset markets is in turn supported by securities financing and derivatives markets – these subsequent layers of the system are shown in panels (c) and (d). Securities financing markets (panel (c)) can be separated into repo markets, where cash is exchanged for securities and securities lending markets where securities are exchanged for other securities as well as cash. Repo markets allow leveraged investors to access the cash needed to purchase securities on secondary markets. Broker-dealers intermediate the market by recycling cash from cash providers – MMFs, CCPs and commercial banks – to leveraged investors. Repo markets are large in absolute terms – the volume of gilt repo and reverse repo outstanding across the UK financial system is £700bn – as they support other functions of the UK financial system.

Securities lending markets facilitate the movement of securities between leveraged and unleveraged investors to allow them to engage in short-selling and to access the necessary collateral to back their funding. The absolute size of the UK securities lending market can be estimated by looking at total GBP securities on loan, around £200bn as of the middle of 2018. Broker-dealers also sit in the middle of the securities lending market and match securities lenders and securities borrowers. Both the repo market and securities lending market rely on the government bond market as the principal source of collateral.

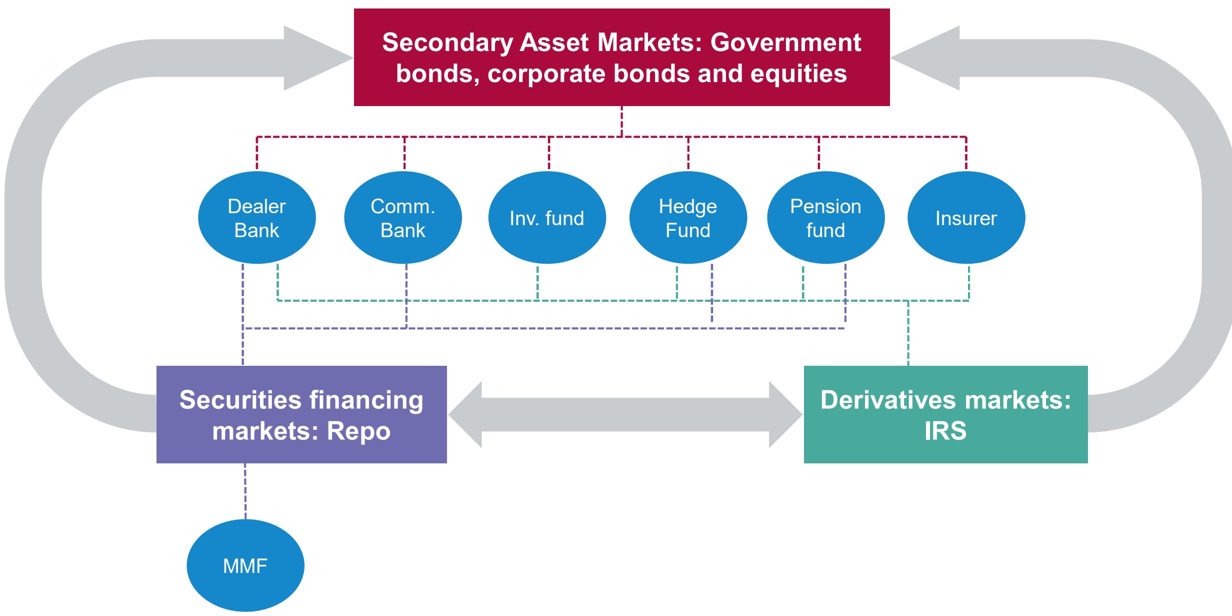
Panel (d) shows the functioning of derivatives markets. These are used to hedge positions in secondary asset markets, to speculate and to access leverage. The market is dealer-intermediated, with CCPs sitting in the middle of the majority of inter-dealer trades. There are two-way cash and margin flows between market participants. Derivatives markets are extremely large in notional terms, once the various types of derivatives used across the system have been accounted for. The notional value of GBP Interest Rate Swap (IRS) contracts alone – the derivative contracts this paper focuses on – is $28.5 tn. Interest rate swaps are used by market participants to manage interest rate risk and to access leveraged exposure to movements in interest rates.

3. Model description

This section describes the structure of the model. We begin by describing the markets for tradeable securities, repo and derivatives; we then set out the objectives and constraints of each agent.

Figure 2 presents a schematic of the sectors we capture in the model, alongside the asset and funding markets in which they interact. The model captures most of the market participants that are critical for the functioning of the UK's financial system. All the major secondary markets for securities are included: government bonds; corporate bonds; and equities. So too is the main secured financing market: the repo market. We also capture the interest rate swap (IRS) market, which is both the largest derivatives market and also the derivatives market most closely tied to the provision of market-based finance.

Figure 2: *Markets, sectors and interconnections in the model*



We model the main 'buy-side' investors: pension funds; insurance companies; and investment funds. Hedge funds act as arbitrageurs. Turning to the banking sector, we differentiate the functions of a broker-dealer, which intermediates repo and IRS markets, and a commercial bank, which acts as a provider of funding to the repo market. Finally, money market funds are included as a provider of funding into the repo market. We summarise each sector via a representative agent, which is intended to reflect its typical behaviour and balance sheet position.

3.1. Markets for securities, funding and derivatives

3.1.1 Tradeable securities

There are three markets for tradeable financial securities in the model: corporate bonds; equities; and government bonds.[3] These asset prices are determined endogenously within the model. The equilibrium price vector equates agents' buy (demand) and sell (supply)

[3] We assume that all the tradeable markets are secondary markets where trading takes place of securities already in issuance. We abstract from primary markets and assume no new issuance or redemption of securities, i.e. the total volume of corporate bonds, equities and government bonds remains fixed. This is a reasonable assumption given the relatively short time horizon of the model.

orders, alongside the demand and supply of repo funding.[4] Movements in the prices of corporate bonds and equities are informative about how the provision of market-based finance, and hence real economy financing, could be affected in the scenarios we consider.

Holders of these tradeable securities are assumed to mark them to market. This allows us to model the feedback effect between asset prices and funding and regulatory constraints for individual agents. It also allows us to capture 'fire sale' externalities that link agents/sectors via their common holdings of assets. Actions by one agent therefore have spill-over effects to the solvency and liquidity positions of other agents in the system.

We model securities issued by UK institutions only. Moreover, only UK-domiciled financial institutions are assumed to participate actively in these markets. We abstract from currency denomination in the model and treat all securities as if they have been issued in pounds sterling (£). While we include agents outside of the United Kingdom (henceforth referred to as the 'rest of the world') as a passive holder of these securities, we do not model their demand and supply, which is assumed to remain unchanged over the simulation horizon.

Agents also hold other assets whose prices are not determined within the model. One such asset is cash, which is held as a deposit at the commercial bank. We also include a residual 'other assets' category, which includes claims on the rest of the world, securities and other assets outside the scope of the model (e.g. asset backed securities and property). Agents can buy and sell such assets, but doing so does not change their price, i.e. we assume that UK firms are price-takers in such markets.

3.1.2 Repo market

We assume all repos are collateralised by UK government bonds ('gilts').[5] This effectively precludes the possibility that the default – or potential default – of a counterparty in the model might impact the solvency of its creditors.[6] Though agents have several other types of debt liability[7] in the model – including longer-term bonds – their repo funding is the only element determined endogenously within the model. This reflects the repo market's

[4] We make the simplifying assumption that demand and supply orders are satisfied as long as all agents have the balance sheet capacity to accommodate and fund trades. In practice, there may be significant frictions in some markets that hinder market clearing, particularly those that are dealer intermediated, e.g. corporate bond markets. See Baranova et al. (2017) for a model where markets 'break' when selling pressure exhausts the intermediation capacity of the dealer.

[5] While risky securities are also used as collateral in repo transactions, around 90% of sterling repo is collateralised with government bonds.

[6] This was an important channel of contagion between financial institutions during the global financial crisis; see Brazier (2017).

[7] Agents in the model also have a variety of other non-traded liabilities, including equity, bonds (the dealer), deposits (the commercial bank) and customer policies (the pension fund and insurer).

crucial role in the system of market-based finance (CGFS (2017)).[8]

New repo lending creates money, which is held as a deposit at the commercial bank. Only the commercial bank can create new bank deposits. It does so by entering into a repo transaction with the dealer, and in doing so expands both its assets (i.e. the reverse repo transaction) and liabilities (the dealer's deposit). The commercial bank's ability to create deposits is constrained by its leverage and other constraints outlined below.[9] The dealer then circulates bank deposits within the financial system via the repo market, borrowing cash from the money market fund and commercial bank and lending it to the pension fund and hedge fund.

There are two maturities of repo in the model: short-term repos mature within the period we study (assumed to correspond to one month); long-term repos mature beyond this horizon. The quantity of short-term repo funding is determined endogenously, and responds when lenders pull funding and/or borrowers adjust the amount they wish to borrow. Because haircuts on repo can only be set at their inception, an increase in haircuts only affects short-term repo lending. The quantity of funding extended via longer-term repos is fixed. This set-up means that the dealer – which intermediates in this market by borrowing short-term funds and lending at a longer tenor – can experience shortfalls in its funding that arise from the withdrawal of short-term repo funding.

The haircut h varies with the deviation of government bond prices from their initial level:

$$h_t = h_{t-1} + \max(0, \alpha^h(\frac{p_{GB,t} - p_{GB,t-1}}{p_{GB,t-1}} - \theta^h) + \epsilon_t^h) \quad (1)$$

where h_{t-1} is the initial haircut level, α^h is an elasticity coefficient, θ^h denotes the threshold level after which asset price falls begin affecting the haircut level; $p_{GB,t-1}$ and $p_{GB,t}$ are the initial and current price of government bonds respectively. In addition, the haircut is subject to exogenous shocks ϵ^h.[10]

Agents borrowing cash via the repo market may need to encumber more government bonds either to meet an increase in the haircut, or if the market price of government bonds falls. The cost of borrowing (the 'repo rate') is also exogenous. Cash providers (the money market fund and the commercial bank) are assumed to accommodate the demand for repo

[8]Whilst financial institutions also borrow via other markets, these tend either to be less important short-term sources of funding for non-bank institutions (for example unsecured lending is extended predominantly between banks) or are economically similar to repo (e.g. margin trading offered by prime brokers is collateralised and margined in a manner similar to repo); see Baranova et al. (2016).

[9]This contrasts with traditional textbook treatments of banks, whereby financial intermediaries are constrained by their holdings of central bank reserves.

[10]Haircuts are often related to the volatility of the collateral asset. We have in mind that price falls in excess fo θ_h increase this volatility, and thus the haircut.

lending passively until their constraints bind. In stress, therefore, dynamics in this market play out via the withdrawal of the quantity of repo funding rather than an increase in the price at which such funding is extended. This is in line with the experience of government bond-backed repo during the crisis in 2008 (Copeland et al. (2014)).

3.1.3 Interest rate swap derivatives

Our model captures agents' trades in IRS. We focus on this market for three reasons. First, IRS contracts are closely linked to the provision of market-based finance as they are used by market participants to hedge interest rate exposure on their liabilities and to access synthetic leverage.[11] Second, the quantity of IRS outstanding dwarfs that of other synthetic instruments.[12] And third, it allows us to capture the interaction between the government bond market and the IRS market.

We use trade repository data to estimate each sector's participation in the IRS market, and hence its exposure when interest rates change. Consistent with this, we assume the pension fund and insurer use derivatives to hedge their long-term liabilities to policy holders, and therefore gain on derivatives when interest rates fall. By contrast, the investment fund and hedge fund use derivatives to maintain a target level of total leverage across both cash and synthetic instruments. The dealer is assumed to intermediate the IRS market and to have no exposure to changes in interest rates itself.[13] The money market fund and commercial bank are assumed not to participate. While in reality commercial banks use derivatives to hedge the interest rate risk inherent in the maturity transformation they conduct, we have nevertheless excluded these agents given their limited aggregate exposure to interest rate risk in the data.

Agents' derivatives positions reference the market price of government bonds: changes in the government bond yield determine the floating rate of the IRS.[14] Positions are marked-to-market, so their value changes with the government bond yield. The change in the value of an agent's derivative position (often known as the DV01) is given by the product of the

[11] It is possible to access synthetic leverage through the use of IRS swaps as these permit obtaining large notional exposures provided there is sufficient capital to satisfy margin requirements. Absent IRS, investors need to have either the same value of capital or outright holdings of bonds in order to get the same notional exposure as available through the IRS.

[12] The BIS estimates that there are $427tn IRS outstanding at the end of 2017 compared to only $87tn for foreign exchange derivatives, the next largest derivatives market (BIS (2018)).

[13] This is equivalent to assuming that the dealer runs a matched book on IRS contracts, so that it perfectly matches the agents on either side of the trade. In reality, the dealer may also have some proprietary directional positions on interest rates.

[14] In reality, IRS typically reference interest rates that reflect bank funding costs (e.g. LIBOR). But because, there are no explicit funding costs in our model, we instead assume that the IRS references the interest rate on the government bond.

notional value of their IRS position, its duration,[15] and any change in the government bond yield.

Derivative positions are subject to margin requirements. Agents must post an initial margin amount in government bonds, which is set exogenously at the inception of each derivative contract. Additional initial margin is required if the value of government bonds falls below the required amount. Derivatives contracts are also subject to variation margin. This involves a transfer of cash between the two counterparties when the market value of the position changes. If the value of the derivative position falls (rises) relative to its initial value, the agent must pay (receive) cash margin to reflect this.

Supply and demand dynamics in the derivatives market differ to those in the repo market in two respects. First, the derivatives market need not clear domestically. We instead assume the rest of the world takes the other side of any residual net derivative exposure. Second, the size of the derivatives market is not constrained. Although the dealer intermediates the market for IRS, we assume that its capacity to do so is effectively limitless. This is because the intermediation of two perfectly-matched derivatives trades gives rise to relatively low capital requirements.[16] We make these two simplifying assumptions because we focus, at least for now, on liquidity risks from margin calls rather than the risks from changes in the quantity of IRS provided or counterparty credit risk.[17]

3.2. Agents' behaviour

This section describes the behaviour of each agent. These behaviours are formed and calibrated using a combination of empirical research, structural models and supervisory judgement. The subsections that follow describe the seven agents of the model. These are grouped into four categories as follows: long-term investors (the pension fund, life insurer and investment fund); an arbitrageur (the hedge fund); cash providers (the money market fund and commercial bank); and an intermediary (the dealer). A summary of agents' behaviours and constraints is given in Table A.1.

[15] We estimate the duration of each agent's IRS position using trade repository data.

[16] Unlike for repo, the dealer intermediating two derivative transactions only maintains capital against the gross net replacement cost, not the full notional amount of the trade.

[17] Risks from a fall in the quantity of IRS contracts – i.e. not being able to enter an IRS contract you would like to – would involve not being able to hedge your interest rate risk to the extent you want to and not being able to attain your desired level of leverage. Counterparty credit risk in the context of IRS contracts is where your counterparty is unable to pay its variation and initial margin payments and defaults instead.

3.2.1 Long-term investors

Generic portfolio optimisation problem

Long-term investors – the life insurer, pension fund and investment fund – are assumed to use the same approach to choosing their optimal asset allocations. Following Markowitz (1952), each long-term investor chooses a vector, ω, of portfolio allocation weights to maximise:

$$E(r_p) - \frac{1}{2}\lambda^i Var^i(r_p) \tag{2}$$

where $E(r_p)$ is the perceived expected return of the portfolio ($r_p = \Sigma_j \omega_j r_j$), $Var^i(r_p)$ is the perceived variance of the portfolio return, λ^i is the risk aversion coefficient; i denotes the investor type, and ω_j and r_j are the portfolio weights and returns on asset j. Long-term investors have the same information about expected returns on each asset class. However, their perceptions of the variance of some asset classes differ, as does their risk aversion parameter – this is one source of heterogeneity in long-term investors' responses to shocks. We calibrate these parameters to match agents' initial asset allocation weights; the risk aversion and perceived asset volatility parameters are subsequently assumed to remain unchanged during simulations.

Long-term investors adjust their desired asset allocations following shocks to fundamental components of asset prices. The speed of adjustment varies across investors.[18] Pension funds are assumed to be the slowest-moving, adjusting their portfolios in full to reflect updated expectations of asset returns only after six months, while insurers and investment funds are assumed to adjust their portfolios over three months and one month respectively. This implies that we only capture one sixth and one third of pension funds' and insurers' adjustment during the one-month time horizon of our model. The mixed investment fund is assumed to rebalance in full over the month covered by the model simulation.

Rebalancing takes place against a backdrop of moving market prices, which also influences the final volume of buy or sell orders placed by these agents. For example, if the pension fund wants to reduce its desired asset allocation in equities in a situation where equity prices are falling, it may end up as a net buyer in order to meet its desired asset allocation weight.

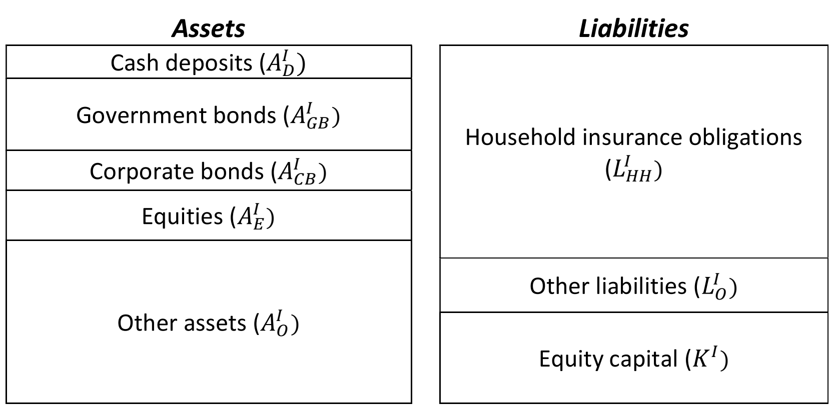
[18]The notion that some long-term investors vary their desired asset allocation relatively slowly in response to changes in macroeconomic fundamentals is supported by industry studies; see FSB Annual Report (2017). This may reflect the fact that strategic changes in asset allocations typically require consensus at board meetings, which are typically held infrequently. While we assume a default speed of adjustment in the model, this is an exogenous parameter that can be varied for sensitivity analysis.

In choosing their portfolios, long-term investors adopt the following decision sequence. First, investors address their short-term liquidity needs that arise from initial and variation margin calls on their IRS positions. Following this, they update their long-term asset allocation weights given new asset price fundamentals using the generic portfolio optimisation approach described above. Finally, they assess whether all constraints and internal targets are satisfied and, if needed, sell tradeable securities to delever. In doing so, they use updated asset allocation weights when deciding how to proportion sales across different asset classes.

The life insurer

The insurance company in our model represents the UK life insurance industry. The insurer receives exogenous life insurance premiums from the household sector and invests these premiums in financial assets on their behalf. It uses the returns on these investments to meet its future liabilities to the household sector. The insurer also enters IRS contracts in order to hedge against changes in the value of its liabilities, which would otherwise increase as interest rates fall. We assume the insurer does not participate in the repo market, consistent with available data. The insurer's balance sheet therefore consists of cash (deposits), financial securities and derivatives, which are matched both by its liabilities to the household sector, liabilities to other institutions, and the (residual) value of its shareholders' equity.

Figure 3: *Life insurer's balance sheet*



The present value of the insurer's obligations to households L^I_{HH} varies with the interest rate on the government bond: $L^I_{HH} = \frac{V^I_{HH,t_0}+\epsilon^I_{HH}}{(1+r_{GB})^{(T^I)}}$ where $V^I_{HH,t_0} = L^I_{HH,t_0}(1+r_{GB,t_0})^{T^I}$ is the future value of insurance obligations to households at the initial time t_0; T^I is the average duration of insurance obligations, and ϵ^I_{HH} is an exogenous shock to the value of insurer's obligations to households.

The insurer chooses its post-shock asset holdings $\{A^I_{D,t}, A^I_{GB,t}, A^I_{CB,t}, A^I_{E,t}, A^I_{O,t}\}$ via the following sequence of decisions:

1. The insurer meets any liquidity outflows caused by IRS initial and variation margins;
2. It rebalances its portfolio in the direction of its desired portfolio weights. These are the weights that maximise equation 2;
3. If required, it deleverages to meet regulatory solvency constraints.

Discussing the first and third of these actions in turn, the insurer transacts in IRS to reduce the volatility of its portfolio. To reduce counterparty risk in its derivatives exposures, the insurer is required to post initial margin, IM^I, in the form of unencumbered government bonds. That is, it must satisfy:

$$IM^I_t = (1-h)p_{GB,t}\tilde{A}^I_{GB,t} \tag{3}$$

where $\tilde{A}^I_{GB,t}$ represents unencumbered government bonds on the insurer's balance sheet ($\tilde{A}^I_{GB} \leq A^I_{GB}$).

This exposes the insurer to liquidity risk. In particular, it must post additional unencumbered government bonds to replenish its initial margin when the value of its collateral falls. In such a circumstance, we assume it adopts the following sequential decision rule:

1. The life insurer uses existing unencumbered gilts on its balance sheet to meet the margin call. If sufficient gilts exist, the process stops;
2. Otherwise the insurer uses its cash holdings to purchase additional government bonds. Again, if sufficient cash exists to purchase the required amount of gilts (net of any shortfall made up in step 1), the process stops;
3. Otherwise the insurer sells risky assets, in proportion to its initial portfolio weights, to purchase additional government bonds. If this step generates insufficient bonds to meet the call, the insurer defaults.

The insurer must also meet calls for variation margin VM^I if its derivative position moves against it. Such payments must be made in cash. Variation margin calls are given by the product of the sensitivity of the insurer's balance sheet to a 1 basis point change in the interest rate, Δ^I, with the change in interest rates. That is,

$$VM^I_t = 10000\Delta^I(r_{GB,t} - r_{GB,t-1}) \tag{4}$$

To meet variation margin, the insurer adopts a similar sequential decision rule to the above:

1. It first uses its existing cash buffer. If $VM_t^I \leq A_{D,t}^I$, the process stops;

2. Otherwise, the insurer sells risky assets (in proportion to initial holdings). If this also generates insufficient cash, the insurer defaults;

The life insurer must also react to any breach in its solvency requirement. This constraint is intended to capture that imposed on UK life insurers by the Solvency II regulation (Douglas et al. (2017)).[19] Under these rules, the insurer must ensure its solvency ratio – defined as the ratio of its shareholder equity to its risk-weighted capital – remains above a minimum level, $\bar{k}^I$. That is,

$$k^I \equiv \frac{K^I}{\kappa_{nm}^I + (p_{CB}A_{CB}^I + p_E A_E^I + A_O^I)\kappa_m^I} \geq \bar{k}^I \tag{5}$$

where K^I is the insurer's capital level ($K^I = A^I - L_{HH}^I - L_O^I$), κ_{nm}^I is capital that the insurer is required to maintain against non-market risks (e.g. longevity risk), κ_m^I is the average capital charge on risky assets, and p_{CB} and p_E denote the prices of commercial bonds and equities respectively. This formulation assumes the capital charge on government bonds is zero.

Market movements of asset prices and shifts in the insurer's obligations to the household sector change the proximity of the regulatory minimum. We assume that when the insurer's solvency constraint binds, it de-risks its portfolio by selling risky assets and buying government bonds, holding its overall level of assets and hence its capital unchanged. In these circumstances, the insurer sells corporate bonds, equities and other assets proportionally to its initial holdings. That is,

$$\frac{p_{i,t}A_{i,t}^I}{\Sigma_i p_{i,t}A_{i,t}^I} = \frac{p_{i,t-1}A_{i,t-1}^I}{\Sigma_i p_{i,t-1}A_{i,t-1}^I} \tag{6}$$

for $i = CB, E, 0$.

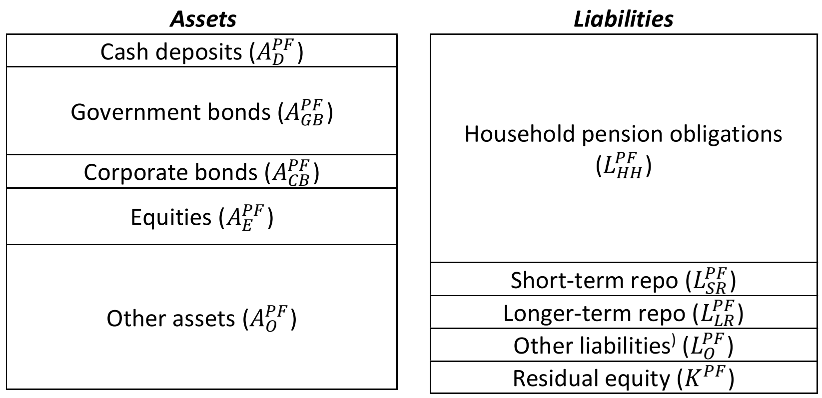
The pension fund

The pension fund in our model represents defined benefit pension schemes provided by

[19]See https://www.eiopa.europa.eu/Pages/Supervision/Insurance/ for details of solvency regulation for UK life insurers.

UK private companies.[20] It has a similar business model to the life insurer: it receives cash from households that it uses to purchase financial assets, the returns on which allow it to meet future obligations to the household sector (Figure 4).

Figure 4: *Pension fund's balance sheet*



The pension fund seeks to stabilise the sensitivity of its solvency position to changes in interest rates. To achieve this, it holds a levered portfolio of government bonds (its 'hedge' portfolio); that is, it uses government bonds as collateral to borrow cash in the repo market, which it invests in additional government bonds. This levered exposure offsets the effect of changes in interest rates on its liabilities: if interest rates fall, the gains the pension fund makes on its hedge portfolio partially offset the increase in the present value of its liabilities.[21]

Following Douglas et al. (2018), the pension fund chooses its post-shock asset holdings $\{A_{D,t}^{PF}, A_{GB,t}^{PF}, A_{CB,t}^{PF}, A_{E,t}^{PF}, A_{O,t}^{PF}\}$ and repo borrowing $\{L_{SR,t}^{PF}\}$ in an analogous sequence to the life insurer:

1. The pension fund first meets any liquidity outflows caused by IRS initial and variation margins or repo withdrawal;

2. It then rebalances its growth portfolio to achieve desired portfolio weights. These are the weights that maximise equation 2;

3. Finally, it adjusts its hedge portfolio to achieve its hedge ratio target (see below).

Taking these actions in turn, the pension fund, like the insurer, must satisfy initial and

[20] In particular, we focus on those defined benefit pension funds whose members are protected by the Pension Protection Fund's 'lifeboat' fund.

[21] Consistent with available data, the pension fund agent is not fully hedged against interest rate risk. Therefore, shifts in interest rates lead to larger movements in the present value of its liabilities than in the value of the hedge portfolio.

variation margin requirements on its IRS exposures, and it must post sufficient collateral to borrow in the repo market. This exposes it to liquidity risk. The pension fund's overall need for unencumbered government bonds resulting from its long-term repo borrowing (L_{LR}^{PF}) and IRS initial margin (IM^{PF}) is given by:

$$p_{GB,t}\tilde{A}_{GB,t}^{PF} = \frac{1}{(1-h)}(IM^{PF} + L_{LR}^{PF}) \tag{7}$$

where $\tilde{A}_{GB,t}^{PF} \leq A_{GB,t}^{PF}$. IM^{PF} is set to 1% of pension fund's IRS exposure at the start of the simulation.

In order to meet this collateral call, the pension fund adopts the following sequential decision rule:

1. It uses existing unencumbered gilts on its balance sheet to meet the margin call. If sufficient gilts exist, the process stops;

2. Otherwise it uses its cash holdings to purchase additional government bonds. Again, if sufficient cash exists to purchase the required amount of gilts (net of any shortfall made up in step 1), the process stops;

3. Otherwise it sells risky assets, in proportion to their initial portfolio weights, to purchase additional government bonds. If this step generates insufficient bonds to meet the call, the pension fund defaults.

The pension fund also faces a potential cash demand from variation margin calls $VM_t^{PF} = 100\Delta^{PF}(r_{GB,t} - r_{GB,t-1})$, where the notation is analogous to that used for the insurer's problem. Its first recourse in this case is to access the repo market, which, provided it has sufficient unencumbered collateral, allows it to maintain its cash buffer. Failing this, we assume the pension fund runs down its cash buffer. And in the last instance, it sells risky securities in the proportion in which it holds them.[22] Furthermore, there is a possibility that the broker-dealer refuses to roll over short-term repos to the pension fund. We assume that the pension fund uses available cash (deposits) to cover any repo outflows. However, if this is insufficient, the fund liquidates assets from its growth portfolio (in proportion to its holdings).[23]

As with the insurer, the value of the pension fund's obligations to households varies with changes in the interest rate on government bonds. That is $L_{HH}^{PF} = (V_{HH,t_0}^{PF} + \epsilon_{HH}^{PF})(1 + r_{GB})^{T^{PF}}$ where $V_{HH,t_0}^{PF} = L_{HH,t_0}^{PF}(1 + r_{GB,t_0})^{T^{PF}}$ and where the notation is analogous to that of

[22]The pension fund liquidates only risky assets from its 'growth portfolio' to meet variation margin since government bonds from the fund's 'hedge portfolio' have the specific function of matching liabilities.

[23]The pension fund responds to cuts in repo by using cash and 'risky' assets instead of selling government bonds because it want to preserve its hedge ratio.

the insurer. Shocks to the value of these obligations lead the pension fund to adjust its asset portfolio via a key behavioural constraint for the pension fund: its so-called 'hedge ratio'.

The hedge ratio is given by the ratio of (a) the sensitivity of its assets (including derivatives) to interest rate movements over (b) the sensitivity of its liabilities to interest rate movements:

$$hr^{PF} \equiv \frac{p_{GB} A^{PF}_{GB} D^{PF}_{GB} + DV01^{PF}_{GB}}{L^{PF}_{HH} D^{PF}_{HH}} = \bar{hr}^{PF} \tag{8}$$

where D^{PF}_{GB} and D^{PF}_{HH} represent the duration of the pension fund's government bond portfolio and obligations to households, respectively, $DV01^{PF}_{GB}$ is the sensitivity of the pension fund's IRS position to changes in government bond yields and $\bar{hr}^{PF}$ is the target hedge ratio. We assume that the pension fund increases this target when its 'funding ratio' – the ratio of its assets not purchased with borrowing to its pension obligations to households – rises. In this event, it uses the additional surplus to 'lock in' a higher hedge ratio:

$$\bar{hr}^{PF}_t = \max(\bar{hr}^{PF}_{t-1}, \bar{hr}^{PF}_{t-1} + \Delta FR_t) \tag{9}$$

where $\Delta FR_t = \frac{A^{PF}_t - L^{PF}_{R,t} - L^{PF}_{O,t}}{L^{PF}_{HH,t}} - \frac{A^{PF}_{t_0} - L^{PF}_{R,t_0} - L^{PF}_{O,t_0}}{L^{PF}_{HH,t_0}}$.

Shocks to asset prices and to the value of its liabilities cause the pension fund's hedge ratio to deviate from its target level. If $hr^{PF}_t < \bar{hr}^{PF}_t$, the pension fund increases its government bond holdings in order to improve its hedge position. The purchase of government bonds is funded by a combination of new repo borrowing and the sale of assets from its growth portfolio.[24] On the other hand, if $hr^{PF}_t > \bar{hr}^{PF}_t$, the pension fund takes no action. If the repo market cannot provide the funding needed to achieve the targeted hedge ratio, the pension fund turns to the derivatives market and enters into additional IRS positions to increase its hedge ratio.

Investment funds

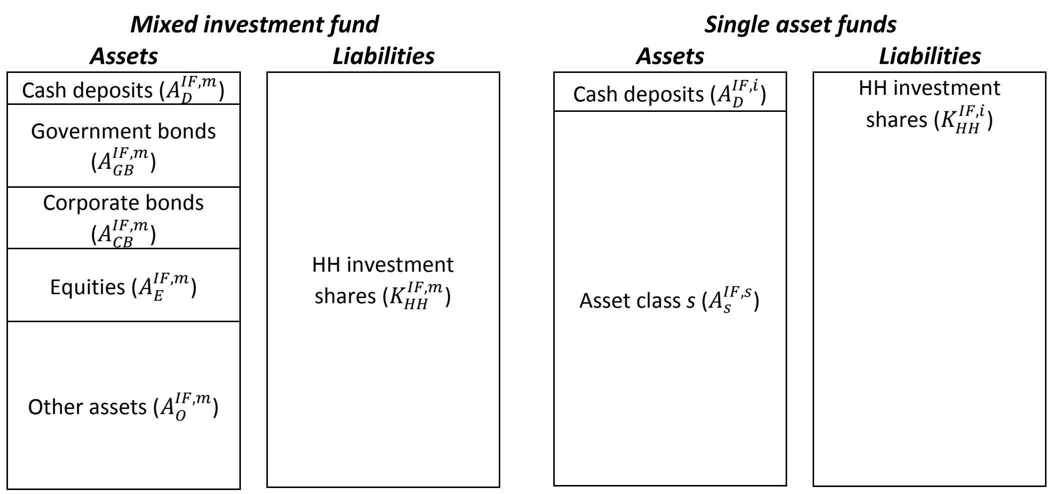
Investment funds in the model represent the sum of all investment funds provided by UK-managed asset management companies. We distinguish between mixed-asset funds and single-asset funds.[25] The former invests in a portfolio of assets with portfolio weights

[24]The split between repo borrowing and asset sales to fund government bond purchases maintains the ratio of pension fund's government bond holdings to its repo borrowing constant over time.

[25]The split of the investment fund entity into mixed and single-asset funds reflects the structure of the sector. While the mixed fund decides its optimal asset allocation, the single asset fund is restricted by its mandate to the one investment asset it can hold. As this translates into different behavioural responses to shocks, we choose to model the two types of fund separately and aggregate their total asset supply/demand volumes.

chosen to maximise expected risk-adjusted returns. On the other hand, four single asset funds invest individually in government bonds, corporate bonds, equities and other assets respectively. Investment funds' assets consist of financial securities, cash and derivatives, while their liabilities consist of investment shares owned by the household sector, and IRS exposure in the case of the mixed fund (Figure 5). Neither fund type participates in the repo market, consistent with available data.

Figure 5: *Balance sheets of investment funds*



The mixed investment fund chooses its post-shock asset holdings $\{A_{D,t}^{IF,m}, A_{GB,t}^{IF,m}, A_{CB,t}^{IF,m}, A_{E,t}^{IF,m}, A_{O,t}^{IF,m}\}$ to implement its desired portfolio weights given by equation 2, subject to it meeting redemption requests from the household sector Ξ_{HH}^{IF}. We assume redemption flows vary systematically with funds' performance, consistent with empirical evidence (e.g. Chevalier and Ellison (1997); Goldstein et al. (2017)). That is,

$$\Xi_{HH,t}^{IF,j} = \rho^{IF,j}((p_t^{IF,j} - p_{t-1}^{IF,j})A_{t-1}^{IF,j}) - \epsilon_t^{IF,j} \tag{10}$$

where j indexes the type of fund (mixed, single-asset), Ξ_{HH}^{IF} is the redemption from the fund in period t, $p_t^{IF,j} A_t^{IF,j}$ is the market value of fund type j at time t, $\rho^{IF,j}$ captures the flow-performance sensitivity of fund type j, and $\epsilon_t^{IF,j}$ is an exogenous shock.

Redemptions are made in cash, which funds raise by selling assets in proportion to their original holdings ('vertical slicing'). This behaviour is consistent with a recent survey of asset management firms conducted by the Bank of England and Financial Conduct Authority (Bank of England (2015)). A similar assumption is made in Cetorelli et al. (2016).

Single asset investment funds hold one type of traded security, alongside cash deposits for liquidity management purposes. Because of their limited mandate, these funds do not react to shocks to asset returns. Instead, they either receive inflows from households that they channel into the asset class in question or they experience redemptions that they meet by selling the asset. When meeting redemptions, the single-asset funds first run down available cash deposits before liquidating their portfolios.

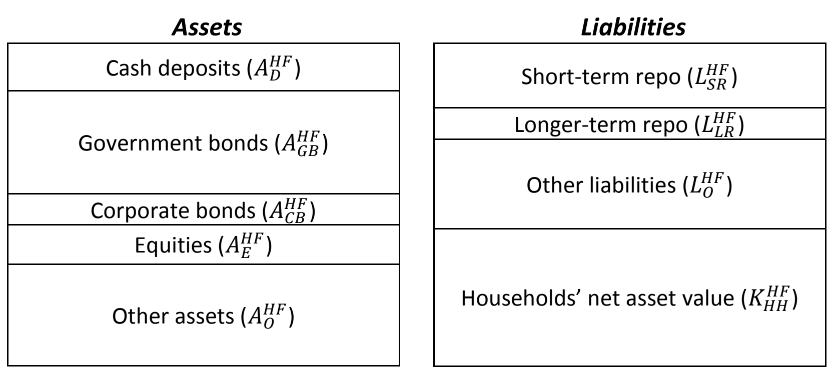
In addition to the risk of redemption shocks, the mixed fund faces liquidity risks from its participation in the derivatives market that are analogous to those faced by insurers and pension funds. We assume an identical decision sequence as for those agents when initial margin or variation margin calls are made. In addition, the mixed fund targets a given leverage ratio by adjusting its IRS exposure. For any new IRS contracts, the fund needs to provide initial margin using its stock of unencumbered government bonds.

3.2.2 Arbitrageurs

The hedge fund

The hedge fund represents the sum of all hedge funds managed in the UK. Its assets consist of securities, deposits, 'other assets' and derivatives; its liabilities consist of repo borrowings, other long-term borrowing, derivative liabilities, and the 'net asset value' of the household sector (Figure 6).

Figure 6: *Hedge fund's balance sheet*



The hedge fund chooses its post-shock asset holdings $\{A_{D,t}^{HF}, A_{GB,t}^{HF}, A_{CB,t}^{HF}, A_{E,t}^{HF}, A_{O,t}^{HF}\}$ and short-term repo borrowing $\{L_{SR,t}^{HF}\}$ to maximise the return of its portfolio by taking advantage of arbitraging opportunities in asset price valuations subject to satisfying its liquidity constraints arising from its participation in IRS and repo markets and self-imposed solvency target – leverage level. Furthermore, the hedge fund is subject to investor redemption outflows.

Similar to other agents, the hedge fund follows the sequence of decisions:

1. It first meets collateral calls from repo and IRS initial margins, and cash calls from variation margin on IRS positions;
2. Next, it sells assets to meet any investor redemptions;
3. Then, it adjusts its repo and IRS positions to ensure it meets the target leverage ratio;
4. Finally, it purchases or sells assets based on the divergence between market prices and its internal asset price target (described below).

Like the long-term investors in the model, the hedge fund faces liquidity risk from its participation in repo and IRS markets. In particular, it must have sufficient government bonds to cover collateral requirements on its long-term repo borrowings and initial margin calls from its IRS positions. We assume it takes the same cascade of actions as the pension fund in order to meet these constraints.

Another source of liquidity risk stems from investors redeeming from the fund. Redemptions Ξ_{HH}^{HF} are assumed to vary pro-cyclically with the value of the entire fund. That is,

$$\Xi_{HH,t}^{HF,j} = \rho^{HF}(A_t^{HF} - A_{t-1}^{HF}) - \epsilon_t^{HF} \tag{11}$$

where ρ^{HF} is the pro-cyclicality coefficient, and ϵ^{HF} is an exogenous shock to redemptions. Redemptions are met by selling a 'vertical slice' of assets, i.e. selling assets in proportion to initial holdings. The exception is encumbered government bonds, which are not sold given they are needed to continue to meet repo and IRS initial margin collateral requirements.

Finally, like the investment fund, the hedge fund aims to meet an exogenously-determined target for its leverage position:

$$k^{HF} \equiv \frac{(A^{HF} + GNE_{IRS}^{HF})}{(K_{HH}^{HF} + L_O^{HF})} = \bar{k}^{HF} \tag{12}$$

where $\bar{k}^{HF}$ is the hedge fund's target leverage ratio and GNE_{IRS}^{HF} is the IRS derivatives gross notional exposure. When it deviates from this target, we assume the hedge fund adjusts by varying, first, its repo borrowing and, if the full adjustment cannot be carried out through repo, the hedge fund turns to the IRS market to adjust its exposures there.

We assume that the hedge fund employs a 'value investment strategy', under which it seeks to profit from perceived divergences between the prevailing market prices of assets and its own estimates of the target prices of the assets. The price target for government bonds is given by:

$$\hat{p}_{GB} = \frac{V_{GB,T}}{(1 + rf + \pi)^T} \tag{13}$$

where V_{GB} is the principal payment of the bond, rf is the long-term risk-free real rate, π is the rate of inflation, and T is the maturity of the bond. Similarly, the price target for corporate bonds is:

$$\hat{p}_{CB} = \frac{V_{CB,T}}{(1 + rf + \pi + E[loss_{CB}] + \xi_{CB})^T} \tag{14}$$

where V_{CB} is the principal payment of the corporate bond, $E[loss_{CB}]$ is the hedge fund's expectation of credit losses from corporate defaults, and ξ_{CB} is the corporate bond risk premium, which we assume remains constant. Lastly, the equity price target is given by a simple dividend-discount relation:

$$\hat{p}_E = \frac{E[Div]}{(rf + \pi + \xi_E - g)} \tag{15}$$

where $E[Div]$ represents expected dividends in the next year, g is the expected long-term growth rate of dividends, and ξ_E is the equity risk premium.

If market prices deviate from these targets, the hedge fund buys undervalued assets ($\hat{p}_i > p_i$) using its available cash holdings and sells overvalued assets ($\hat{p}_i < p_i$). The hedge fund's asset demand is a quadratic function of the gap to target:

$$\Delta A_{i,t}^{HF} = \Phi_{i,t}(\min[1, \left(\frac{\hat{p}_i - p_i}{\alpha}\right)^2]) \tag{16}$$

where α controls the strength of the hedge fund's conviction about arbitrage opportunities. If $\alpha = 0$, the hedge fund would trade as much as possible to arbitrage away even tiny price deviations from fundamentals. As α increases, the hedge fund's willingness to do this reduces.[26] We have set $\alpha = 0.15$, meaning that the hedge fund buys / sells to a lesser extent when the difference between market prices and its target is less than 0.15 in absolute terms.

$\Phi_{i,t}$ is the maximum amount of a given asset that the hedge fund is able to buy or sell, defined as:

$$\Phi_{i,t} = \begin{cases} A_{D,t}^{HF}\left(\frac{A_{i,t}^{HF}}{A_t^{HF} - A_{D,t}^{HF}}\right) & \text{if } \hat{p}_i > p_i \\ -\tilde{A}_{i,t}^{HF} & \text{if } \hat{p}_i < p_i \end{cases} \tag{17}$$

[26] Grossman and Miller (1988), De Long et al. (1990) and Campbell and Kyle (1993) present models in which arbitrageurs act more aggressively the further away prices move from fundamentals.

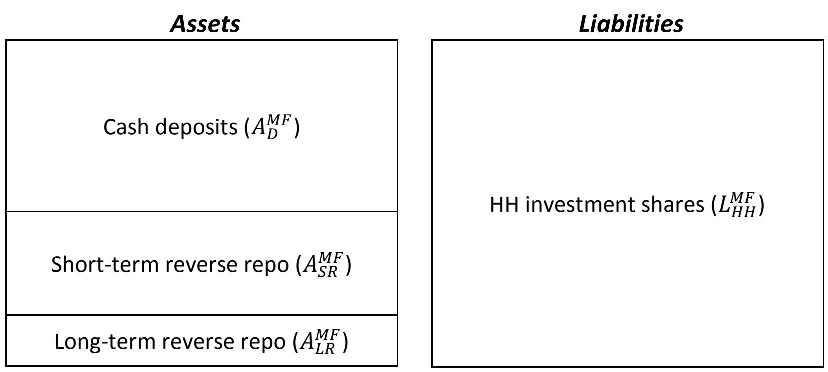
That is, when an asset is undervalued the hedge fund will purchase up to the proportion of its assets (excluding deposits) represented by that asset. When an asset is overvalued the hedge fund will sell up to its total unencumbered holdings of that asset – we do not incorporate the possibility of short selling in this version of the model. We plot this function in Figure A.4 for alternative values of α.

3.2.3 Cash providers

The money market fund

The money market fund (MMF) obtains its funding from the household sector and invests the proceeds in long-term ($>$ 1 month) and short-term ($\leq$ 1 month) reverse repos to broker-dealers, while also holding cash (deposits) for liquidity management purposes (Figure 7).

Figure 7: *Money market fund's balance sheet*



We assume the MMF restricts its provision of reverse repo to the broker-dealer when the broker-dealer's leverage ratio deteriorates. We model this via a simple function, which relates the MMF's reverse repo extension to the dealer (as a share of its net asset value) to the amount of headroom the dealer has above minimum leverage requirements. That is,

$$\frac{A_{R,t}^{MF}}{L_{HH,t}^{MF}} = \begin{cases} \frac{A_{R,t-1}^{MF}}{L_{HH,t-1}^{MF}} & \text{if } k_t^{BD} > k_{t-1}^{BD} \\ \frac{k_t^{BD} - \bar{k}_t^{BD}}{k_{t-1}^{BD} - \bar{k}_t^{BD}} \frac{A_{R,t-1}^{MF}}{L_{HH,t-1}^{MF}} & \text{if } \bar{k}_t^{BD} < k_t^{BD} \leq k_{t-1}^{BD} \\ 0 & \text{if } k_t^{BD} < \bar{k}_t^{BD} \end{cases} \tag{18}$$

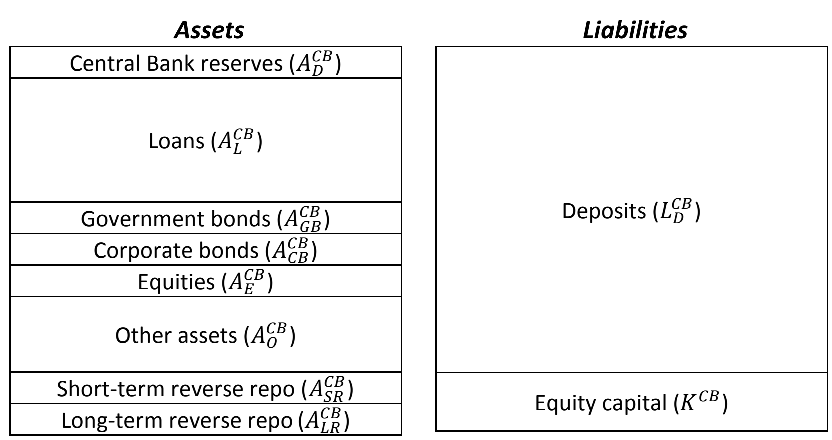
where k_t^{BD} is the broker-dealer's equity-to-asset ratio (leverage ratio) and $\bar{k}^{BD}$ is the regulatory minimum. Once the MMF determines its desired reverse repo provision to the broker-dealer, it implements this by adjusting its short-term repo contracts. Long-term reverse repo previously extended by the MMF does not expire during the simulation period and cannot be adjusted.

The MMF is also subject to the risk of investor redemptions. But unlike the investment fund and the hedge fund, its redemptions are exogenous and unrelated to performance. We assume the MMF meets any redemptions by refusing to roll-over short-term reverse repo to the broker-dealer, using the received cash to meet redemptions. In addition, the MMF reduces proportionally its deposits in the commercial bank, maintaining its desired asset split between repo and deposits following the redemption outflows.

The commercial bank

The commercial bank represents a traditional deposit-funded bank that extends finance to the real economy. Its balance sheet is comprised of bank loans to corporates and households, which we treat as exogenous, some tradeable securities, reverse repo extended to the dealer, and reserves at the central bank. It is funded via cash deposits – including those of other agents in the model – and equity capital. We abstract from the commercial bank's involvement in the IRS market and the liquidity risk this entails; post-crisis, commercial banks hold relatively large liquid asset buffers and can access central bank liquidity facilities, minimising such risks (Figure 8).

Figure 8: *Commercial bank's balance sheet*



The commercial bank plays the role of cash provider in the model.[27] It provides repo funding to the dealer. We assume its liquidity provision is insensitive to the dealer's creditworthiness, unlike the case for the MMF. The only limits on its reverse repo lending capacity are the regulatory constraints its faces.[28] These include constraints on its risk-weighted capital ratio, its leverage ratio (capital relative to unweighted assets), and its liquidity coverage ratio (LCR), which requires its high quality liquid assets (HQLA) to exceed its runnable liabilities.[29] HQLA include traded securities, reverse repo and 'other' tradable assets.

The bank's risk-weighted asset capital constraint is:

$$k_t^{CB,RW} \equiv \frac{K_t^{CB}}{\sum_i \theta_i A_t^{CB}} \geq \bar{k}^{CB,RW} \tag{19}$$

where K^{CB} is the commercial bank's equity, A^{CB} represents the total assets of the bank, and θ_i are risk weights. Its leverage constraint is:

$$k_t^{CB,LEV} \equiv \frac{K_t^{CB}}{A_t^{CB}} \geq \bar{k}^{CB,LEV} \tag{20}$$

And its liquidity coverage ratio is:

$$\frac{\sum_i \omega_i A_t^{CB}}{\delta L_D^{CB}} \geq \overline{lcr} \tag{21}$$

where ω_i are liquidity risk weights that define HQLA, L_D^{CB} are the commercial bank's deposit liabilities, δ is the 'run-off' rate on deposits in the LCR and $\overline{lcr}$ is the target LCR.

The commercial bank is willing to extend reverse repo to the dealer as long as all three constraints outlined above are satisfied. If one or more constraints are breached, the bank switches to deleveraging in order to return to its constraints. In doing so, the commercial bank chooses which assets to sell to minimise fire sale losses given its priors on the price-impact of sales in different markets. Our particular calibration of fire sales employs the Amihud (2002) illiquidity measure, defined as the ratio of the absolute value of returns to traded volume, calibrated to reflect the market impact of sales in normal conditions (Greenwood et al. (2015) and Cetorelli et al. (2016)). In the simulations we report, market impacts of sales can differ significantly from those expected *ex ante*.

[27]In this way, the commercial bank acts as the creator of liquidity in the repo market – similar to the role it plays in traditional money creation. Any reverse repo extended to the dealer on the asset side of its balance sheet is matched by a deposit from the dealer on the liability side of the balance sheet.

[28]Implicitly, therefore, funding the dealer is assumed to be a profitable activity.

[29]This stylised representation of the Liquidity Coverage Ratio is similar to that used by Cecchetti and Kashyap (2016).

Therefore, the commercial bank operates in two regimes. It extends reverse repo to the dealer (to meet its repo demand) if no constraints are breached. And it liquidates assets with the goal of minimising fire sales losses and pulls reverse repo if constraints are breached. Following Coen, Lepore and Schaanning (2018), we assume that in the event of binding constraints, the commercial bank chooses its post-shock (t) asset holdings $\{A^{CB}_{D,t}, A^{CB}_{GB,t}, A^{CB}_{CB,t}, A^{CB}_{E,t}, A^{CB}_{O,t}\}$ and its reverse repo activity $\{A^{CB}_{SR,t}, A^{CB}_{LR,t}\}$ to minimise the expected loss due to fire sales:

$$\mathcal{L}^{CB}_t = -\alpha(A^{CB}_{GB,t}\tilde{E}[\Delta p_{GB,t}(A^{CB}_{GB,t})] + A^{CB}_{CB,t}\tilde{E}[\Delta p_{CB,t}(A^{CB}_{CB,t})] + A^{CB}_{E,t}\tilde{E}[\Delta p_{E,t}(A^{CB}_{E,t})] + A^{CB}_{O,t}\tilde{E}[\Delta p_{O,t}(A^{CB}_{O,t})]) - (1-\alpha)(\Delta A^{CB}_{SR,t} + \Delta A^{CB}_{LR,t}) \quad (22)$$

subject to it satisfying the risk-based capital, leverage and liquidity coverage constraints described above. The term $\tilde{E}[.]$ denotes the price impact of sales expected by the commercial bank in different markets – we do not impose model-consistent expectations so these expectations can differ from the general equilibrium price impacts generated by our model. The parameter $1-\alpha$ is the relative weight the commercial bank places on deleveraging by pulling reverse repo. We calibrate this to reflect the idea that bank is reluctant to damage existing relationships with its counterparties.

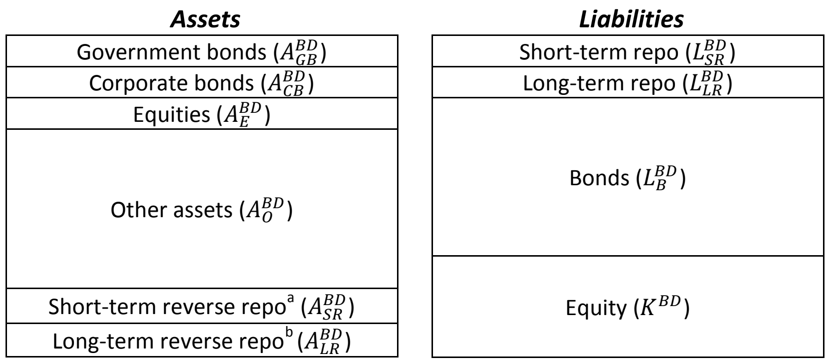
In the event of an extremely large shock that pushes the commercial bank's equity to zero (i.e. it defaults), it is assumed that the bank withdraws from the funding market (by not rolling over maturing reverse repo) and refrains from selling its traded securities. This represents a stylised resolution process where a bank in default sells assets gradually to minimise losses.

The broker-dealer

The primary role of the broker-dealer in our model is to intermediate the repo and derivative markets. It borrows via the repo market from the money market fund and the commercial bank, and lends via the repo market to the hedge fund and pension fund. The broker-dealer does not take proprietary positions in the derivatives market. In practice, this means that the IRS positions it arranges for its clients do not appear on its balance sheet. Alongside repo, the broker-dealer funds its activities by issuing bonds – the price and quantity of which is assumed to remain unchanged during the period of the model – and equity (Figure 9).

Like the commercial bank, the broker-dealer's behaviour is not explicitly driven by profit maximisation. Instead, it simply accommodates demand for repo by borrowers

Figure 9: *Broker dealer's balance sheet*



and maintains its inventory of securities, to the extent that it is able to, given the various solvency and liquidity constraints it faces.

There are two liquidity constraints for the broker-dealer. First, it faces the risk of its repo funding being pulled by the commercial bank and MMF. In the event of a loss of repo funding, the broker-dealer responds by both cutting its short-term reverse repo lending and liquidating assets.[30] We assume it does so in proportion to the share of assets funded by repo. For example, if 80% of the broker-dealer's repo borrowing funds its matched book, then a £100 reduction in available funding leads to an £80 fall in the reverse repo lending and a £20 reduction in its holdings of marketable assets. Or more formally:

$$A_{SR,t}^{BD} = \max(0, \frac{A_{SR,t-1}^{BD}}{L_{SR,t-1}^{BD}} L_{SR,t}^{BD}) \tag{23}$$

and

$$A_{i,t}^{BD} = \max(0, \frac{A_{i,t-1}^{BD}}{\sum A_{i,t-1}^{BD}} (1 - \frac{A_{SR,t-1}^{BD}}{L_{SR,t-1}^{BD}}) L_{SR,t}^{BD}) \tag{24}$$

where $i = GB, CB, E, O$. We assume the dealer unwinds it repo book in this way because, in a matched book, collateral flows from cash-borrowers to cash-lenders so both sides of the book must be unwound at the same time.

A second source of liquidity risk is the need to post additional government bond collateral to meet haircuts on its repo funding. When the price of government bonds falls or haircuts increase, the broker-dealer is required to post additional collateral. If its existing holdings of government bonds are insufficient to cover the extra collateral required, the

[30] The broker-dealer cannot unwind its long-term reverse repo because it is obligated to provide funding for the maturity of the contract.

dealer must buy additional collateral to meet the call. We assume the purchase is funded by selling a vertical slice of other securities. That is,

$$A_{i,t}^{BD} = \begin{cases} A_{i,t-1}^{BD} & \text{if } \frac{L_{R,t-1}^{BD} - A_{R,t-1}^{BD}}{1-h} \leq p_{GB,t} A_{GB,t-1}^{BD} \\ \max[0, A_{i,t-1}^{BD} - (\mu \frac{A_{i,t-1}^{BD}}{\sum_i A_{i,t-1}^{BD}}) \frac{1}{p_{i,t-1}}] & \text{otherwise} \end{cases} \tag{25}$$

where $i = CB, E, O$ and $\mu = \frac{L_{R,t-1}^{BD} - A_{R,t-1}^{BD}}{1-h} - p_{GB,t} A_{GB,t-1}^{BD}$ is the collateral shortfall. The second condition states that the dealer cannot sell more from an asset than its holdings.

Besides liquidity, the broker-dealer also faces a solvency constraint on its leverage position[31]:

$$k_t^{BD} \equiv \frac{K_t^{BD}}{A_t^{BD}} \geq \bar{k}^{BD} \tag{26}$$

where $\bar{k}^{BD}$ is the regulatory leverage minimum. If the broker-dealer's leverage ratio falls below $\bar{k}^{BD}$, we assume it deleverages by first unwinding its short-term reverse repo position. That is,

$$L_{SR,t}^{BD} = \max(0, L_{SR,t-1}^{BD} + \frac{K_{t-1}^{BD}}{\bar{k}^{BD}} - A_{t-1}^{BD}) \tag{27}$$

and

$$A_{SR,t}^{BD} = \max(0, A_{SR,t-1}^{BD} + \frac{K_{t-1}^{BD}}{\bar{k}^{BD}} - A_{t-1}^{BD}) \tag{28}$$

If this proves insufficient to restore the minimum leverage ratio, it then sells a vertical slice of its other marketable assets. We assume this sequence of actions because deleveraging its repo book carries no direct negative price impact. Similar to the commercial bank, we assume that if the dealer experiences a shock that wipes out all its equity, it exits the repo market (does not roll over expiring short-term repo) and does not engage in selling its traded securities.

3.2.4 Closing the model – other agents' behaviour

We conclude the description of the model by setting out the behaviour of various 'latent' agents. These include the central bank, which issues reserves held by the commercial bank. There are also agents representing private nonfinancial companies and the household

[31]For simplicity, we assume that the dealer does not face a risk-weighted asset capital constraint because, at least for intermediation in the repo market, the leverage ratio appears to be the binding constraint (CGFS (2017)).

sector. We assume these agents hold assets passively (i.e. an exogenous quantity). They do, however, interact with the active agents via their redemptions from investment funds and hedge funds during stress. Finally, there are market participants domiciled outside the United Kingdom whose assets (liabilities) account for some proportion of the liabilities (assets) of agents within the model. The assets and liabilities of these foreign investors are assumed to be exogenous. Their inclusion does, however, allow us to account for all agents who hold UK financial assets.

3.3. Market clearing and equilibrium

We define an equilibrium in our model as a set of market prices $\{p_{GB,t}, p_{CB,t}, p_{E,t}\}$ at which asset and funding markets clear, and all agents satisfy their funding and solvency constraints. The asset market clearing condition is:

$$\Delta A^{I}_{i,t} + \Delta A^{PF}_{i,t} + \Delta A^{IF}_{i,t} + \Delta A^{HF}_{i,t} + \Delta A^{MF}_{i,t} + \Delta A^{CB}_{i,t} + \Delta A^{BD}_{i,t} = 0 \tag{29}$$

for $i = GB, CB, E$.

The funding market clearing conditions are:

$$A^{BD}_{SR,t} = L^{PF}_{SR,t} + L^{HF}_{SR,t} \tag{30}$$

and

$$A^{MF}_{SR,t} + A^{CB}_{SR,t} = L^{BD}_{SR,t} \tag{31}$$

Our simulation approach is as follows:

1. The prices of the three securities are initially assumed to be in equilibrium. In other words, the aggregate supply and demand of securities and funding across the representative agents exactly matches, so that none wishes to trade. Prices of the three securities are normalised to 1.

2. We introduce a shock. For instance, this could reflect a change in macroeconomic fundamentals, which directly influences the expected return on the three traded securities, or a change in regulation, e.g. a change to the life insurer's minimum solvency requirement.

3. The agents in the model observe the shock and follow their behavioural rules to update their desired portfolios and their demand and supply of repo funding.

4. Given the prevailing demand-supply imbalance, we posit a new price vector and check whether securities and funding markets both simultaneously clear.

5. We iterate steps (3) and (4) until an equilibrium price vector is found.[32]

4. Parameterisation

One contribution of our paper is the creation of a new dataset describing UK financial institutions' balance sheets, which combines information from a range of regulatory, statistical and commercial sources.[33] The full set of sources used is provided in Table B.1.

This dataset includes information on the stock positions of each of the seven sectors included in our model. We use it to calibrate agents' starting balance sheets, as summarised in Table B.2. As far as we are aware, it is the only dataset which provides a detailed split of assets and liabilities across such a wide range of UK financial sectors. To construct the dataset, we combine public and private balance sheet data for different sectors; for example, we use publicly available data from the Office for National Statistics (ONS) on UK investment funds, but private regulatory data for banks and insurers. We use use this dataset to calibrate agents' starting balance sheets, which are shown in Table B.2. All data are as of Q4 2016 unless otherwise specified.

Figure B.1 presents a 'tree-map' visualisation of the relative magnitudes of the balance sheets of the different UK financial sectors in our data. In total, we account for £16.8tn of assets (and a corresponding amount of liabilities and equity). The assets of the system are split across UK managed funds (pension funds, hedge funds, open-ended investment funds and investment trusts), insurers (unit-linked and non-unit-linked life insurers and non-life insurers) and banks (wholesale dealers and other commercial banks, both headquartered in the United Kingdom and in the rest of the world (RoW)). Figures B.2a and B.2b present a breakdown of asset and liability categories respectively. We identify model agents' holdings of almost £2.3tn of UK government bonds, corporate bonds and equities, the assets that correspond to the traded financial securities in our model. We estimate that our data cover around 50% of the stock of UK government bonds, and around 40% of the stock of outstanding UK corporate bonds and equities. The rest of the stock is held by sectors not covered by our dataset – for example, the Bank of England, non-financial UK sectors and the RoW.

We make a number of adjustments to our dataset, summarised in Table B.1, to map

[32] In general, this model – as is common with many such models with leverage constraints (see e.g. Jeanne and Korinek (2010) and Schmitt-Grohe and Uribe (2016) – gives rise to multiple equilibria. In such circumstances, we choose either the equilibrium price vector that is closest to the initial equilibrium or the stable equilibrium.

[33] Although previous work has provided high-level information on balance sheets across the UK's financial system (Burrows and Low (2015)), the asset-liability breakdown provided in this paper is substantially more detailed.

from the real-life sectors in the data to the agents in the model. This involves splitting some sectors and aggregating others to focus on types of behaviour (for example, we combine unit-linked life insurance business with open-ended investment funds) and some aggregation of asset and liability types to reflect the model setup.

Figure B.3 shows the holdings of the three traded assets split by agent. The model's traded asset markets are made up of £1tn of UK government bonds, £737bn of UK equities and £545bn of UK corporate bonds. As shown in Figure B.3, the pension fund sector is the largest holder of government bonds in the model (42% of total holdings), while investment funds, and in particular single-asset funds, are the largest holders of equities (39% of total holdings). Holdings in the corporate bond market are more evenly split, with the pension fund, life insurer and commercial bank collectively holding around 75% of the total stock.

One important aspect of our mapping from balance sheet data into the model is that we do not include derivative assets and liabilities on our modelled balance sheets. As described in Section 3, we model the impact of interest rate swaps on the liquidity positions of the model's agents. However, we implicitly assume that agents have economically offsetting positions at the start of the model, and thus no net asset or liability on their balance sheets. In practice the derivative assets and liabilities of UK financial sectors are very large – around £4.7tn in our dataset. It is likely that many of these assets and liabilities offset each other in terms of the risk factors we consider, even if they cannot be netted for accounting purposes – long and short interest rate contracts with different counterparties, for example. In addition, we only model a subset of derivatives contracts, excluding credit, foreign exchange and other types of derivative. For these reasons we do not include derivatives on the balance sheets in our model. This is equivalent to treating derivatives (other than IRS) as fixed assets and liabilities. However, it does mean that balance sheet ratios in our model need to be adjusted to match reality – for example, removing a large proportion of banks' assets and liabilities inflates their leverage ratio (equity divided by total assets) even though the sensitivity of their equity in absolute terms to changes in traded asset prices is unaffected.

Tables B.3-B.8 document our parameterisation of the model. This reflects a mix of data, values provided by the existing literature, and our judgement. In calibrating the regulatory constraints agents face (Table B.3), we first set risk weights and LCR parameters (HQLA weights, deposit outflow assumptions) using regulatory requirements from Basel III and Solvency II. While our model captures the majority of key balance sheet items for the sectors considered, our model-based solvency and liquidity ratios nevertheless diverge from those observed in the data.[34] To account for this, we calibrate agents' constraints in such

[34] This is caused by the omission of derivative assets and liabilities from agents' balance sheets, as well as the fact that we use simple balance sheet measures of leverage and liquidity which do not consider regulatory adjustments to measures of exposure, equity and consolidation.

a way so as to preserve, in percentage terms, their observed 'headroom' over minimum requirements. For example, if in the data commercial banks have 30% headroom over their actual regulatory minima, we apply this same proportionality factor when calibrating banks' headroom in the model. This entails choosing values for regulatory minima that differ from those observed in reality.[35]

To provide a sense of the degree of 'distance to constraints' implied by our calibration, Figure B.4 illustrates the effects of various shocks on the capital positions of the commercial bank, dealer, hedge fund, insurer and pension fund.[36] There is some heterogeneity in the impact of these shocks across firms. In particular, shocks to the value of UK corporate bonds and equities have relatively small effects on the dealer and commercial bank given their limited direct exposures (under 10% of their portfolios), while shocks to these assets have more significant impacts for the insurance company and pension fund. The overall implication of our calibration though is that it takes extremely large shocks relative to those observed historically for firms to breach their solvency constraints.[37] Figure B.5 repeats the exercise for firms' liquidity buffers. In this case, we focus on shocks to risk-free real interest rates, as these are most relevant for determining margin calls in the model. In our baseline calibration, no agent faces a liquidity shortage following these shocks. While the requirement to post additional collateral to back its repo funding depletes the hedge fund's unencumbered government bond holdings, it holds sufficient deposits to fund additional government bonds purchases to meet demand.

We split our data on the banking sector along broad functional lines into a broker dealer, which focuses on capital markets business, and a commercial bank which focuses on lending to the real economy and provision of deposit services. In reality, in the UK at least, these functions are often provided within the same banking group. We cross check our split of the data by comparing our commercial bank agent's balance sheet against that of a large, UK-headquartered banking group with a representative 'commercial bank' business

[35]We assume throughout that agents' deleveraging behaviour only takes effect when they formally breach regulatory requirements. For example, the commercial bank only begins to sell its marketable assets when it breaches its minimum capital ratio. In practice, we might expect deleveraging to occur sooner than this. There might be market constraints, for instance, that increase sharply in stress and that drive agents' behaviour, which make some regulatory buffers effectively unusable. The stress scenario we present in section 5 explores this possibility, where we consider the impact of bringing some key intermediaries closer to their deleveraging points.

[36]The shocks here are mechanically applied to value of the relevant assets rather than being the equilibrium outcomes of the model. For shocks to traded assets, we use the hedge fund's pricing equations as a proxy for the fundamental value of the assets. Shocks to other assets and bank loans are applied as a percentage of the initial value.

[37]The reason for this is that we assume that firms run through the entirety of their capital buffers prior to taking defensive actions, such as fire selling certain assets. In practice, this 'tipping point' in behavioural responses may occur before buffers have been fully exhausted. We explore the implications of relaxing this assumption in section 5.

model. We find that the proportions of asset and liability types on the two balance sheets are broadly similar.

The parameters governing agents' behaviour are set out in Table B.4. Our choice of rebalancing horizons for the pension fund, the insurance company and the mixed investment fund reflects information on the investment decision horizons of these sectors. The pension fund is assumed to be the slowest moving investor, taking 6 months to rebalance its portfolio in full. As a result, only one sixth of its rebalancing is assumed to occur within the time horizon of the model. The life-insurer rebalances its portfolio over 3 months, meaning that one third of its desired rebalancing occurs within our horizon, while the investment fund is assumed to adjust in full. Table B.5 shows the parameters governing the portfolio optimisation problem of these agents. While we assume they share common perceptions of expected returns and asset return correlations, their risk aversion coefficients and perceptions regarding asset return volatility differ. To set these parameters, we calibrate agents' risk aversion parameters to match the share of bonds versus risky assets in their respective portfolios, and their perception of the volatility of corporate bonds and other assets to match their respective holdings of each. This implies that these investors will update their desired portfolios differently, even when they share a common understanding of the shock.

We have used new proprietary datasets to calibrate the liquidity risks created by agents' activities in IRS and repo markets. The IRS parameters presented in Table B.6 have been calibrated using data reported under the European Market Infrastructure Regulation (EMIR) to trade repositories – in particular, to DTCC Derivatives Repository Limited and Unavista Limited. Aggregate positions have been calibrated by adding up the positions of individual firms within each sector. This of course abstracts from the heterogeneity of positions across firms within each sector. For example, pension funds' broadly neutral aggregate position masks the fact that, roughly speaking, one half of firms use repo to gain leverage and hedge this in the IRS market, while the other half uses the IRS market outright. Table B.7 covers the parameters governing the repo market. These have been calibrated using the Bank of England's Sterling Money Market Dataset.[38] There is some maturity transformation in the broker-dealer's repo book: in our calibration, 66% of its repo borrowing is short-term (i.e. matures within the one month period considered here), while 61% of its reverse repo lending is short-term.

[38]Harris and Taylor (2018) provide background on this dataset.

5. Results

We begin our presentation of the outputs from this model with a discussion of the determination of equilibrium prices. Following this, we discuss the impact of a range of alternative individual shocks of varying magnitudes. Finally, we consider a multi-layered stress scenario that combines the effects of several coincident shocks into a coherent overall scenario.

5.1. Price determination

To build intuition about how the model works, Figure A.5 presents a stylised summary of how long-term investors interact with agents that face potential constraints (a category that includes hedge funds, dealers, insurers and commercial banks) in determining asset prices. On the horizontal axis, long-term investors' supply of marketable assets is shown (where moving from left to right indicates an increase in supply and thus a reduction in demand) along with constrained agents' demand (where moving from left to right indicates an increase in demand, and thus a reduction in supply) , with equilibrium being where these two lines intersect. On the vertical axis is the price of the marketable asset; for illustrative purposes we use the corporate bond price.

The curve defining long-term investors' net sales of the asset (their 'net supply') is upward-sloping and continuous: for prices above their initial level of 1, these agents' portfolios will be overweight in the asset class in question and rebalancing considerations will drive an increase in sales. Constrained agents' demand is downward-sloping and shallow in the neighbourhood of the initial (target) price, reflecting arbitrage activity by hedge fund, with the slope of this curve in this region reflecting the α parameter (see Figure A.4). When prices fall beyond a certain point, however, this curve becomes backward-bending. This occurs where the capital or leverage constraint binds.[39] In this region, further decreases in the price raise leverage, requiring these agents to reduce their asset holdings to meet the constraint. In general, if intersection occurs in the shallow, downward-sloping region of constrained agents' demand, fluctuations in the equilibrium price will tend to be small; if instead it occurs in the steep, backward-bending region of constrained agents' demand, equilibrium price moves will be amplified, potentially materially so.

In the upper panel in Figure A.6, we illustrate the impact of the arrival of news that the outlook in the corporate sector has deteriorated, such that expected dividend growth is lower and credit losses higher. In response to this news, the hedge fund reduces its target

[39] Backward-bending demand curves are a common feature of models with leverage constraints, see Cabellero and Krishnamurthy (2001) for an example.

price for corporate bonds, generating a downward parallel shift in constrained agents' demand curve. Long-term investors, by contrast, are assumed to respond only slowly to this news, so to induce these agents to increase their corporate bond holdings, the price must fall to generate the requisite expected return.[40] The adjustment will be orderly in this case, with net sales of the asset by constrained agents and net purchases by long-term investors; prices decline modestly, albeit by less than the decline in the hedge fund's target price, i.e. the change in the equilibrium price is less than the vertical distance between the constrained agents' pre- and post-shock demand curves. In the lower panel, we illustrate the impact leverage limits becoming binding for some constrained agents. This could reflect credit losses suffered on exposures external to the model for example. The effect of this shock is to shift constrained agents' demand to the left, and if the shock is large enough, equilibrium will occur in the steep, backward-bending region of this curve. Price falls would be far larger in this case, reflecting the feedback loop between lower prices, tighter leverage constraints and forced asset sales by constrained agents.

Moving beyond this stylised description of the model, Figure A.7 illustrates the nonlinear relationship between equilibrium asset prices and shock magnitudes that is generated in the full model. The figure plots the equilibrium price of equities (purple dots) alongside the hedge fund's price target (grey line given by equation 15), for different sized shocks to risk-free real interest rates. We have reduced the capital headroom of the commercial bank relative to the baseline calibration to illustrate how the bank's capital requirement acts as one tipping point in the model. The equilibrium equity price falls monotonically as risk-free rates increase. Initially, the equilibrium remains above the hedge fund's target price. This reflects the assumed slow-moving behaviour of long-term investors, whose asset portfolios are large relative to the hedge fund (around four times larger in our calibration); it also reflects our assumption that hedge funds do not fully arbitrage away divergences with their target prices ($\alpha > 0$). When the shock to risk-free rates reaches 30 basis points, however, the commercial bank's leverage ratio binds, forcing it to fire-sell assets. This leads to a large discontinuous decline in asset prices, which overshoot the hedge fund's target price. In this case, the hedge fund's ability to arbitrage the price divergence is limited by its funding capacity (i.e. its leverage ratio).

[40]For exposition purposes, we have held long-term investors' demand curve fixed in this example. In the model, these agents do revise down their expected returns on this asset, leading to an adjustment in their desired portfolio weights. The speed of portfolio adjustment varies by sector, with the investment fund adjusting most quickly, and the pension fund reacting most slowly.

5.2. Individual shocks

In this section, we illustrate the impact of various individual shocks in our model. We begin by looking at the case of an increase in expected defaults on corporate bonds.

Figure A.8 illustrates the impact of a 3 standard deviation shock to credit losses on a range of key model output variables. The shock distribution is calibrated using 20 years of historical data for the United Kingdom. The proximate impact of this shock is to reduce expected returns on corporate bond holdings, reducing demand by the hedge fund, whose target price fall. The shock also causesthe pension fund, insurance company and investment fund to reduce their target portfolio weights (all else equal). A knock-on consequence of this is an increase in the demand for government bonds, and to a lesser degree for equities, as investment funds and insurance companies rebalance their portfolios towards these assets. Overall, the model therefore predicts a fall in the price of corporate bonds, with government bonds and equities increasing in price (yields decreasing). Quantitatively, the corporate bond spread relative to government yields increases by around 120 basis points.

Turning to other output variables, we observe only small movements in sectors' net positions, with the largest move being a £7bn increase in corporate bond holdings by the life insurer (relative to initial holdings of over £130bn), driven by rebalancing considerations. Given these asset price moves, we observe a small 2.1% increase in the value of hedge funds' equity; to restore its leverage position, the hedge fund therefore raises its repo borrowing by £9bn (relative to initial repo borrowing of £160bn), which is funded by increased reversed repo provision by the commercial bank, intermediated by the dealer. Finally, with lower government bond yields, the present value of pension and life insurance obligations increases, reducing the value of equity for these agents.

Table A.2 documents results for other single shocks we can consider in the model. For each shock type, we present results for shock magnitudes ranging from 1 to 3 standard deviations. In general, our results indicate that, taken in isolation, single shocks drawn from historical distributions result in a relatively orderly price adjustment in the system. The largest price impacts in the model occur following shocks to the 'other assets' category, unsurprising given that these assets account for the majority of agents' portfolios in the model and that the shock assumes a perfectly correlated reduction in the value of these assets across sectors. Investors' redemptions from the investment fund sector are small in all cases except for the 3 standard deviation fall in the value of 'other assets', in which case redemptions reach 0.8% of total assets under management.

5.3. Multi-layered stress scenario

In this section, we illustrate some of the features of our model through the lens of a multi-shock stress scenario. The scenario is chosen to highlight the nonlinearities in our model when agents hit constraints. The core of this scenario is a deteriorating outlook for credit risk and profitability in the UK corporate sector. Such an outlook could reflect a macroeconomic slowdown driven by the unwinding of a corporate debt boom, for instance. Expected credit losses on UK corporate loans and bonds (assumed to be a weighted average of investment-grade and high-yield bonds) rise by 50 basis points, while expected dividend growth declines by 50 basis points.

A typical banking system stress test would apply these loss rates, together with commensurate shocks to corporate asset valuations, and assess whether the resulting depletion in banks' capital buffers might threaten their solvency. Given the scale of buffers that have been built since the global financial crisis, losses of this magnitude would not threaten banks' resilience.[41] Banks' risk-based capital and leverage ratios would remain significantly above their regulatory minima, and as a result, there would be no further implications from the test.

What insights do we obtain from using our model, with its focus on interconnections and spillovers across sectors, over and above that provided by a purely bank-centric test? For clarity of exposition, we present the scenario in three cumulative 'layers', ordered in terms of increasing severity. The first layer is a straight 'run' from the applying this shock to the model; the second considers the implication of it occurring alongside binding leverage constraints for broker-dealers; and the third considers the coincidence of these shocks with binding risk-based capital constraints for commercial banks. We present the results from each layer in Table A.3 and Figures A.9-A.10. When interpreting these results, we note that the model is conditioned on no policy response by the authorities, i.e. the central bank does not cut policy rates, provides no emergency liquidity assistance and does not act as market maker of last resort – factors that arguably provided support to falling asset prices during the financial crisis.

Scenario layer 1: Deteriorating corporate outlook

The immediate impact of this shock is to reduce the expected return on UK corporate bonds and UK equities. As a consequence, the fast-moving investors in our model – the hedge fund and investment funds – reduce their portfolio demand for these assets and

[41] As a rough ready reckoner, we would expect losses from this shock to be only around 0.2% of our commercial bank's loan portfolio, given that around 40% of UK banks' loans to UK borrowers are to financial and non-financial corporates.

correspondingly increase their demand for gilts. The shock has a significantly larger relative impact on the hedge fund's target price for equities than on corporate bonds. As a result, the hedge fund becomes a large net seller of equities (Figure A.9, panel (1)), exerting significant downward pressure on the market price. This is sufficient to bring the share of equities in investment funds' portfolios in line with their revised target weight without requiring any additional sales of equities. The slower-moving investors in the model – pension funds and life insurers – take the other side of the market in this sell-off. Although their expected return on corporate bonds and equities also falls, their investment demand is dominated by rebalancing considerations within the period we consider, causing them to act countercyclically.

Overall, despite the large magnitude of the shock, the model predicts a relatively orderly adjustment in prices in response (A.3). Corporate bond prices decline by 3.6%, a 1st percentile move in the 20-year historical distribution of monthly changes; equity prices decline by 9.1% (5th percentile of one-month moves in the FTSE all-share index); and gilt prices *increase* by 2.7%, reflecting their safe-haven status.

Scenario layer 2: Broker-dealer leverage ratio binds

The second layer builds on the first by introducing a binding leverage limit for the broker-dealer. In particular, we reduce the dealer's capital headroom such that it begins the simulation with a small capital deficit relative to its constraint. This could reflect precautionary behaviour by the broker-dealer in the face of greater uncertainty about risk in the financial system, leading it to maintain a larger 'voluntary' capital buffer than in normal times. It could also reflect a rise in the market minimum, i.e. the point at which investors begin to require significantly higher credit premia to continue to fund the dealer. Yet another interpretation for this shock would be losses suffered by the dealer on its non-UK asset portfolio. The reduction in headroom we impose is equivalent to the effective minimum leverage ratio increasing by 30% alongside losses of 4.7% on the dealer's other assets.

As a result of these shocks, the broker-dealer breaches its leverage requirement. As the dealer's leverage increases, the MMF becomes increasingly concerned about counterparty risk and pulls its short-term reverse repo lending to the dealer. This forces the broker-dealer to deleverage its balance sheet. The dealer reacts in the main by pulling its reverse repo, which in turn has adverse effects on 'downstream' investors reliant on dealer-intermediated repo funding. In aggregate, there is a £138bn decline in reverse repo lending by the dealer, and a decline of about the same magnitude in combined repo borrowing by the hedge fund and pension fund (Figure A.10, panel (2)). As a result, we observe a small increase in the volume of corporate bond sales by the hedge fund as the funding available to it declines significantly below its desired level (represented by the bar and cross respectively in Figure A.10, panel (2)). Its additional sales of corporate bonds are relatively small, despite the large reduction in funding, because the hedge fund repays much of the withdrawn funding by reducing its deposit holdings and selling non-UK assets.

The net effect of this combined shock is to amplify the fall in risky asset prices further (A.3). Corporate bond prices decline by 5.4% (a 0.5th percentile monthly move); equity prices decline by 10.2% (a 4th percentile move), and government bond prices increase modestly by 1%. This scenario highlights the mutually reinforcing interplay between solvency and liquidity constraints in shaping the response of asset prices.

Scenario layer 3: Commercial bank capital requirement binds

The final layer engages the commercial bank's risk-based capital requirement. We decrease the bank's capital headroom to create a similar capital deficit as for the dealer, with the same motivation as outlined above. In this case the reduction in headroom is equivalent to increasing the bank's effective minimum risk-based capital ratio by 50% alongside additional credit losses on the bank's loan portfolio, taking its total loan losses – including those resulting from the initial shock – to 5.4%. Losses on this scale are very large, well beyond one-month credit losses observed in recent history.

In response to this shock, the commercial bank is forced to begin liquidating its tradeable securities portfolio to reduce its leverage. As Figure A.9, panel (3) shows, it concentrates its selling in this scenario in the equity market.[42] This reflects the balance of two considerations. First, as it is the risk-based constraint that binds in this scenario, assets with higher risk weights have the largest marginal contribution for the purpose of alleviating the constraint. Equity holdings have the highest risk weight in our setup (see Table B.3). By contrast, government bonds sales would have zero marginal contribution to alleviating the constraint given their zero risk weight.[43] Second, the commercial bank views the corporate bond market as relatively illiquid compared to the equity and government bond markets, and so expects a smaller price impact of sales in the latter. The commercial bank does not reduce its reverse repo provision to the broker-dealer, given the low risk weight applied to this lending and the large demand-driven reduction in its funding to the dealer (Figure A.10, panel (3)). However, as in layer 2 of the scenario, the hedge fund's repo borrowing is constrained by available supply, and so it is forced to sell all three assets even though

[42]The commercial bank also sells 'other' assets, which are not shown because we treat their price as fixed.

[43]We find qualitatively different results in this scenario when instead the leverage requirement binds, with a much larger reduction in government bond prices.

prices are below its price targets.

In summary, in this scenario corporate bond prices fall by around 8%, government bond prices fall by 2%, and equity prices decline by more than 20% (A.3), implying a £221bn reduction in the value of UK tradeable assets. Looked at in terms of bond yields, these price changes correspond to government and corporate bond yields increasing by 13 basis points and 99 basis points respectively.[44] Given that the expected loss rate on corporate bonds increased by 50 basis points in this scenario, this implies a roughly 35 basis point rise in the pure *liquidity* component of the corporate bond spread. Movements in corporate bond yields and spreads of this magnitude would likely have significant effects on business investment and the wider macroeconomy.[45] Aggregate one month asset price moves of this magnitude are clearly very extreme, but not unprecedented. For example, in July 2002 and October 2008 the FTSE 100 index fell by 22% and 30% respectively.

5.4. Discussion

5.4.1 The impact of alleviating capital and liquidity constraints

Which constraints contribute most to the adverse dynamics in this scenario? To analyse this question, we hypothesise the existence of a social planner with a given amount of cash resources available that can be used to alleviate the different constraints agents face. Where should these resources be deployed to obtain the greatest 'bang for buck' in this particular scenario?[46]

Figure A.11 records the impact on asset values of providing additional cash to each agent, in amounts ranging from £5bn to £50bn. We consider both 'capital injections', where the cash is used to purchase equity in the sector in question, and 'liquidity injections' where the cash takes the form of an unsecured loan. We assume throughout that these interventions are unanticipated by agents in the model. And we do not consider how these abstract capital and liquidity injections could be implemented in practice. Some types of constraints never bind in our model: it is not possible for the investment fund or money market fund to face a capital shortfall, for instance, given their liabilities comprise

[44] Relative to baseline yields of 2.5% and 3.5%, and assuming maturities of 20 years and 10 years for government bonds and corporate bonds, respectively.

[45] As an illustration of the potential real effects that could result, we use estimates provided by Gilchrist and Zakrajsek (2012) for the United States of the impact of shocks to their measure of the 'excess bond premium', which captures the component of overall credit spreads not explained by the contribution of expected default risk. They find that a one standard deviation shock to the excess bond premium – around 20 basis points – reduces real GDP at its trough by around 0.5%. Assuming these effects to be linear, this implies that the jump in the liquidity spread in our scenario might, if it were to persist for several quarters, be expected to reduce the level of real GDP (relative to trend) by as much almost 1%.

[46] In principle, our aim here is to uncover the value of the Lagrange multipliers on the various constraints in this specific scenario. These multipliers will of course differ according to the scenario considered.

investment shares only; similarly, as the commercial bank in our model represents the entire deposit-taking banking sector, it cannot face a liquidity shortfall. Other constraints happen to not bind in the particular stress scenario we consider, although one could conceive of other plausible scenarios in which they would. In our scenario, the marginal value of alleviating solvency constraints faced by the hedge fund and life insurer is zero, for example; so too is that of alleviating the funding constraint faced by the money market fund.

Our model predicts that alleviating the commercial bank's capital constraint in this scenario has the largest 'bang for buck' impact on asset prices. In particular, a £15bn capital injection – enough to push the commercial bank's capital ratio above the constraint – generates a significant uplift in asset prices, raising the value of system-wide assets by £126bn, undoing more than half of the £221bn destruction in the market value of assets in the original scenario. Increasing the capital provision beyond this level, however, has no marginal benefit; given its assumed behavioural rule, the bank maintains the additional capital in the form of a larger management buffer once its constraint ceases to bind. The impact of alleviating the dealer's capital constraint in this scenario is somewhat smaller (roughly 60% as large on average); however, a planner with £10bn would benefit the system most by using this to purchase new equity in the dealer.

In absolute terms, we find the largest absolute impact on system-wide assets from providing investment funds with additional cash, forestalling their need to fire sell assets to meet redemptions (Figure A.11, panel (a)).[47] Cash injections for the investment fund have a roughly linear impact on the model's results. At £40bn and above,the impact dominates that of providing capital to the commercial bank. At this point, the boost to asset prices becomes sufficiently large as to alleviate the commercial banks' capital constraint indirectly, removing the banks' need to deleverage by selling assets, steering the system away from the negative self-reinforcing cycle of falling asset prices and funding squeezes. This highlights the importance of taking into account the general equilibrium effects of such interventions: while forced asset sales by the commercial bank are the key proximate driver of adverse dynamics in this scenario, alleviating procyclical asset sales by the investment fund sector has the largest impact on this problem (in absolute terms).

5.4.2 Sensitivity analysis

In this section, we examine the sensitivity of the results from this stress scenario to varying various key parameters and assumptions in the model. In particular, we consider the effect

[47]This exercise is purely intended to uncover mechanically the importance of procyclical redemptions in this particular scenario. It has no implications for the desirability of requiring funds to maintain larger liquidity buffers.

of:

(a) Heightened redemptions from the funds sector: we apply exogenous redemption shocks of 4.2% of assets to the two investment funds, equivalent to the largest monthly outflows seen during the financial crisis (Baranova et al. (2017a)), and a shock of half the size (2.1%) to the hedge fund; we also increase the flow-performance 'procyclicality' coefficients (see Table B.4) by 50%, so that falling asset prices lead to greater endogenous redemptions from funds;

(b) Varying the size of the investment fund sector: we double the size of the single and mixed investment fund sectors while leaving the balance sheets of other agents unchanged;

(c) Faster portfolio adjustment by insurance companies and pension funds: in the baseline model pension funds are assumed to adjust their portfolio weights over a six-month period, so one sixth of their adjustment occurs in a simulation, and insurance companies over a three-month period. We test the sensitivity to these parameters by doubling the speed at which these agents adjust their portfolio weights (so pension funds make one-third of their adjustment and insurance companies two-thirds).

(d) More aggressive arbitrage behaviour by the hedge fund sector: as described in Equation 16, the parameter α controls how aggressively the hedge fund responds to market prices deviating from its targets. We reduce α from 0.15 in the baseline model to 0.075, increasing the hedge fund's aggressiveness.

Table A.4 summarises the results of this exercise. While these results are scenario-specific, they do provide an indication of the relative importance of these elements of the model in driving our results.

The largest effect on asset prices across these exercises is obtained by imposing greater redemptions from the fund sector: government bond prices fall a further 8.5 percentage points, corporate bonds a further 4.7 percentage points, and equity prices fall by a further 7 percentage points. This is both because the assumed shock is very large, and because increased redemptions interact with an already stressed financial system experiencing large price falls. The impact on government bond prices is particularly significant, caused in part by the fact that funding markets are impaired. As it is, the hedge fund is constrained in its ability to borrow in the repo market, so does not lever up to purchase more government bonds as their price falls. The fall in government bond prices (higher yields) reduces the net present value of insurance and pension fund liabilities, increasing these sectors' equity/net worth. Other agents see their net worth deteriorate, however, reflecting lower asset valuations.

Increasing the size of the investment fund sector generates lower corporate bond prices (which decline a further 4.7 percentage points), but marginally higher prices for government bonds and equities. This in part reflects the increased buying power of the mixed investment fund, which in the scenario re-weights away from corporate bonds and towards government bonds and equities more aggressively than other long-term investors. In addition, procyclical redemptions from a larger fund sector means larger asset sales, particularly in the corporate bond market where empirical evidence suggests the flow-performance relationship to be strongest (Goldstein et al. (2017)). We also observe lower corporate bond prices in an exercise where insurers and pension funds adjust their portfolio weights more quickly (corporate bond prices decline a further 2.6 percentage points). However, in this case, the model also generates a pronounced rise in government bond prices, as these agents rebalance towards safer assets.

Finally, we find no effect on repo volumes in any of the sensitivity exercises. This is a scenario-specific result: binding capital constraints for the dealer mean that short-term repo has already been withdrawn to the maximum extent possible, and none of the parameters we change affect this. We also find no effect from varying α. This is because the hedge funds arbitrage behaviour plays a very limited role in this scenario, given that funding markets are not functioning, limiting its ability to purchase price-depressed assets. For comparison we tested the same lower value of α in layer 1 of the scenario, where only fundamental shocks are in play. In that case, asset prices fell by a further 2 percentage points compared to the baseline model, driven by more aggressive selling by the hedge fund sector.

5.4.3 The role of solvency concerns at the life insurer

We complete the discussion of the model's results by exploring the role played by the life insurance company in shaping the model's results. In the stress scenario presented in Section 5, long-term investors act countercyclically: they provide liquidity by purchasing equities and bonds that have fallen in value, supporting risky asset prices and thereby preventing additional amplification. In alternative severe stress scenarios, however, there is the possibility that losses from falling asset prices might deplete the life insurer's capital sufficiently to cause its solvency constraint to bind. And in such circumstances, we find that the life insurer's defensive actions can lead to a negative spiral which ultimately causes markets to fail to clear.

When the life insurer's capital constraint binds, it responds by de-risking its balance sheet: it buys government bonds and sells risky assets (i.e. corporate bonds and equities). This generates two negative side-effects which the life insurer does not take into account.

First, its sales of risky assets tends to reduce their prices, leading to additional losses. Second, as it buys government bonds this causes their price to increase and yield to decrease. Falling government bond yields inflate the value of the insurer's liabilities, further damaging its equity position. In response to these two effects the insurer is forced to de-risk even more aggressively, setting off a vicious cycle. In some scenarios, the negative feedback loop from the insurer's de-risking becomes so virulent as to cause markets to fail to clear. That is, the insurer's need to de-risk is such that demand for government bonds exceeds available supply – and this cannot be sufficiently alleviated by higher risky asset prices or government bond yields.

While we would caution about taking these results literally (in reality, we might expect additional supply of government bonds to be forthcoming, including from rest of the world investors, if prices rise sufficiently far), they nevertheless highlight the fundamental role played by the life insurer in shaping the behaviour of asset prices.[48]

6. Conclusion

This paper presents a model that can be used to assess the resilience of the UK's system of market-based finance. The core of this model is a set of representative agents, whose behaviour corresponds to key sectors of the UK's financial system. These agents interact in asset, funding (repo), and derivatives markets and face a range of solvency and liquidity constraints on their behaviour. When shocks are large, or when headroom relative to these constraints is small, the model can generate an adverse feedback loop in which lower asset prices cause solvency/liquidity constraints to bind, leading intermediaries to pull funding, greater deleveraging, pushing asset prices lower still.

We illustrate this feedback loop via a stress scenario in which a deteriorating corporate sector outlook coincides with heightened redemptions from investment funds and tighter leverage limits at key intermediaries. This scenario highlights the potential interplay between solvency and liquidity constraints in shaping the response of asset prices in our model. We find the reaction of the broker-dealer, which pulls significant reverse repo provision to 'downstream' investors to meet its leverage limit, amplifies the shock substantially. Similarly, the behaviour of the commercial bank, an important cash provider to the repo market, intensifies the funding squeeze further. Our results point to the life-insurer's solvency position as a key tipping point for the system. And that a social planner faced with the scenario we describe would have the biggest bang for her buck by increasing

[48]This is reminiscent of the experience in the early 2000s, following the collapse of the dot-com bubble, where insurers' disposal of equities led to large price declines (Impavido and Tower (2009), Bank of England (2014)).

the liquidity of the investment fund sector.

We suggest several avenues for future research. First, as ours is a model of representative agents, we are necessarily silent about within-sector heterogeneity, which is undoubtedly an important omission, e.g. it precludes an analysis of CCPs role in the resilience of market-based finance. Similarly, we treat all corporate bonds as a single asset class at present, precluding an assessment of riskier market segments. Second, our model abstracts from some important markets, notably securities lending (hence preventing us from capturing short-selling effects) and credit derivatives; we also pay insufficient attention in this draft to the role of rest-of-the-world agents and markets. Third, there may be value in using insights from this model to build summary indicators of the resilience of the system. One such indicator might involve keeping track of the stock of unlevered funding that might support market prices in an actual stress event.

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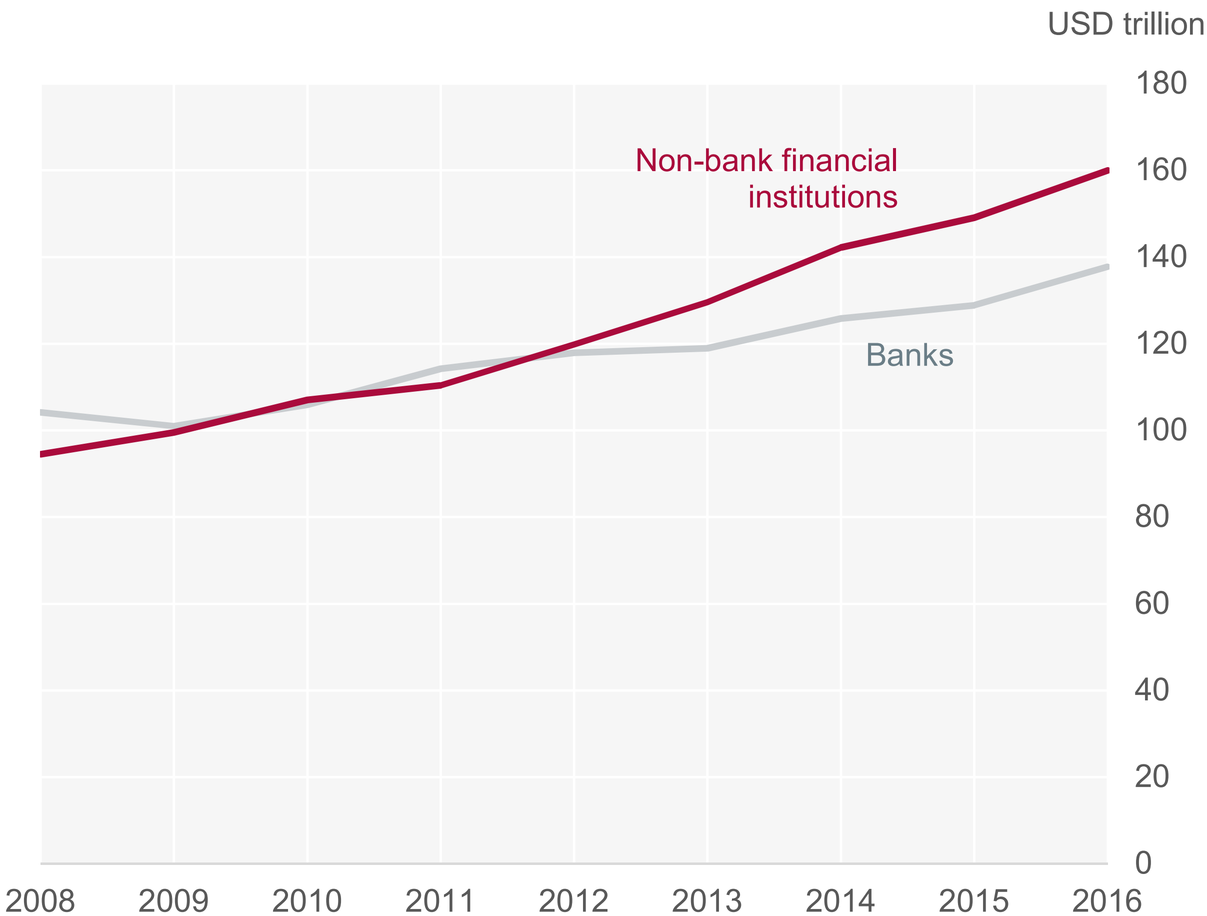
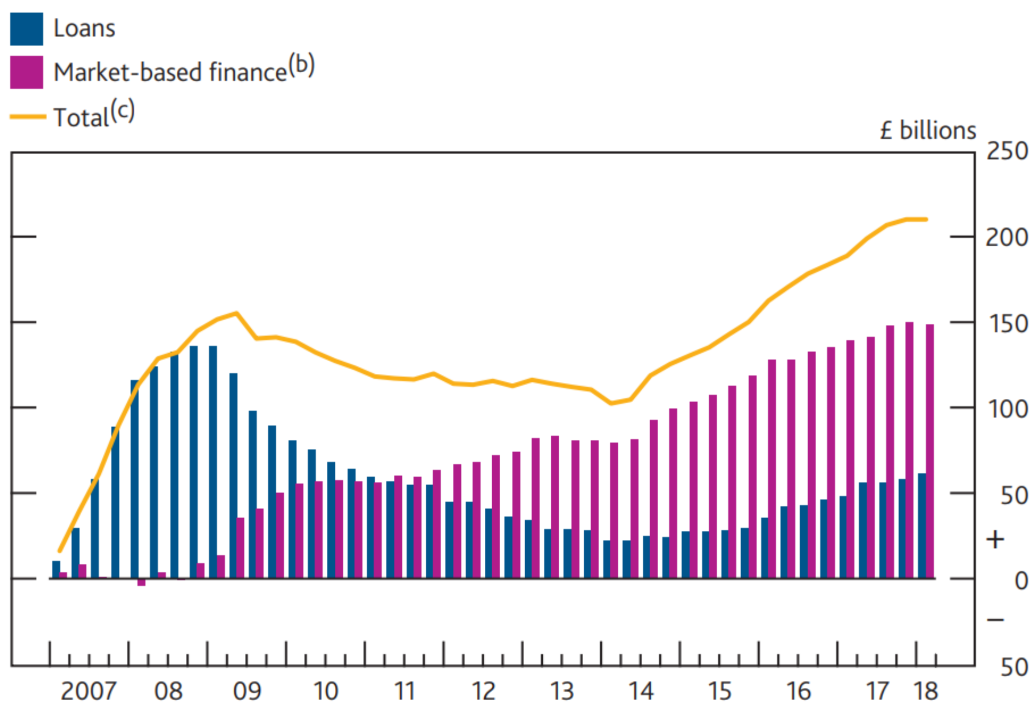
Appendix: Figures and tables

Figure A.1: *Total assets of bank and non-bank sectors globally*



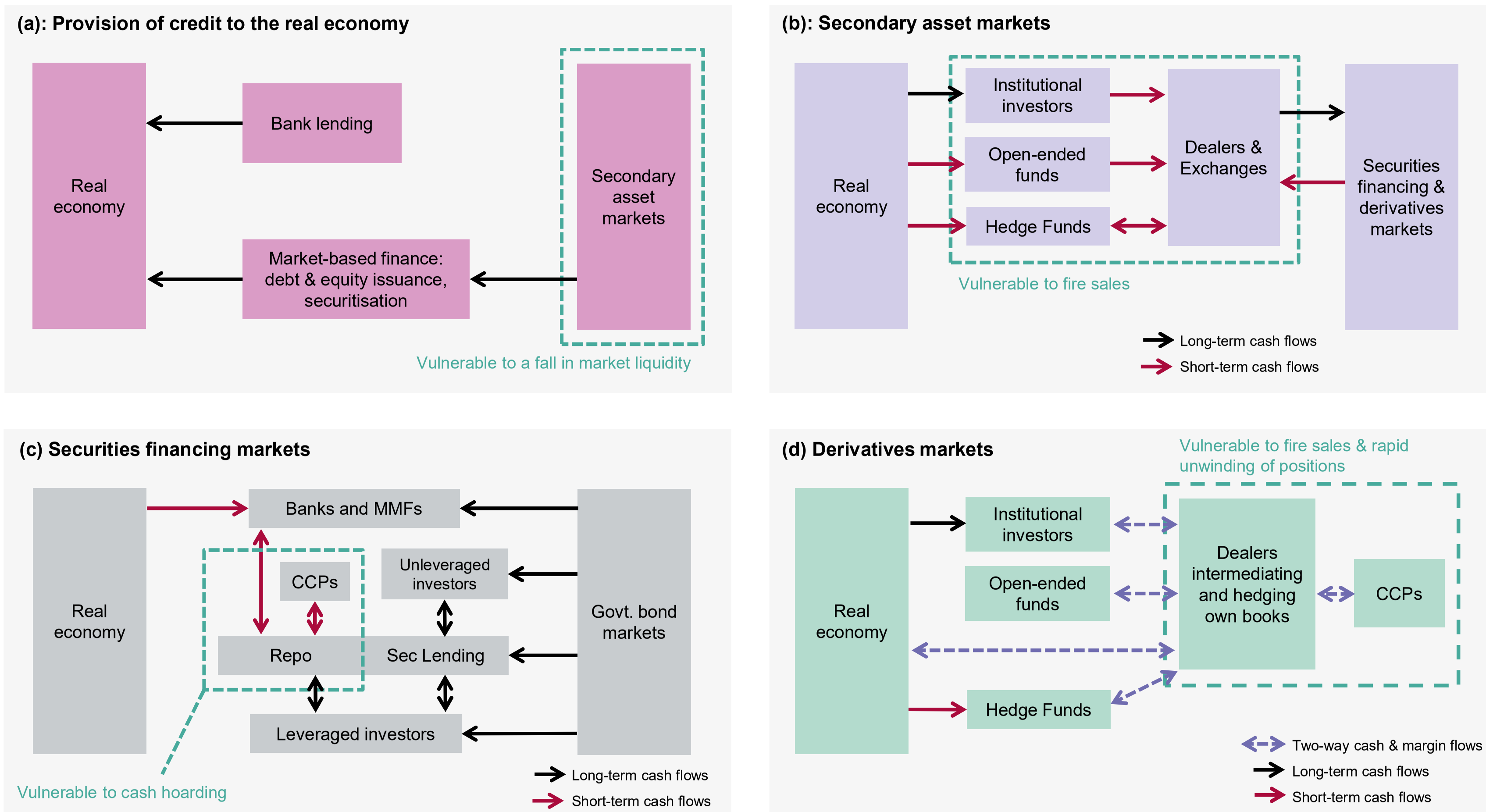
Source: FSB Shadow Banking Monitor Dataset (2017).

Figure A.2: *Cumulative net finance raised by UK private non-financial corporations*[(a)]



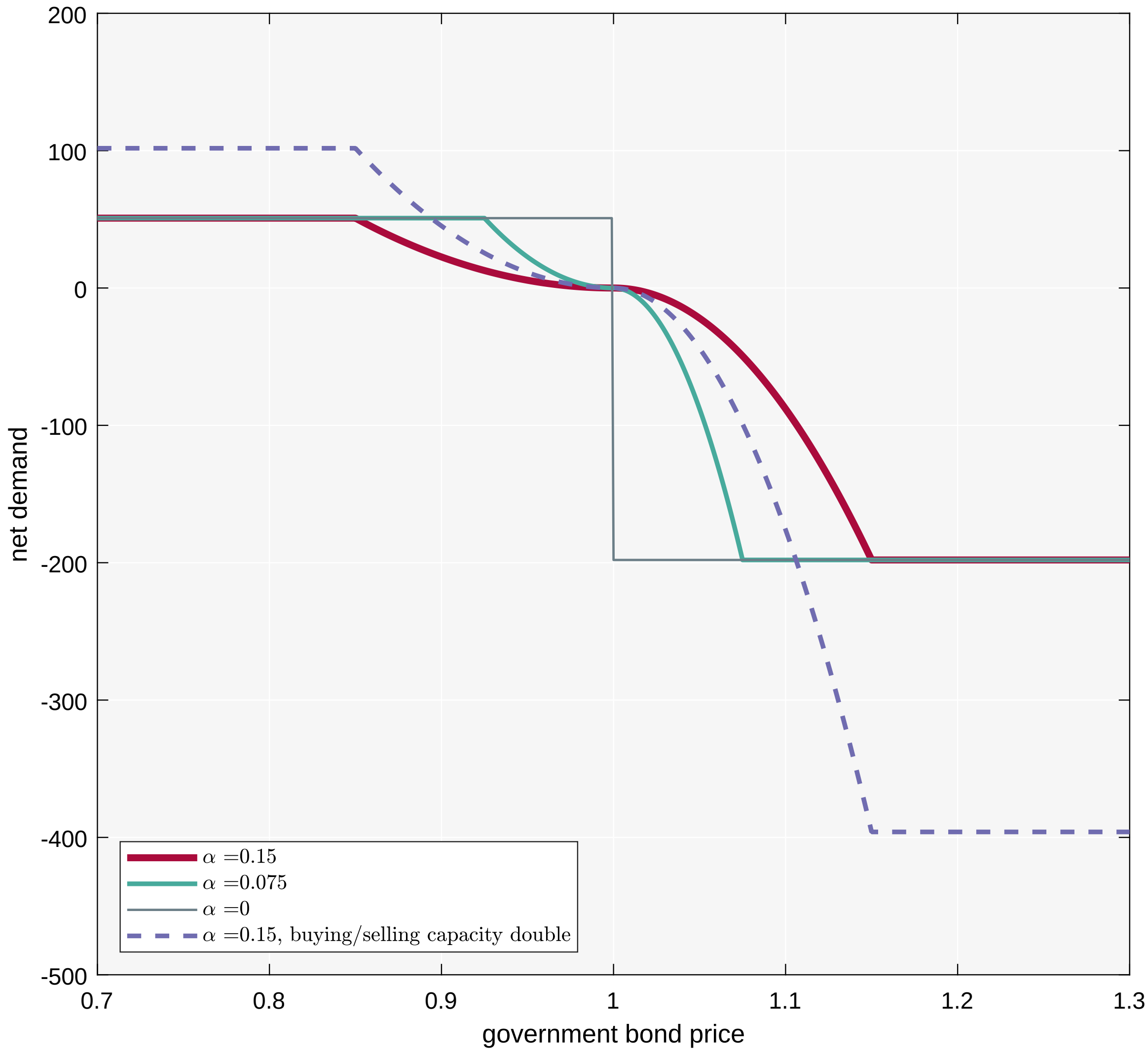
Notes: (a) Finance raised by PNFCs from UK monetary financial institutions and from capital markets. Data cover funds raised in both sterling and foreign currency, converted to sterling. Seasonally-adjusted other than for bonds and commercial paper. (b) Market-based finance is composed of bonds, equities and commercial paper. (c) Owing to the seasonal adjustment methodology, the total series may not equal the sum of its components.
Source: Bank of England.

Figure A.3: *Stylised 'birds-eye' view of the market-based finance system*



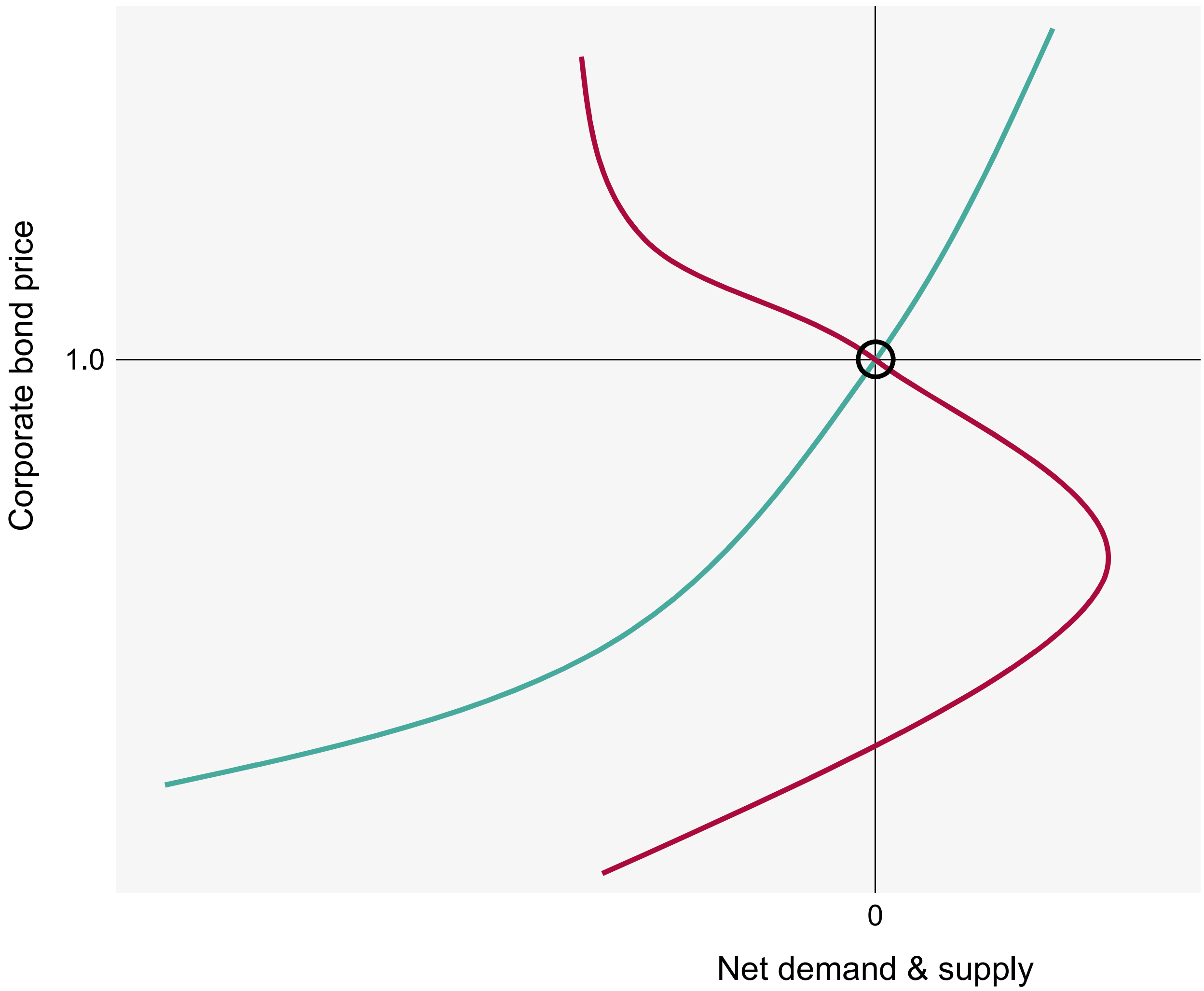
Source: Author's calculations.

Figure A.4: *Role of hedge fund in the model*



Notes: The hedge funds target price is 1.
Source: Authors' calculations.

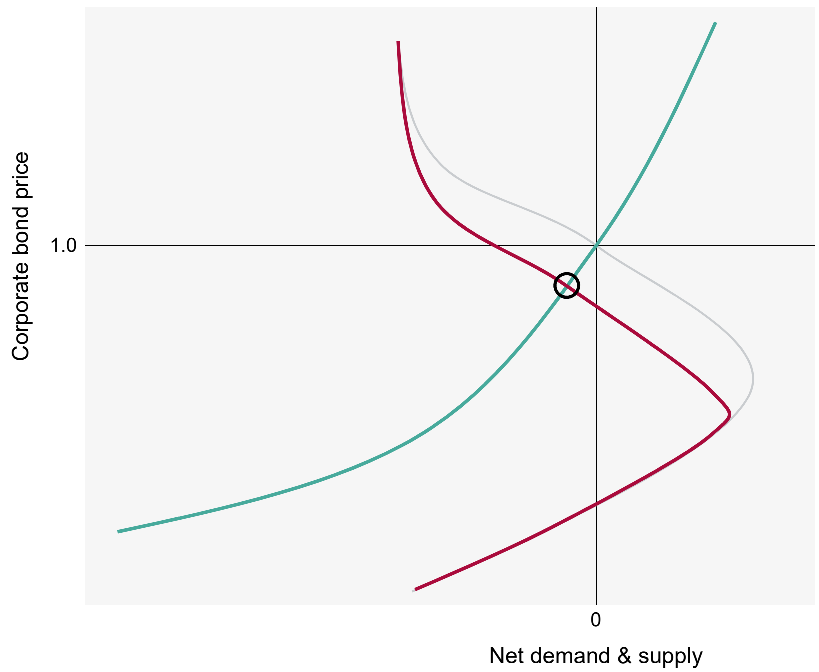
Figure A.5: *Stylised price determination in the model*



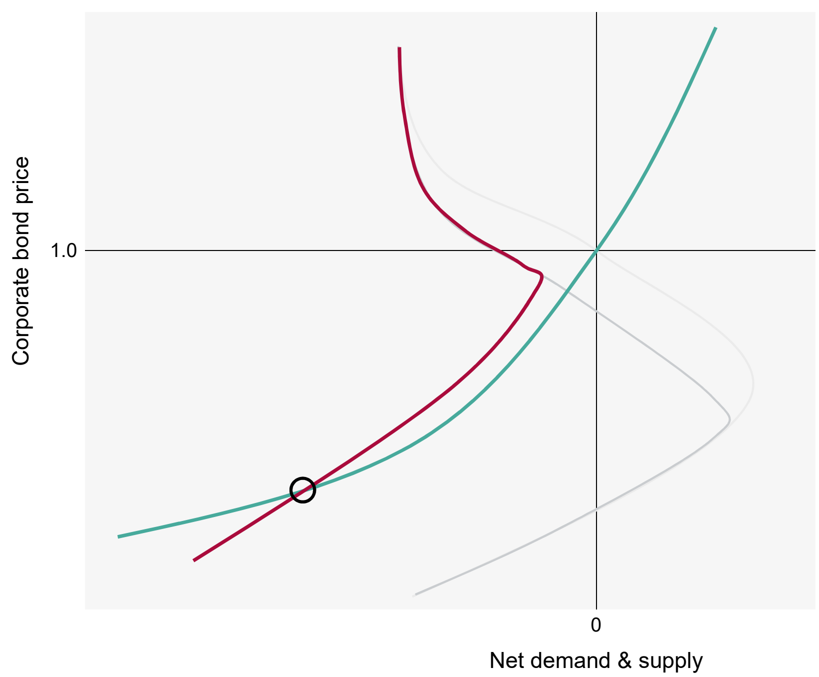
Notes: Constrained agents' demand is illustrated by the red line, with demand increasing from left to right. Unconstrained agents' supply is illustrated by the teal line, with supply increasing (and therefore demand decreasing) from left to right. The circle indicates the model's initial equilibrium.
Source: Authors' calculations.

Figure A.6: *Stylised price determination in the model in the face of shocks*

(a) *Shock to fundamentals*

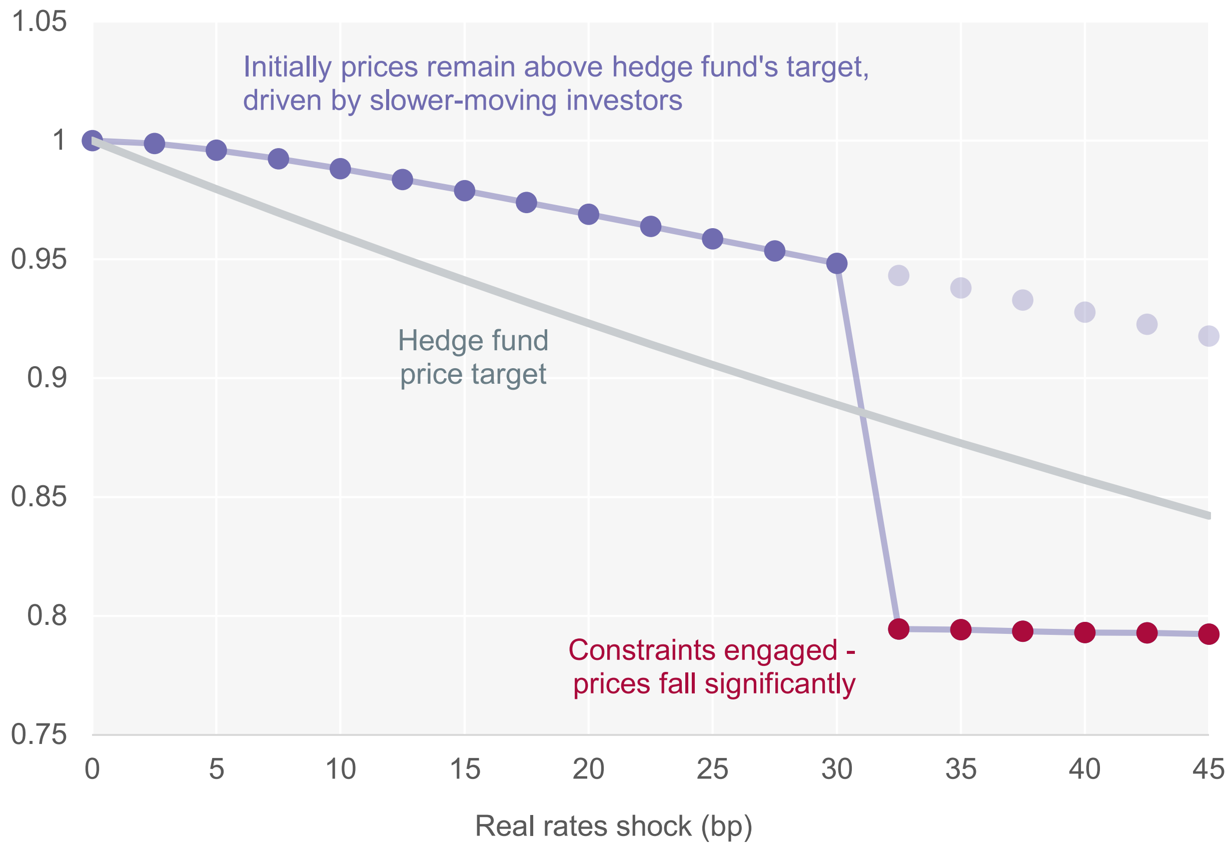


(b) *Shock to fundamentals and capital constraints*



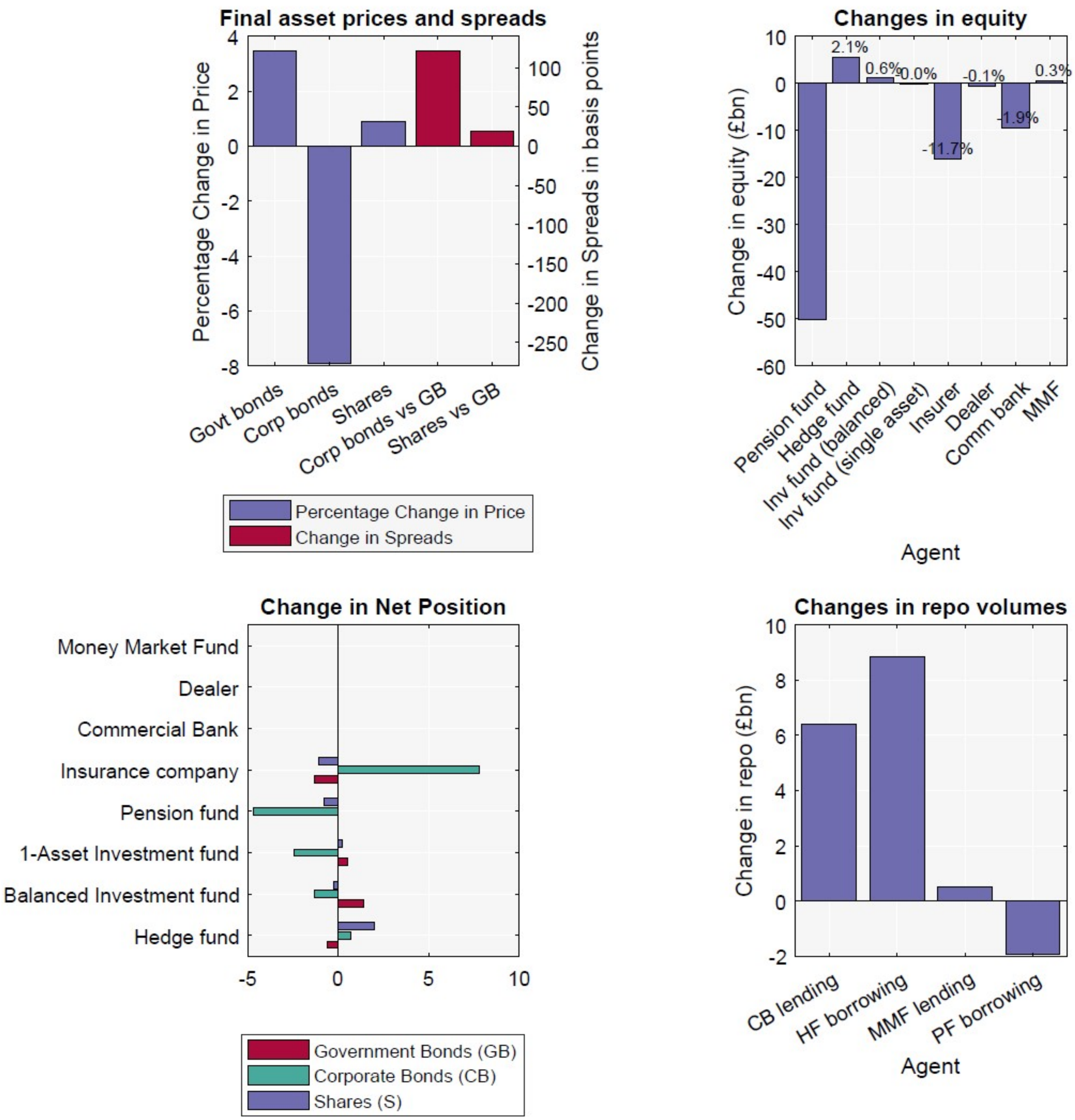
Notes: Constrained agents' demand is illustrated by the red line, with demand increasing from left to right. Unconstrained agents' supply is illustrated by the teal line, with supply increasing (and therefore demand decreasing) from left to right. The circles indicate the model's equilibrium in each scenario.
Source: Authors' calculations.

Figure A.7: *Non-linear price response by constraints*



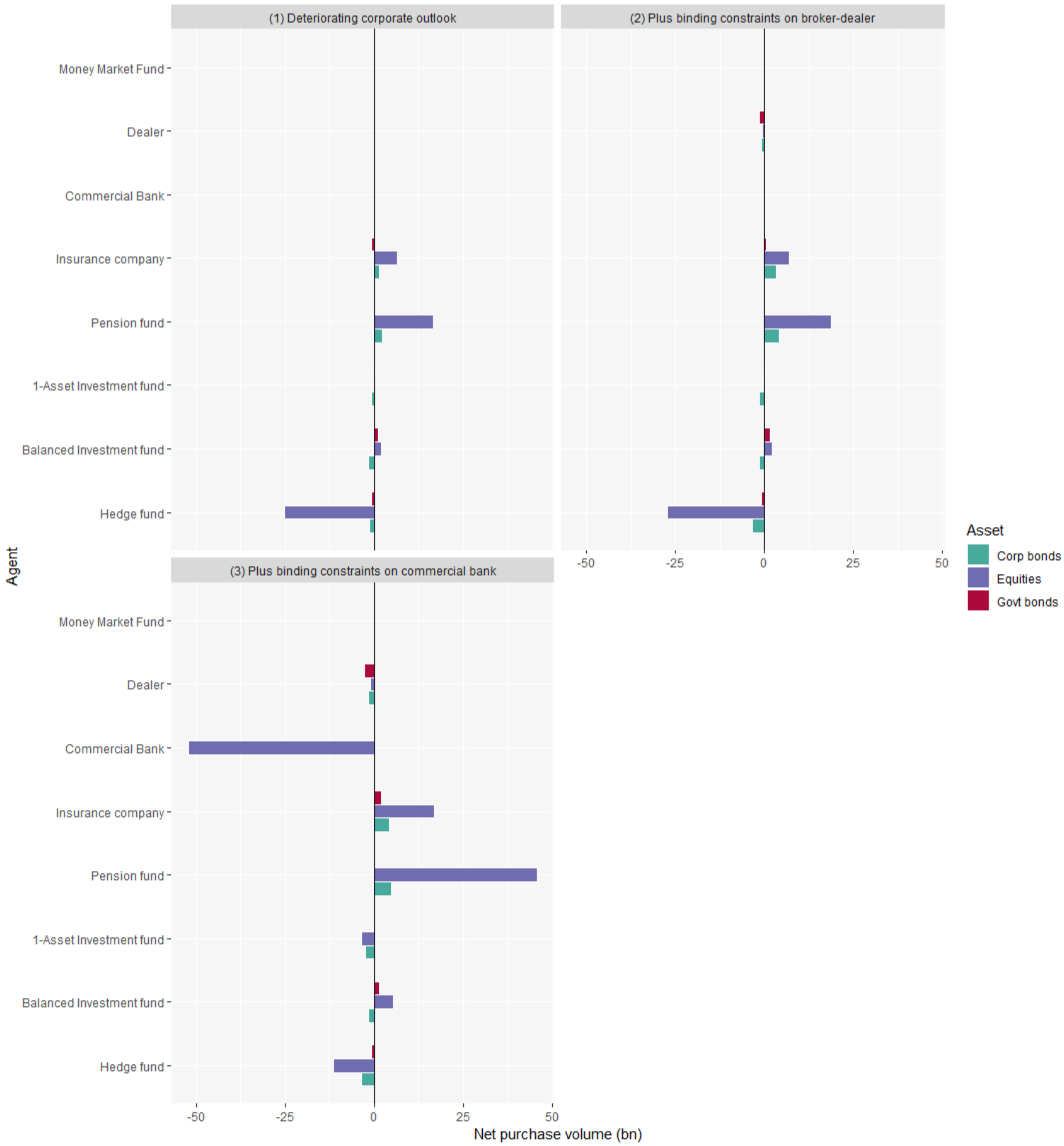
Notes: Equilibrium prices are not equal to the hedge-fund price target because of hedge-fund limitations and behaviour of institutional investors.
Source: Authors' calculations.

Figure A.8: *Impact of a 3 sd shock to expected credit default losses on key model outputs*



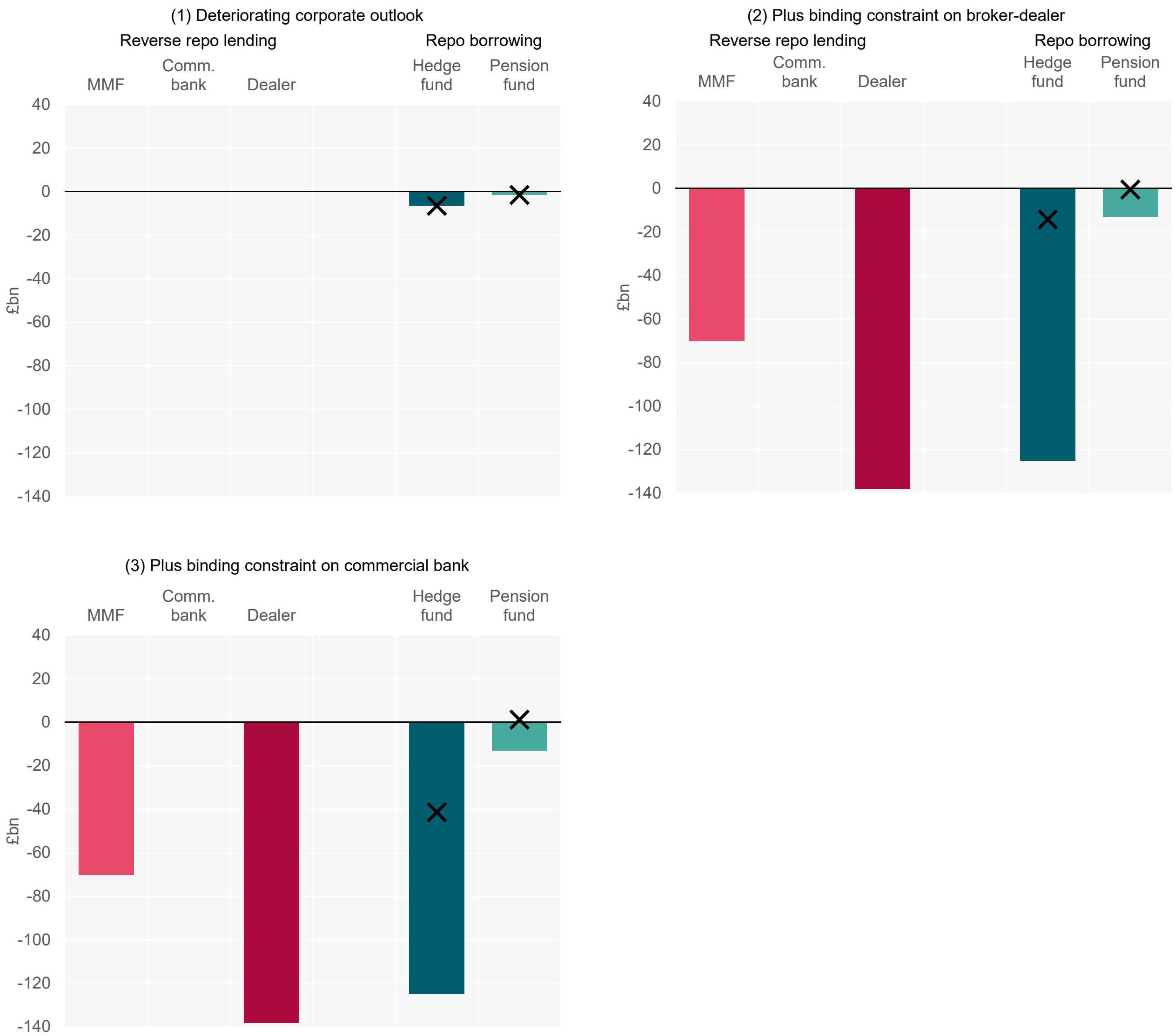
Source: Authors' calculations.

Figure A.9: *Net purchase volumes (£bn) by sector in the stress scenario*



Notes: This figure presents the net volume of sales by each sector in each of the three layers of the simulation.
Source: Authors' calculations.

Figure A.10: *Repo market activity (£bn) in the stress scenario*



Notes: This figure presents the impact on repo market activity in each of the three layers of the simulation. Bars show actual changes in lending and borrowing, while crosses indicate the borrowing agents' desired change in repo funding.
Source: Authors' calculations.

Figure A.11: *Impact of alleviating capital and liquidity constraints*

(a) *Absolute impact on value of traded securities in the mode (£bn)*

Size of improvement (£bn) →	5	10	15	20	25	30	35	40	45	50
Inv. fund liquidity	18	34	56	75	92	105	117	127	156	175
Comm. bank capital	0	0	126	126	126	126	126	126	126	126
Hedge fund liquidity	18	35	48	60	69	78	85	92	98	104
Dealer capital	13	69	70	70	70	75	75	79	79	79

(b) *'Bang for buck' ratios*

Size of improvement (£bn) →	5	10	15	20	25	30	35	40	45	50
Inv. fund liquidity	4	3	4	4	4	3	3	3	3	3
Comm. bank capital	0	0	8	6	5	4	4	3	3	3
Hedge fund liquidity	4	4	3	3	3	3	2	2	2	2
Dealer capital	3	7	5	4	3	3	2	2	2	2

Notes: This chart presents the impact on the value of tradeable securities in the model – a proxy for welfare – from the provision of capital and liquidity of the magnitude reported in the columns. The upper panel shows the absolute impact on system-wide assets; the lower panel repeats the exercise, but records the 'bang for buck' ratio, defined as the improvement in system-wide asset values divided by the intervention amount. Cells coloured green indicate interventions with positive impact, with darker shades indicating a larger impact. Bordered cells in the lower panel highlight the interventions with largest bang for buck.
Source: Authors' calculations.

Table A.1: *A summary of agent behaviours (objectives and constraints)*

Agent	Objective(s)	Constraints:			
		Solvency/leverage	Funding/liquidity		
			Repo mkt	Derivatives mkt	Investor redemptions
Life insurer	Portfolio of traded securities managed to optimise risk-adjusted returns. Hedges exposure to interest rates in market for IRS.	Regulatory constraint on ratio of assets to shareholder capital. If breached, sells risky assets	-	Posts initial margin in form of govt bonds. Must meet variation margin call in cash. Does so by (i) reducing cash holdings, (ii) selling risky assets.	-
Pension fund	'Growth' portfolio of equities, corp bonds and 'other assets', managed to optimise risk-adjusted returns. 'Hedge' portfolio of both govt bonds (leveraged via repo market) and IRS, managed to maintain constant hedge ratio.	-	Faces potential margin calls when haircuts increase in repo market. Meets by selling (i) govt bonds and (ii) risky assets.	Posts initial margin in form of govt bonds. Must meet variation margin call in cash. Does so by (i) reducing cash holdings, (ii) selling risky assets.	-
Investment fund	Mixed fund consisting of traded securitises and other assets, managed to optimise risk-adjusted returns. Range of single-asset funds that invest only in one type of security. Mixed fund levered via derivatives market.	-	-	Posts initial margin in form of govt bonds. Must meet variation margin call in cash. Does so by (i) reducing cash holdings, (ii) selling risky assets.	Redemptions from household must be met in cash. Achieved by selling assets in proportion in which they are held ('vertical slice').
Hedge fund	Three single asset funds that invest in different traded securities. Arbitrages deviations between market prices and fundamentals. Obtains leverage in repo market and via IRS.	Targets self-imposed leverage ratio.	Faces potential funding shortfall when haircuts rise in repo market. Meets by (i) selling govt bonds, (ii) by selling risky assets.	Posts initial margin in form of govt bonds. Must meet variation margin call in cash. Does so by (i) reducing cash holdings, (ii) selling risky assets	Redemptions from household must be met in cash. Achieved by selling assets in proportion in which they are held ('vertical slice').
Broker dealer	Intermediates repo and derivatives market. Does so passively, i.e. to maximum extent constraints allow. Hedges residual interest rate risk via IRS.	Regulatory constraint on its leverage ratio.	Faces potential funding risk in repo market. Meets by withdrawing reverse repo provision.	Posts initial margin in form of govt bonds. Must meet variation margin call in cash. Does so by (i) reducing cash holdings, (ii) selling risky assets.	-
Money market fund	Extends funds to dealer and places deposit with commercial bank. Does so passively, i.e. to extent that constraints allow. Allocation changes with creditworthiness of dealer.	-	-	-	Redemptions from household must be met in cash. Achieved by withdrawing funding from other agents in proportion with which it extends them.
Commercial bank	Holds some illiquid assets (loans). Extends funding to dealer. Does both passively i.e. to maximum extent that constraints allow. Allocation changes with creditworthiness of dealer.	Regulatory constraints on risk-weighted capital and leverage ratios and liquidity coverage ratio. Meets by selling assets in manner designed to minimise losses.	-	-	-

Table A.2: *Summary of single shock results*

Shock	Size of shock (bps)	Δ price (%) Govt. bonds	Δ price (%) Corp. bonds	Δ price (%) Equities	Δ yield (bps) Corp. bonds	Δ spreads (bps) Corp. bonds	Δ ST repo (%)	Δ equity (%)	Redemptions (%)
Expected credit losses	18 (1sd)	1.4	-2.3	0.5	28.1	36.7	1.9	-0.9	0.0
	36 (2sd)	2.5	-5.0	0.7	61.6	77.1	3.1	-1.8	0.0
	55 (3sd)	3.5	-7.9	0.9	99.1	120.9	4.1	-2.7	0.1
Long-term risk-free rate	21 (1sd)	-0.7	-0.8	-3.3	9.7	5.1	-4.1	-0.9	0.1
	42 (2sd)	-1.9	-2.2	-7.6	26.8	14.4	-9.8	-2.1	0.2
	63 (3sd)	-3.4	-3.9	-11.8	47.3	25.0	-15.6	-3.1	0.4
Expected long-term dividend growth	-47 (1sd)	-0.1	3.6	-8.5	-41.9	-48.8	-6.7	-1.7	0.1
	-94 (2sd)	-0.4	6.2	-16.8	-71.5	-74.3	-13.6	-3.4	0.2
	-140 (3sd)	-0.6	8.4	-23.1	-96.0	-99.6	-18.7	-4.8	0.3
Value of commercial bank loans	6 (1sd)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	7 (2sd)	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
	9 (3sd)	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
Value of other assets	277 (1sd)	-1.0	-2.7	-2.6	33.0	26.8	-5.0	-6.8	0.1
	554 (2sd)	-1.9	-5.5	-5.1	68.4	55.9	-10.1	-13.5	0.2
	831 (3sd)	-14.0	-13.6	-14.2	176.3	78.7	-100.0	-19.4	0.8

Notes: The three shock sizes represent one, two and three standard deviations in the recent historical distribution. Changes in short-term repo and equity are shown as a proportion of the aggregate values. Redemptions are relative to aggregate investment fund, hedge fund and MMF assets.
Source: Authors' calculations.

Table A.3: *Stress scenario results*

Simulation	Δ price (%)			Δ yield	Δ spread	Δ ST repo (%)	Δ equity (%)	Redemptions (%)
	Govt. bonds	Corp. bonds	Equities	Corp. bonds	Corp. bonds			
(1) Deteriorating corporate outlook	2.7	-3.6	-9.1	43.9	60.6	-4.7	-4.6	0.3
(2) Plus binding constraint on broker-dealer	1.0	-5.4	-10.2	67.1	73.4	-90.6	-5.5	0.4
(3) Plus binding constraint on commercial bank	-2.0	-7.9	-21.4	98.8	85.7	-100.0	-8.9	0.9

Notes: This table shows the changes in key variables as a result of the different layers of the stress scenario in Section 5. Changes in short-term repo and equity are shown as a proportion of the aggregate values. Redemptions are relative to aggregate investment fund, hedge fund and MMF assets.
Source: Authors' calculations.

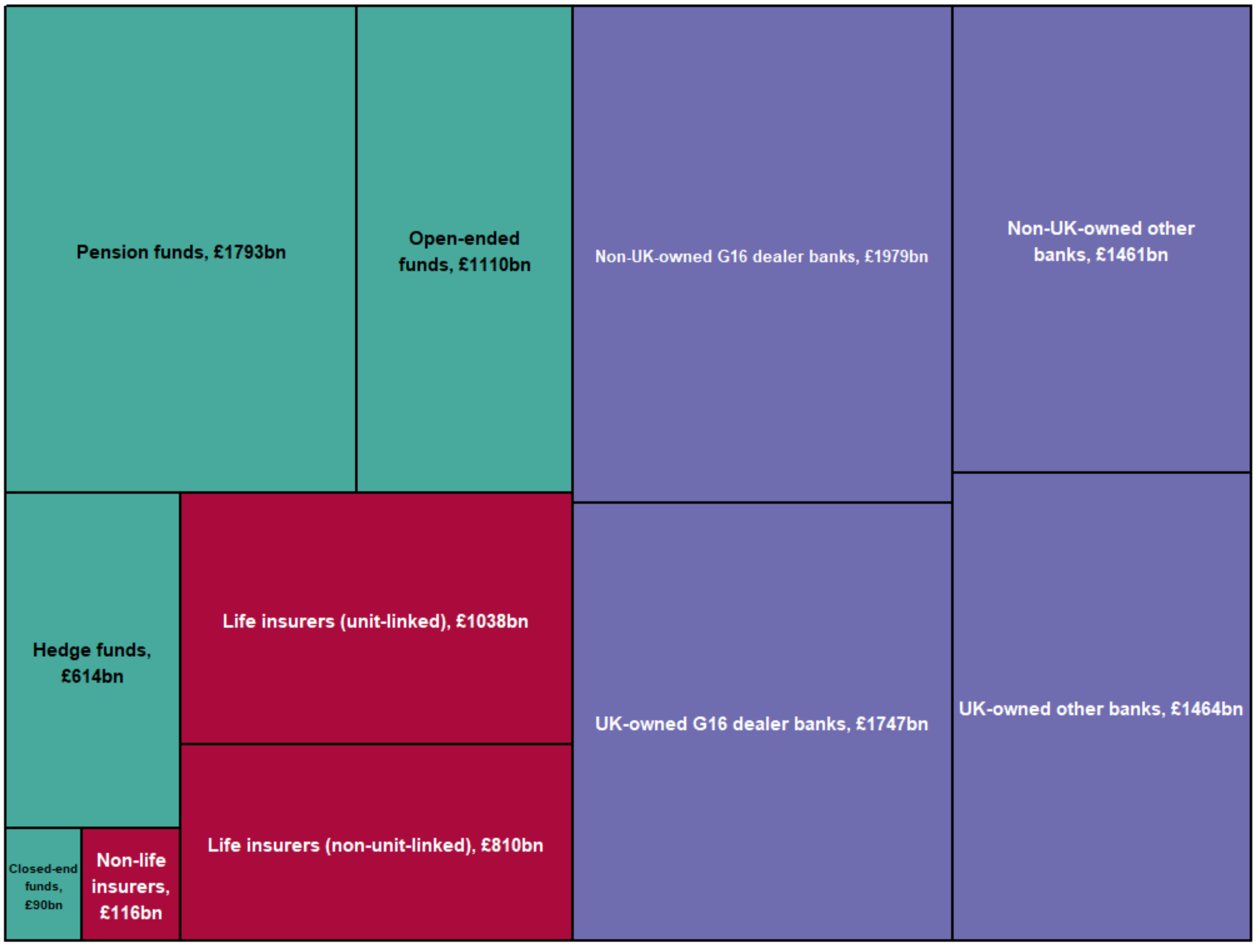
Table A.4: *Sensitivity analysis results: incremental changes compared with stress scenario*

Model adjustment		Δ price (pp)		Δ yield (bps)	Δ spread (bps)	Δ ST repo (pp)	Δ equity (pp)	Redemptions (pp)
	Govt. bonds	Corp. bonds	Equities	Corp. bonds	Corp. bonds			
Increased redemptions	-8.5	-4.7	-7.0	4.9	-28.8	0	-1.6	3.7
Larger fund sector	0.6	-1.9	0.3	29.8	2.8	0	-3.5	0
Faster ICPF portfolio adjustment	4.9	-2.6	-0.1	66.1	31.4	0	-2.3	-0.1
Greater hedge fund 'conviction'	0	0	0	0	0	0	0	0

Notes: This table shows the incremental change in results compared with the third layer of the stress scenario in Section 5. Changes in short-term repo and equity are shown as a proportion of the aggregate values. Redemptions are relative to aggregate investment fund, hedge fund and MMF assets.
Source: Authors' calculations.

Appendix B: Model parameterisation

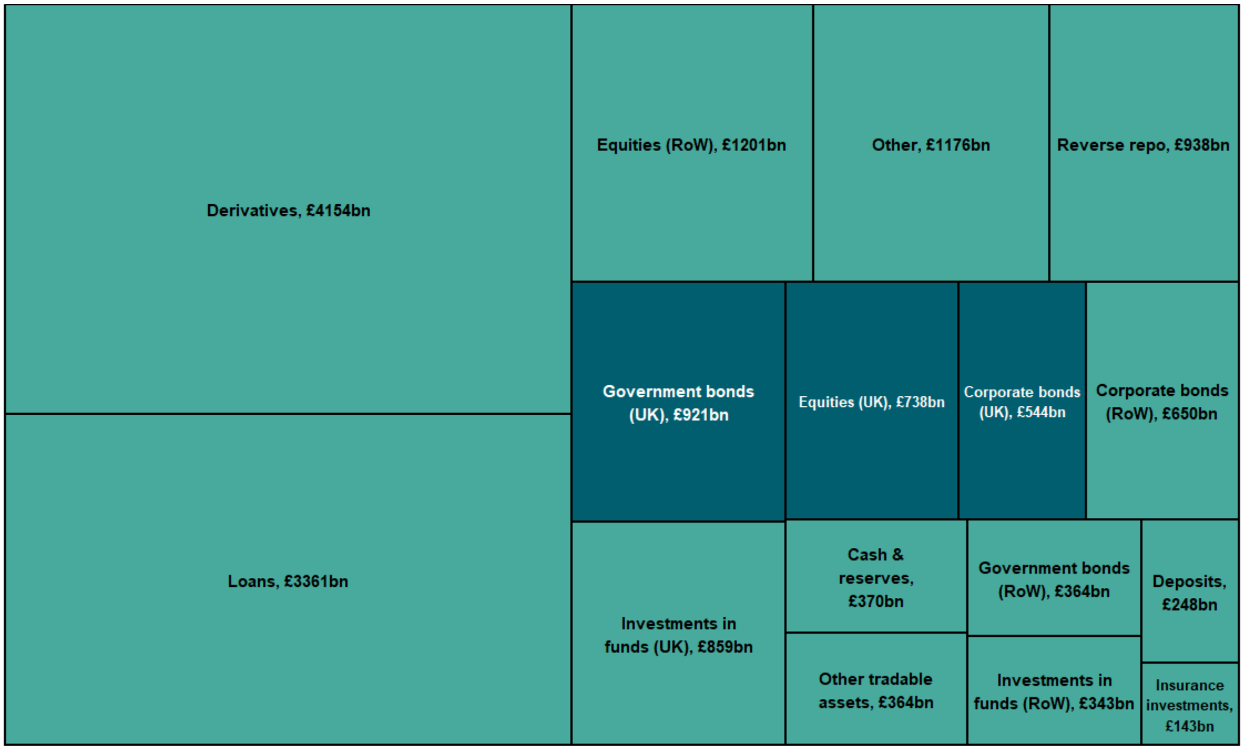
Figure B.1: *Balance sheets of different sectors in the model*



Notes: Colours indicate different types of sector, with funds shown in teal, insurers in red and banks in purple. This figure excludes the accounting value of derivative assets and liabilities, the effect of which is particularly pronounced on G16 dealer banks' balance sheets (e.g. just under half of non-UK-owned G16 dealer banks' assets are derivatives out of a total of £4.7tn). The figure was created using the 'treemap' package for R (Martijn Tennekes (2017), R package version 2.4-2). Available for download at https://CRAN.R-project.org/package=treemap.

Figure B.2: *Breakdown of assets and liabilities*

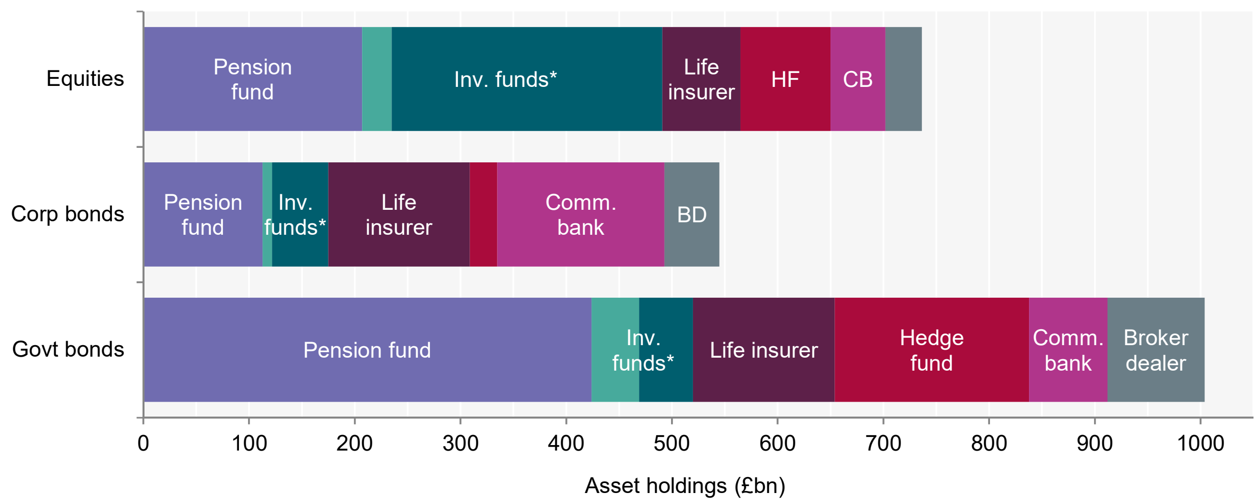
(a) *Asset classes*



(b) *Liability type*

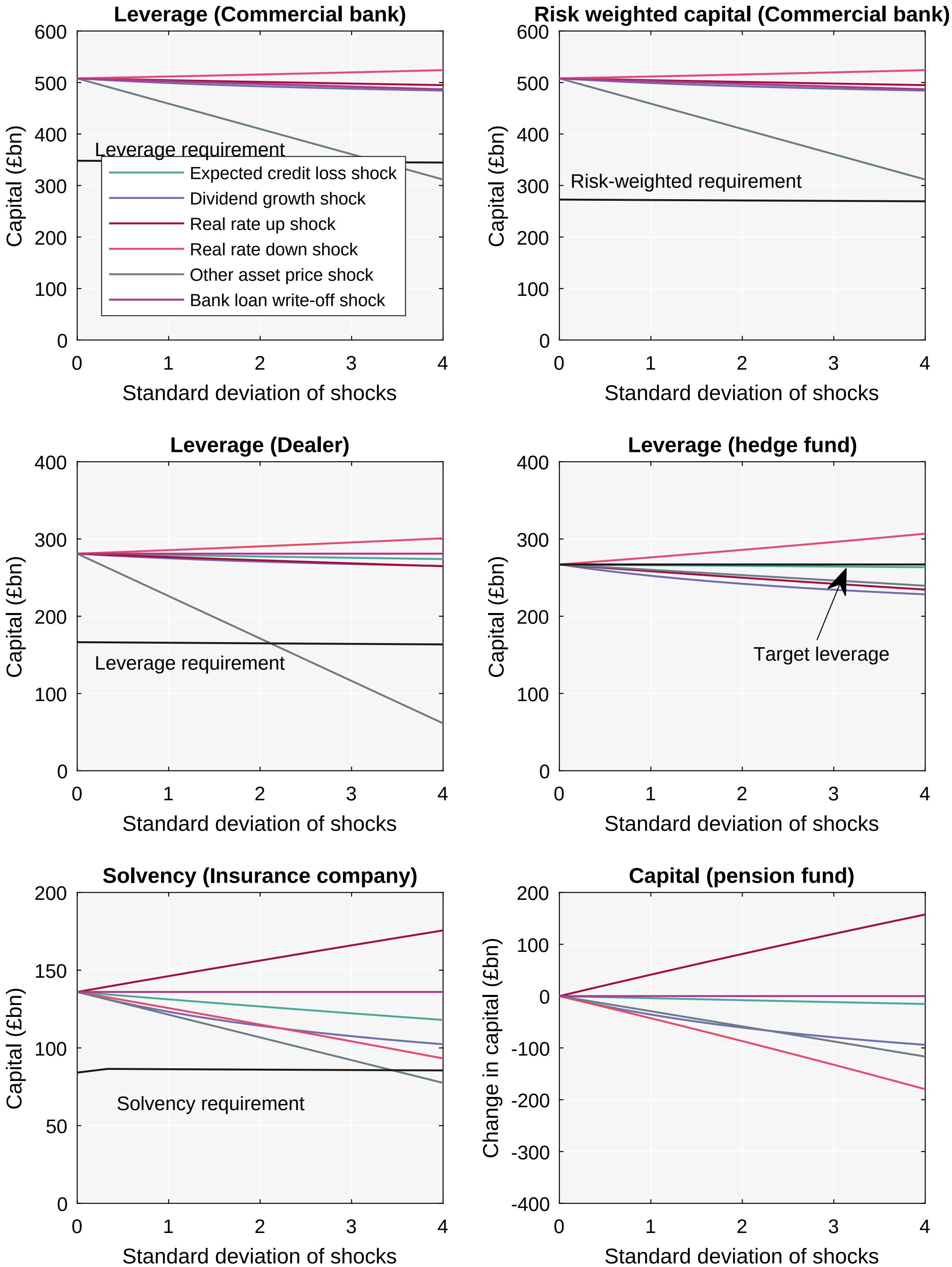
Source: Authors' calculations.

Figure B.3: *Asset holdings by sector (£bn)*



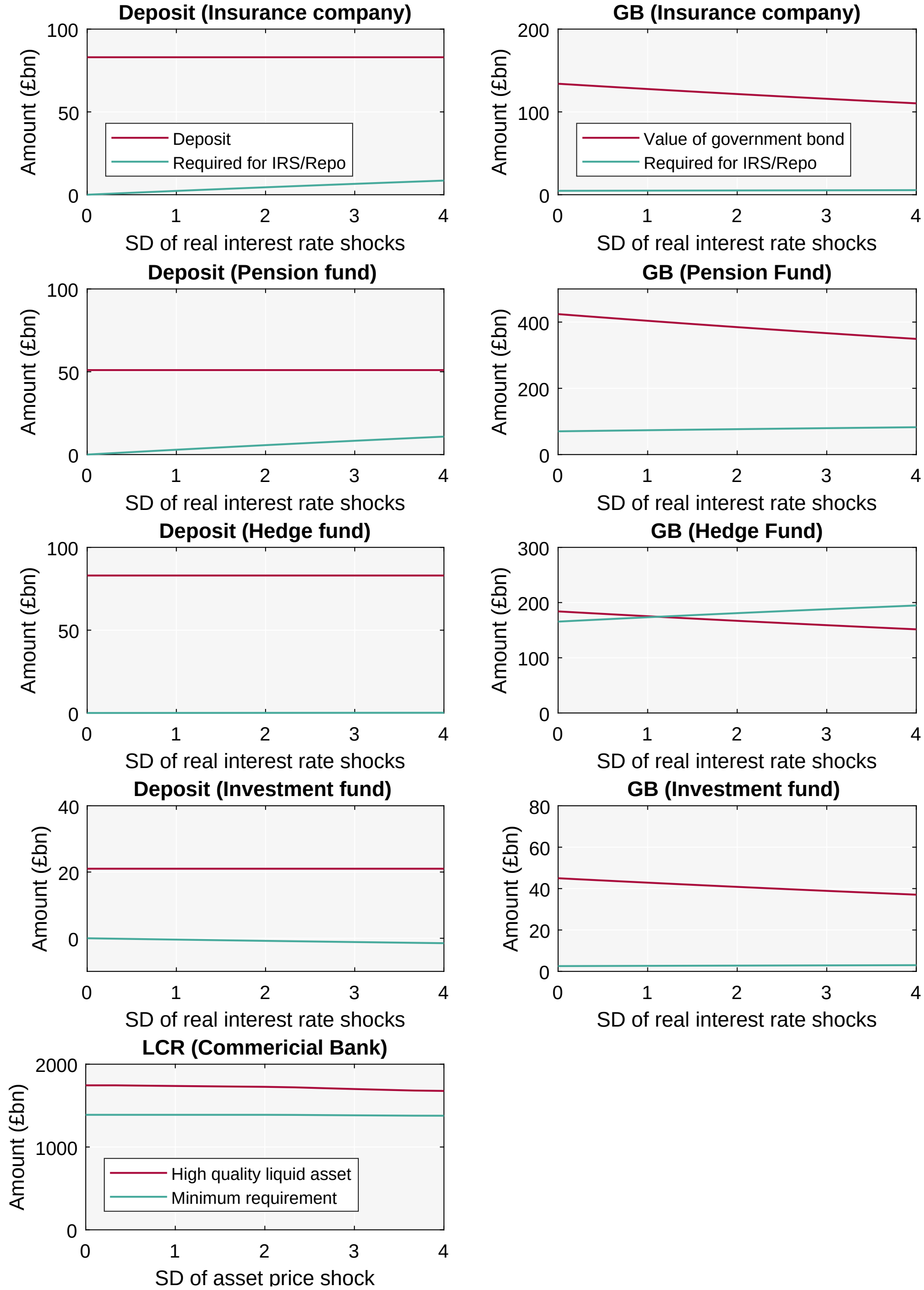
Notes: Mixed and single asset investment funds are indicated by darker and lighter shades respectively.
Source: Authors' calculations.

Figure B.4: *Sensitivity of capital headroom to selected single shocks*



Notes: The requirement level also varies according to shocks. Since the fluctuation of the requirement level is negligible across shocks, the average requirement level in each point is plotted in the charts.
Source: Authors' calculations.

Figure B.5: *Sensitivity of liquidity headroom to selected single shocks*



Notes: 'Deposit' reflects the cash flow caused by haircut shocks and variation margin posted for interest rate swaps. 'Value of government bond (GB)' reflects the change in amount caused by the mark to market revaluation of bonds encumbered for repo and IRS initial margin and unencumbered bonds. Commercial banks high quality liquid asset reflects the mark to market revaluation of all three assets.
Source: Authors' calculations.

Table B.1: *A summary of data sources used to calibrate the model*

Data source	Coverage and description	Publicly available?	Modelled sector
Office for National Statistics (ONS) 'MQ5' dataset	Annual, survey-based estimates of the balance sheets of UK: self-administered pension funds, investment trusts, unit trusts and property unit trusts. We map data on pension funds directly to the pension fund agent. For the investment fund agent we combine ONS data on investment trusts, unit trusts and property unit trusts with Bank of England data on unit-linked life insurers.	Yes	Pension fund and open-ended investment fund (OEIF)
Bank of England Solvency II returns	Detailed reporting on UK insurers invested assets, and summary information on their liabilities collected by the Bank of England under the EU Solvency II regulation. We map unit-linked insurers assets and liabilities to the investment fund agent, and the remainder (non-life and non-unit-linked life insurers) to the insurance company agent.	No	Life insurer
Bank of England Bankstats	Data collected by the Bank of Englands statistical function on banks and building societies assets and liabilities. Covers UK-based banking entities as well as branches of RoW banks operating in the UK. Along with the supplementary data on some investment firms described below, we split our bank balance sheet data along broad functional lines to map to the dealer and commercial bank agents balance sheets. Please note these series differ from those seen in the regular Bankstats publications due to differences in construction and methodology.	Yes in summary form	Broker-dealer and commercial bank
Bank of England FSA001 return	Regulatory balance sheet data collected by the Bank of England. The FSA001 return is less detailed than Bankstats data, but importantly covers some large investment firm subsidiaries which are not included in Bankstats. We use this data to supplement Bankstats when mapping to the dealer and commercial bank balance sheet.	No	Broker-dealer and commercial bank
IOSCO (2017)	September 2016 survey of the global hedge fund industry. We use the results to inform the split assets and liabililties on the hedge fund's balance sheet.	Yes	Hedge fund
Financial Conduct Authority (2017)	September 2014 survey of hedge fund management companies with operations in the UK. We use these data to estimate the total assets under management and net asset value of UK-managed hedge funds.	Yes	Hedge fund
IMMFA (2017)	Data on the total assets of prime sterling money market funds (MMFs). We use the IMMFAs estimate of prime sterling MMFs as a proxy for the total size of our UK MMF. We then make some simple assumptions about the breakdown of assets it holds.	Yes	MMF

Table B.2: *Initial balance sheets of model agents (£bn)*

Assets	Insurer	Pension fund	OEIF (mixed)	OEIF (single)	Hedge fund	Dealer	MMF	Com. bank
Reserves	-	-	-	-	-	-	-	212
Deposits	83	51	21	9	83	-	86	-
ST rev repo	-	-	-	-	-	137	70	130
LT rev repo	-	-	-	-	-	87	16	86
Govt bonds	134	424	45	51	184	92	-	74
Corp bonds	134	113	9	53	26	52	-	158
Equities	74	207	28	256	85	35	-	52
Loans	-	-	-	-	-	-	-	2,120
Other	500	998	72	710	235	1,877	-	1,678
Total assets	925	1,793	175	1,079	613	2,280	172	4,510

Liabilities	Insurer	Pension fund	OEIF (mixed)	OEIF (single)	Hedge fund	Dealer	MMF	Com. bank
ST repo	-	13	-	-	125	200	-	-
LT repo	-	51	-	-	35	102	-	-
Other	214	15	-	-	186	-	-	-
Pension liab	-	1,714	-	-	-	-	-	-
Insurer liab	575	-	-	-	-	-	-	-
Dealer bonds	-	-	-	-	-	1,697	-	-
Deposits	-	-	-	-	-	-	-	4,002
Inv shares	-	-	175	1,079	267	-	172	-
Equity	136	-	-	-	-	281	-	508
Total liab	925	1,793	175	1,079	613	2,280	172	4,510

Notes: Short-term repo and reverse repo has maturity of less than one month; longer-term repo and reverse repo has maturity greater than one month. Other assets includes non-UK traded assets, asset types not specifically modelled (e.g. commercial property), and assets where no additional information is available. Derivative assets and liabilities are excluded as described in Section 4.

Table B.3: *Calibration of regulatory constraints*

Category	Symbol	Value	Source/rationale
Life insurer:			
Minimum SCR threshold	$\bar{k}^I$	100%	Solvency 2.
Total capital charge	$\bar{k}^I$	£84.13 bn	Value chosen to match UK life insurers headroom over solvency capital requirements in Solvency 2.
Market risk capital charge	κ_m^I	50% of total capital requirement	Douglas et al. (2017).
Non-market risk capital charge	κ_o^I	50% of total capital requirement	Douglas et al. (2017).
Commercial bank:			
Minimum leverage ratio	$\bar{k}^{CB,LEV}$	8.1%	Value chosen to be consistent with UK banks headroom over minimum leverage requirements.
Minimum risk-weighted capital ratio	$\bar{k}^{CB,RW}$	12.0%	Value chosen to be consistent with UK banks headroom over minimum risk-weighted capital requirements.
Risk weights	θ_i	Reserves – 0% Loans – 46% Reverse repos – 20% Government bonds – 0% Corporate bonds – 70% Equities – 100% Other assets – 60%	Calibrated using the revised standardised risk weights in Basel III.
Minimum liquidity coverage ratio (LCR)	$l\bar{c}r$	685%	Value chosen to be consistent with UK banks headroom over minimum LCR requirement.
High-quality liquid assets (HQLA) weights	ω_i	Government bonds – 100% Corporate bonds – 70% Equities – 50% Other assets – 70% Reverse Repos – 100%	Calibrated using the Basel III LCR framework.
Broker-dealer:			
Minimum leverage ratio	$\bar{k}^{BD}$	7.3%	Value chosen to be consistent with UK broker dealer banks headroom over minimum leverage requirements.

Source: For regulatory capital risk weights, see https://www.bis.org/bcbs/publ/d424hlsummary.pdf; for HQLA weights, see https://www.bis.org/publ/bcbs238.pdf.

Table B.4: *Calibration of agents' behaviours*

Category	Symbol	Value	Source/rationale
Rebalancing horizon:			
Life insurer	-	3 months	Assumed to rebalance faster than pension fund, given added pressure from regulation.
Pension fund	-	6 months	Assumed to be the slowest-moving long-term investor in the model, given less pressure from regulation and investors.
Investment fund (mixed)	-	1 month	Assumed to rebalance faster than insurer and pension fund, given pressure from investors and more active management.
Flow-performance 'procyclicality' coefficient:			
Mixed investment fund	$\rho^{IF,m}$	0.2	Baranova et al. (2017a).
Govt bond fund	$\rho^{IF,s_{GB}}$	0.3	Baranova et al. (2017a).
Corporate bond fund	$\rho^{IF,s_{CB}}$	0.64	Baranova et al. (2017a).
Equity fund	ρ^{IF,s_E}	0.09	Baranova et al. (2017a).
Hedge fund	ρ^{HF}	0.1	Baranova et al. (2017a).
Other behavioural parameters:			
Hedge fund uncertainty bound	α	0.15	Determines how aggressively the hedge fund reacts to deviations of the market price from its view of the fundamental price.
Commercial bank liquidity ranking of tradeable assets (1 = most liquid)	$\tilde{E}[\Delta p_i(A_i^{CB})]$	Other assets (1) Equities (1) Govt bonds (2) Corp bonds (3)	Values informed by the approach to modelling the amplification through sales of commonly held assets as part of the stress test of UK banks (2017).

Table B.5: *Portfolio optimisation*

Category	Symbol	Value	Source/rationale
All agents:			
Expected return on govt bond	$E[r_{GB}]$	0.025	Blackrock (2018).
Expected return on corp bond	$E[r_{CB}]$	0.035	Blackrock (2018).
Expected return on equity	$E[r_E]$	0.054	Blackrock (2018).
Expected return on other assets	$E[r_O]$	0.054	Authors' assumption.
Govt bond-corp bond return corr	-	0.45	Blackrock (2018).
Equity-other asset return corr	-	0.5	Authors' assumption.
Govt bond-equity return corr	-	-0.15	Blackrock (2018).
Corp bond-equity return cor	-	-0.24	Blackrock (2018).
Expected dividend growth	g	0.03	Blackrock (2018).
Life insurer:			
Expected return on other assets	$E^I[r_{OA}]$	0.059	Authors' assumption.
Expected corp bond volatility	$Var^I(r_{CB})$	0.186	Authors' assumption.
Expected other asset volatility	$Var^I(r_O)$	0.095	Authors' assumption.
Risk aversion coefficient	λ^I	28.02	Authors' assumption.
Pension fund:			
Expected corp bond volatility	$Var^{PF}(r_{CB})$	0.106	Blackrock (2018).
Expected other asset volatility	$Var^{PF}(r_O)$	0.068	Authors' assumption.
Risk aversion coefficient	λ^{PF}	7.38	Authors' assumption.
Investment fund:			
Expected corp bond volatility	$Var^{IF}(r_{CB})$	0.321	Authors' assumption.
Expected other asset volatility	$Var^{IF}(r_O)$	0.092	Authors' assumption.
Risk aversion coefficient	λ^{IF}	28.07	Authors' assumption.
Hedge fund:			
Expected govt bond volatility	$Var^{HF}(r_{GB})$	0.121	Blackrock (2018).
Expected corp bond volatility	$Var^{HF}(r_{CB})$	0.106	Blackrock (2018).
Expected equity volatility	$Var^{HF}(r_E)$	0.149	Blackrock (2018).

Notes: We assume a slightly higher expected return on other assets for the insurance company in order to better match its starting portfolio to our assumed risk-return optimisation process.

Table B.6: *Interest rate swap market*

Category	Symbol	Value
Life insurer:		
Gross notional exposure (GNE)	-	£470 bn
Initial margin[a]	IM^{I}	£4.7 bn
DV01[a]	-	-£0.071 bn
IRS duration	-	14.6 years
Pension fund:		
Gross notional exposure (GNE)	-	£616 bn
Initial margin[a]	IM^{PF}	£6.2 bn
DV01[a]	-	-£0.11 bn
IRS duration	-	17.9 years
Investment fund:		
Gross notional exposure (GNE)	-	£256 bn
Initial margin[a]	IM^{IF}	£2.6 bn
DV01[a]	-	£0.01 bn
IRS duration	-	11 years
Hedge fund:		
Gross notional exposure (GNE)	-	£551 bn
Initial margin[a]	IM^{HF}	£5.5 bn
DV01[a]	-	£0.0 bn
IRS duration	-	8.3 years

Notes: (a) Initial margin assumed to be 1% of GNE. (b) DV01 is defined as the potential aggregate gain from a 1bp interest rate increase. These parameters have been calibrated using data reported under the European Market Infrastructure Regulation (EMIR) to trade repositories – in particular, to DTCC Derivatives Repository Limited and Unavista Limited, respectively.

Table B.7: *The repo market*

Category	Symbol	Value	Source
Proportion of short-term repo:			
Pension fund	$\frac{L_{SR}^{PF}}{L_{R}^{PF}}$	20%	Bank of England.
Hedge fund	$\frac{L_{SR}^{HF}}{L_{R}^{HF}}$	78%	Bank of England.
Broker-dealer	$\frac{L_{SR}^{BD}}{L_{R}^{BD}}$	66%	Authors' assumption.
Proportion of short-term reverse repo:			
Broker-dealer	$\frac{A_{SR}^{BD}}{A_{R}^{BD}}$	62%	Authors' assumption.
Commercial bank	$\frac{A_{SR}^{CB}}{A_{R}^{CB}}$	82%	Bank of England.
MMF	$\frac{A_{SR}^{MF}}{A_{R}^{MD}}$	60%	Bank of England.
Haircuts:			
Initial govt bond haircut	h	2%	Authors' assumption.
Elasticity parameter	α^h	10%	Authors' assumption.
Minimum price change threshold	θ^h	5%	Authors' assumption.

Notes: We have used detailed transaction-level data on sterling repo markets collected by the Bank of England to calibrate these parameters. This dataset provides detailed information on transactions carried out by dealer banks in the sterling gilt repo market, on which the funding market in the model is based. We use these data to estimate the proportion of different agents borrowing/lending in the repo market maturing within – and outside of – the one-month time horizon considered in the model. This is done by calculating the average daily amount outstanding of transactions of different maturities across different sectors over the course of 2017.

Table B.8: *Duration of assets and liabilities*

Category	Symbol	Value
Life insurer:		
Household insurance obligations	T^I	12 years
Government bonds	-	20 years
Corporate bonds	-	10 years
Pension fund:		
Gross notional exposure (GNE)	-	£616 bn
Initial margin[a]	IM^{PF}	£6.2 bn
DV01[a]	-	-£0.11 bn
IRS duration	-	17.9 years
Investment fund:		
Gross notional exposure (GNE)	-	£256 bn
Initial margin[a]	IM^{IF}	£2.6 bn
DV01[a]	-	£0.01 bn
IRS duration	-	11 years
Hedge fund:		
Gross notional exposure (GNE)	-	£551 bn
Initial margin[a]	IM^{HF}	£5.5 bn
DV01[a]	-	£0.0 bn
IRS duration	-	8.3 years

Notes: (a) Initial margin assumed to be 1% of GNE. (b) DV01 is defined as the potential aggregate gain from a 1bp interest rate increase. These parameters have been calibrated using data reported under the European Market Infrastructure Regulation (EMIR) to trade repositories – in particular, to DTCC Derivatives Repository Limited and Unavista Limited, respectively.