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Abstract

We build a framework to simulate stress dynamics in the UK corporate bond market. This quantifies how the behaviours and interactions of major market participants, including open-ended funds, dealers, and institutional investors, can amplify different types of shocks to corporate bond prices. We model market participants' incentives to buy or sell corporate bonds in response to initial price falls, the constraints under which they operate (including those arising due to regulation), and how the resulting behaviour may amplify initial falls in price and impact market functioning. We find that the magnitude of amplification depends on the cause of the initial reduction in price and is larger in the case of shocks to credit risk or risk-free interest rates, than in the case of a perceived deterioration in corporate bond market liquidity. Amplification also depends on agents' proximity to their regulatory constraints. We further find that long-term institutional investors (eg pension funds) only partially mitigate the amplification due to their slower-moving nature. Finally, we find that shocks to corporate bond spreads, similar in magnitude to the largest weekly moves observed in the past, could trigger asset sales that may test the capacity of dealers to absorb them.

Key words: Corporate bond market, fire-sales, open-ended investment funds, pension funds, insurance companies, dealers, stress simulation.

JEL classification: G10, G20.

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Introduction

The structure of the financial system has changed materially over the past ten years. Market-based finance – the system of markets and non-bank financial institutions that provide financial services to the real economy – has become increasingly important. In the UK, non-bank institutions now account for almost 50% of the UK financial system's total assets, up by 13 percentage points since 2008. Further, during the past five years, nearly three quarters of net finance raised by UK corporates has come from capital markets, as compared to just a third during 2008-2012, with most of such finance coming from the corporate bond market.[1] And globally, credit provision by non-banks has increased by 50% since 2008 and currently accounts for almost 40% of global credit provision.[2]

These developments have had numerous benefits. For example, they have helped mitigate the effect of the reduced provision of credit by banks on the real economy. They have also supported the sharing of risk across the financial system, increasing the diversity of funding sources available to the corporate sector.[3]

An open question is how the new structure of the financial system – with its increased reliance on corporate bond markets – will respond to severe shocks. The behaviour of market participants in stress may be different from that observed in the past, not least given significant changes to the regulatory landscape post-crisis which drive agents' behaviour. Hence, instead of simply relying on past empirical relationships, there is a need to structurally model how market participants, including those in corporate bond markets, may behave in response to future shocks, such as large falls in asset prices, and the extent to which their actions may amplify those falls.

This paper draws on earlier work, in particular that in Baranova et al (2017a),[4] and presents a framework that can be used to simulate the extent to which behaviours and interactions of major participants in the corporate bond market can amplify different types of exogenous shocks to asset prices (e.g. those resulting from changes in economic fundamentals) and lead to sharp increases in corporate funding costs. This amplification arises because market participants are subject to a range of contractual or regulatory constraints. As prices fall, some of them are forced to sell financial assets to ensure those constraints are not breached. And others have

[1] See Bank of England (2018).
[2] See Financial Stability Board (2018). Non-bank financial intermediaries include insurers, pension funds and other financial intermediaries.
[3] See Gruic, Hattori and Shin (2014).
[4] Further, as its core we use the partial equilibrium model of dealer intermediation, along the lines of that in Baranova et al (2017b).

limits on their capacity to absorb those sales and bid the price back to its fundamental level. We refer to this amplification and overshooting of asset prices relative to fundamentals as a 'liquidity premium'.

This paper contributes to the academic literature focussing on modelling the implications of forced asset sales on market prices. To the best of our knowledge we are the first to offer a framework for simulating stress in the corporate bond market caused by the behaviour and interactions of stylised representative agents of buy-side market participants (i.e. open-ended investment funds, unit-linked funds, insurance companies and pension funds), a leveraged buyer of securities (i.e. a hedge fund), and a market intermediary (i.e. a dealer), where the price is endogenously determined in the framework.

The behaviour of agents in the framework is driven by constraints they face from regulation (e.g. minimum leverage ratio requirements for the dealer bank or solvency requirements for insurers), contractual obligations to their investors and policyholders (e.g. for investment funds), and their risk management policies (e.g. for pension funds).

We make different assumptions regarding how quickly investors react to shocks to asset prices. In particular, contractual constraints of funds and the regulatory constraints of insurers bind tightly. We therefore assume these agents re-balance their portfolios promptly in response to shocks.[5] The combination of such re-balancing behaviours gives rise to instantaneous net demand for liquidity in the corporate bond market. This net demand for liquidity is absorbed by the hedge fund and the dealer, with the latter determining the discount to prevailing market prices required for providing such services and hence the post-sale market price. In contrast, pension fund constraints bind less tightly, as they are largely dictated by internal risk management practices. We therefore assume that such investors will respond to shocks more slowly and will be gradually buying/selling assets via the dealer, who will anticipate and factor in such behaviour into the post-sale market price that it sets.

We apply this new framework to simulate stress dynamics in the UK investment-grade corporate bond market. We explore exogenous shocks to the risk-free rate and credit spreads, with the latter being driven either by increased perception of credit or liquidity risk.

We find that the magnitude of amplification effects (over and beyond fundamental asset values) arising from forced sales of corporate bonds depends on the driver of the initial price fall. The

[5] For insurers, this assumption reflects how, under Solvency II regulation, supervisors are required to take remedial actions as soon as possible if insurer's solvency capital requirements are breached.

amplification is larger for shocks to credit risk premia or risk-free interest rates, than for shocks to liquidity risk premia. More specifically, shocks that negatively affect a broad range of asset classes (e.g. upwards shocks to the risk-free rate affect all fixed income assets) and shocks that negatively impact a broad range of market participants (e.g. shocks to credit risk premia negatively affect both funds and insurers, whilst liquidity risk premia shocks impact mainly funds) cause greater amplification effects. We find that a 50 basis point increase in credit spreads driven by deteriorating perceptions of credit risk could be amplified by around 20 basis points, almost twice as much as if it were driven by an increase in perceived liquidity risk. And a 50 bps point increase in the risk-free rate could cause c. 30 bps of amplification.

We further find that the behaviour of long-term institutional investors, such as pension funds, could reduce these amplification effects, especially for large shocks, but is unlikely to eliminate them due to the slower-moving nature of such investors.

We also find that the point of corporate bond market dislocation (i.e. the size of the shock for which the demand for liquidity may begin to exceed the capacity of the dealer to absorb it) depends on the speed of reaction of investors that are forced to sell.

The point of market dislocation further depends on the extent to which shocks to corporate bond prices coincide with the broader market stress that the dealer is exposed to, as well as on the dealer's ability/willingness to reallocate spare capital to market-making corporate bonds from other business lines. For example, shocks to credit spreads of 70 bps could exhaust the capacity of the dealer's market-making desk to absorb sales. However, if the dealer is able to re-allocate spare capital from other business lines, it might be able to continue intermediating markets for shocks to credit spreads of up to 100 bps. Also, for increases in risk-free interest rates, dealers are likely to be able to intermediate the market for larger shock sizes. This could be associated with interest rates usually rising amidst benign macroeconomic conditions, when dealer's willingness and ability to intermediate is generally strong.

This framework could be a useful tool for macroprudential risk assessment and policy design.

First, it facilitates the assessment of how changes in asset prices might be amplified by the behaviour of different types of market participants, as they respond to their constraints. Falls in asset prices, commensurate with changes in economic fundamentals, are not a bad thing and are essential for a well-functioning financial system. However, when they get amplified to below the fundamental values, the real economy could be affected. In particular, such price falls, especially if sustained, could impair the ability of some companies to refinance or service new debt, as well as prompt the cancellation of investments requiring external funding.[6]

Second, it offers an insight into the degree to which the amplification of changes in asset prices is non-linear – that is the amplification varies disproportionally with the size of the initial move. Identifying such 'tipping points' might be of interest to policymakers seeking to gauge the resilience of the financial system to shocks. This framework explores the 'tipping points' that arise due to the limits in the capacity of market intermediaries to absorb temporary imbalances in the demand/supply of securities.

Finally, understanding how the behaviour of different types of market participants may dampen or amplify shocks could be useful for policymakers seeking to develop macro-prudential policies targeted at making market-based finance more resilient.

We proceed as follows. In Section 1 we review related academic literature. Section 2 describes the structure of the UK corporate bond market. Section 3 outlines the general set up of the simulation framework. The behaviour of different types of market participants and how they interact is described in Section 4. Section 5 contains a high-level description of the framework calibration for the UK investment-grade corporate bond market (supported by Annex 2). Section 6 presents the results of the stress simulation. Sensitivity of model results to a few key modelling assumptions is described in Section 7. A final section concludes.

1. Literature review

There are several strands of academic literature that are relevant for our work. As our focus is on modelling amplification dynamics arising from fire-sales (i.e. forced sales of assets by constrained investors) in the corporate bond market, in what follows we review both the papers that investigate investor behaviour under stress and those that simulate how these behaviours interact to amplify shocks in the financial system.

Several papers have investigated empirically the buying and selling behaviour of different types of investors in the corporate bond market in stress and motivate the setup of the simulation framework. For instance, Manconi, Massa and Yasuda (2012) find evidence of forced sales of corporate bonds during the crisis by open-ended investment funds facing redemptions and

[6] See Anderson et al. (2015). Furthermore, sharp falls in asset prices could impact the balance sheets of banks and other financial institutions, impairing the resilience of the core of the financial system and affecting economic growth (Almeida et al. (2009) and Campello et al. (2010)).

insurance companies close to or below regulatory constraints, suggesting that these institutions played a role in propagating stress from toxic (securitised) bonds to broader corporate bond markets. Timmer (2018) and Czech and Roberts-Sklar (2017) investigate the buying and selling behaviour across various types of market participants investing in debt securities and corporate bonds, respectively. Timmer (2018) finds that banks and investment funds behave pro-cyclically (i.e. sell debt securities whose prices have been falling and vice versa), whereas long-term investors (e.g. insurance companies and pension funds) behave counter-cyclically. The author explains these behaviours by differences in balance sheet characteristics. Czech and Roberts-Sklar (2017) find that insurance companies, hedge funds and asset managers are typically net buyers, and dealers are net sellers of sterling corporate bonds, when bond yields rise and prices fall. They also find that asset managers were net sellers of corporate bonds during the stress `taper tantrum' episode in 2013, potentially amplifying changes in prices.

Other papers have investigated the drivers of financial institutions' buying and selling behaviour. For instance, Goldstein, Jiang and Ng (2017) underline a potential fragility in corporate bond open-ended funds due to the fact that investor outflows (i.e. redemptions) are more sensitive to poor performance than investor inflows to good performance. Douglas, Noss and Vause (2017) model UK life insurers' incentives to rebalance their portfolios as their constraints under Solvency II regulation are affected following different types of shocks. Blake (2003) models pension funds as agents that choose their asset allocations to minimise the volatility of pension funds' surpluses/deficits (i.e. the difference between the value of pension fund assets and liabilities) and contributions made by corporate sponsors.

Recent studies focus on the changes in dealer incentives to intermediate corporate bond markets following the introduction of the post-crisis regulatory reforms. Adrian, Boyarchenko and Shachar (2017) find that dealers that are more impacted by post-crisis regulation are less able to intermediate the US corporate bond market. Choi and Huh (2017) find evidence of non-dealers providing liquidity in the US corporate bond market and document a deterioration of market liquidity when accounting for this using standard liquidity measures. Baranova, Liu and Shakir (2017b) develop a partial equilibrium model to assess the price impact of asset sales in the corporate bond market, as determined by a dealer subject to the post-crisis regulatory regime.

Over the past couple of years, several papers have modelled contagion arising from fire-sales of assets by financial institutions of the same type in isolation, mainly focussing on banks or open-ended funds. Greenwood, Landier and Thesmar (2015) and Cont and Schaanning (2017) have modelled fire-sale driven contagion between banks subject to a leverage constraint and assuming an exogenous price impact function. Cetorelli, Duarte and Eisenbach (2016) and Fricke and Fricke (2017) have extended a similar framework to assess contagion due to fire-sales of assets by open-ended investment funds that are subject to investor redemptions.

Several agent-based models (ABMs) have also been developed to simulate fire-sale dynamics in the financial system by different types of financial institutions in response to various initial shocks. Bookstaber, Paddrik and Tivnan (2017) develop an ABM of fire-sale dynamics in the network of dealers and hedge funds in response to a range of shocks, which include falls in asset prices and a redemption shock to hedge funds. Bookstaber and Paddrick (2015) use an ABM to simulate market liquidity dynamics as a result of the interaction between liquidity demanders, liquidity suppliers and market-makers in a limit order book framework. Calimani, Halaj and Zochowski (2017) and Halaj (2018) develop ABMs covering banks, subject to capital and liquidity regulatory requirements, and asset managers, subject to investor redemptions. Banks are interconnected through interbank lending and banks and asset managers are interconnected via common asset holdings. They study the resilience of the banking system and the magnitude of fire-sale and solvency contagion as a result of funding shocks to individual banks or asset managers.

2. UK corporate bond market

As the aim of this paper is to simulate the impact of stress in the UK corporate bond market, in this section we provide a short description of the structure of this market.

As of end-2015, the total amount outstanding of UK corporate bonds was £1.7 trn.[7] Sterling, euro and US dollar denominated bonds accounted for 96% of the total amount outstanding. [8] Most of the amount outstanding (i.e. 91%) was issued by companies with investment-grade ratings.

Bonds issued by UK private non-financial firms account for about a third of the UK corporate bond universe. Non-financial firms issuing corporate bonds are major contributors to UK GDP, accounting for around 50% of total UK business investment and 14% of total UK employment.[9]

[7] This includes bonds issued by both financial and non-financial UK corporates.
[8] Bonds denominated in sterling accounted for around 30% of the market at the end of 2015. Source: Reuters DBI.
[9] Source: Bank of England calculations.

UK corporate bonds are held by different types of market participants. We estimate that UK insurers and pension funds hold about 40% of all UK investment-grade corporate bonds outstanding, with European investment funds holding an additional 25% of the market. The remainder of the market is held by other types of domestic (e.g. banks) and overseas investors.

Most of the trading activity in the UK corporate bond market is done over-the-counter (OTC).[10] Namely, trades are undertaken bilaterally between dealers that act as intermediaries and end-investors (e.g. asset managers, insurance companies, pension funds and hedge funds), with dealers temporarily warehousing corporate bonds on their balance sheets before passing them on to other investors. As a consequence, when wishing to buy/sell bonds end-investors are reliant on the ability/willingness of the dealer to provide intermediation services.

Consistent with the OTC structure, in the sterling segment of the investment-grade corporate bond market the 15 largest global dealers account for around 50% of total monthly volume of bonds sold and bought. Asset managers account for around 20% of the volume bought and sold, and insurance companies for less than 10%.[11]

In past stress episodes, there has been evidence of marked deterioration in the liquidity of corporate bond markets, which has likely amplified price falls driven by changes in economic fundamentals. More specifically, in mid-October 2008 sterling investment-grade corporate bond spreads reached c. 370 bps, having risen by around 120 bps over a month.[12] Although small in size, in 2008 the high-yield segment of the sterling market experienced much larger moves in spreads, up to 600 bps over a month, and a closure for new issuance for a whole year.

3. Framework setup

The simulation framework proposed in this paper explores how the aggregate behaviours and balance sheet constraints of major participants in corporate bond markets could amplify shocks to asset prices. It incorporates a range of market participants, such as open-ended, unit-linked and hedge funds, life insurance companies, pension funds, dealers.

The high-level set up of the framework is summarised in **Diagram 1.**

[10] Around 95% of all transactions in corporate bonds pass through dealer balance sheets (see Anderson et al (2015)).

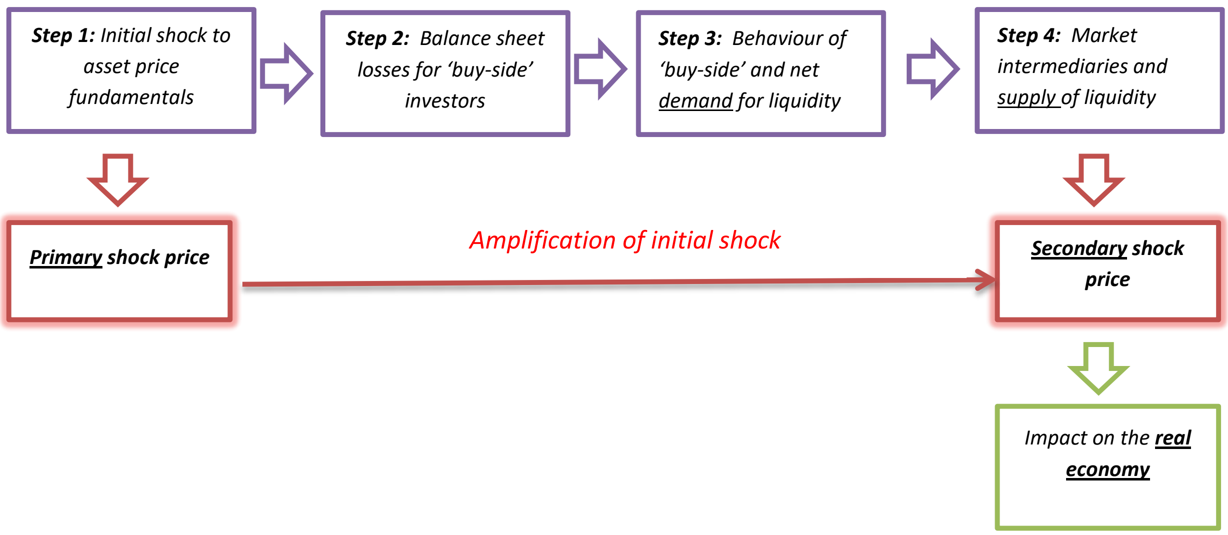
[11] See Mallaburn, Roberts-Sklar and Silvestri (forthcoming) that look at average volume of corporate bonds sold and bought by different market participants in the sterling corporate bond market between 2012 and 2017. Asset managers capture a variety of funds including open-ended investment funds.

[12] The numbers reflect largest historical monthly change in sterling investment-grade corporate bond spreads for the month ending October 13th.

Step 1 – Initial shock: We assume an instantaneous exogenous shock to different components of bond yields – and therefore prices. Since the focus of the simulation is on corporate bond markets, we explore shocks to the risk-free rate, credit risk premia and liquidity risk premia.[13] We apply positive shocks to these components which causes the prices of fixed income assets to fall. We also explore negative shocks to the risk-free rate.[14] We view such shocks as reflective of changes in economic fundamentals. For example, the deterioration in the macroeconomic outlook will affect market participants' expectations of the corporate default rate and the uncertainty around it, which in turn will be reflected in higher credit risk premia. Henceforth we refer to the price of corporate bonds after the application of this shock as the 'primary shock price'.

Step 2 – Balance sheet losses for 'buy-side' investors: The fall in prices of fixed income assets causes losses on the balance sheets of 'buy-side' investors. The 'buy-side' investors that we model are: open-ended and unit-linked investment funds, insurance companies and pension funds.

Diagram 1 – Set up of the simulation framework



Step 3 – Behavioural responses of 'buy-side' investors and net demand for liquidity: Balance sheet losses for these 'buy-side' investors induce behavioural responses, depending on whether their constraints (e.g. regulatory or contractual) bind more or less tightly. Institutions whose constraints bind more tightly are assumed to react quickly (in this case instantaneously).

[13] The range of fixed income assets affected by shocks to yields varies depending on the type of the shock. For example, moves in the risk-free rate affect the prices of both corporate and government bonds, while shocks to credit and liquidity risk premia affect corporate bonds only.

[14] This type of shock causes a negative impact on the balance sheets of liability-driven investors (i.e. insurers, and defined-benefit pension funds).

The aggregate behaviour of such fast 'buy-side' investors results in net demand/supply of liquidity for a given asset class.

Step 4 – Market intermediaries and supply of liquidity: The role of this type of market participants is to intermediate financial markets by temporarily warehousing on their balance sheets assets that are waiting for a buyer. In our framework such investors include hedge funds and dealers. They absorb any net demand for liquidity arising from 'buy-side' investors (i.e. clear the market), as long as their constraints (funding or regulatory) allow them to do so.

Final output – Amplification of the initial shock: Following sales of assets by 'buy-side' investors, dealers clear the market and set the new market price such that it compensates them for their provision of liquidity. This new price, which we call the 'secondary shock price', is below the 'primary shock price'. Hence, the amplification resulting from market participants' behavioural responses to the shock is assumed to be the difference between these two prices. For corporate bonds (and other fixed income securities), this difference can also be expressed as an increase in yield and interpreted as an increase in the liquidity risk premia of these securities. A rise in corporate bond yields will drive up the cost of corporate bond funding, which can then be used to assess the impact of the amplification effects on the real economy.

4. Modelling the behaviour of market participants

As described in **Section 3**, there are six types of market participants in the framework. This section provides a more detailed description of their business models (which in turn defines their balance sheet structure), their constraints and the behavioural responses that arise from these constraints.

In what follows, we use the subscript a to denote different asset classes, such as corporate bonds, government bonds and equities; and the subscript k to denote different types of shock (i.e. those to the risk-free rate, credit and liquidity risk premia). We use Q to denote the quantity of assets sold/bought by each agent. Positive values of Q would correspond to asset sales and negative values to purchases. We use $\tilde{}$ above a given variable to denote its post-shock value, and * to denote optimal values for a given variable obtained solving an optimisation problem.

'Buy-side' investors

Open-ended investment funds. Open-ended investment funds act as agents that invest their investors' money in a variety of financial assets, whilst offering investors the ability to redeem their shares at short notice, often daily. We capture the following key types of funds pursuing different investment strategies: equity, corporate bond, other fixed income (mainly government bonds) and allocation (investing in a mix of equity and fixed income assets).

Drawing on the empirical evidence on fund investors' pro-cyclical behaviour, [15] we assume that fund investors redeem their shares in response to fund losses, with the strength of such behaviour varying by fund strategy. Fund managers are forced to liquidate assets in order to meet those redemptions. We assume they sell assets proportionally to the quantity in which they hold them (i.e. liquidate a 'vertical slice of the portfolio').[16] We further assume that the pressure to liquidate assets is binding for fund managers facing redemptions (i.e. their constraints bind tightly). Thus, asset sales happen shortly after the shock giving rise to demand for liquidity.

More formally, the quantity of asset a sold by the open-ended investment fund following strategy i in response to the adverse shock of type k is

$$Q_{ak}^{OEF_i} = H_a^{OEF_i}(1 - shock_{ak})\sigma^{OEF_i}\ Losses_k^{OEF_i} \tag{1}$$

where $H_a^{OEF_i}$ is the pre-shock amount of asset a held in the portfolio of an open-ended fund of type i; $shock_{ak}$ is the percentage change in the price of asset a for a shock of type k (expressed as a decimal); σ^{OEF_i} is the share of assets that investors of fund type i will redeem following a portfolio loss of 1%;[17] and $Losses_k^{OEF_i}$are the losses, expressed as a percentage of total portfolio, experienced by fund of type i after shock k.

For each fund of type i after a shock of type k, losses (as a percentage of total portfolio) are computed as the sum of the losses on each asset a held in the portfolio

$$Losses_k^{OEF_i} = \sum_a \frac{H_a^{OEF_i}}{A^{OEF_i}} shock_{ak}, \tag{2}$$

where A^{OEF_i} denotes total assets of open-ended fund of type i before the shock. For more detail on the calibration of open-ended fund balance sheet and parameters see **Annex 2**.

For a given shock k, total sales of asset a from all open-ended funds are obtained summing across the sales of different types of funds computed as in equation (1), that is:

$$Q_{ak}^{OEF} = \sum_i Q_{ak}^{OEF_i}. \tag{3}$$

[15] See Goldstein, Jiang, and Ng (2017) and references therein, as well as Morris, Shim, and Shin (2017).
[16] Fund managers could respond to redemption requests in alternative ways, for instance, by selling liquid asset first and by hoarding cash. These alternative assumptions are analysed in Baranova et al (2017a), and we might explore them in future revisions of this work.
[17] This is estimated empirically as in Baranova et al (2017a).

Unit-linked funds. Unit-linked funds are similar to open-ended funds in that they act as agents for policyholders by investing their funds in financial assets. However, investors in unit-linked funds tend to have long-term investment horizons (e.g. due to the majority of such funds being defined-contribution (DC) pension schemes). This implies that investors in such funds may be better able to look through short-term portfolio losses and, hence, are less likely to shift their asset allocations in response to them. Further, most unit-linked policyholders cannot easily redeem their shares for cash at short notice (e.g. as they would suffer punitive charges). However, they do have the option of switching their investments between funds invested in different asset classes.

During the global financial crisis and following large falls in risky asset prices, some unit-linked policyholders chose to de-risk their investments. This is supported by survey evidence which suggests that, although the number of switching investors is usually small, those who do switch react quickly. [18] Consistent with this historical experience, we assume that in response to losses some unit-linked fund investors switch from risky assets denoted by a_R (i.e. equity and corporate bonds) into risk-free denoted by a_{RF} (i.e. government bonds and cash). Once such switching requests are placed, the fund manager will be forced to promptly rebalance its portfolios accordingly (i.e. the constraint in the form of policyholder switching requests binds tightly), creating extra demand for liquidity in risky asset markets.

Put formally, similar to open-ended investment funds, sales of risky assets by a unit-linked fund following a shock of type k are computed as:

$$Q_{a_R k}^{ULF} = H_{a_R}^{ULF}\left(1 - shock_{a_R k}\right) \sigma^{ULF} {Losses_k}^{ULF} \tag{4}$$

where $H_{a_R}^{ULF}$ is the pre-shock amount of risky asset a_R held in the portfolio of risky assets of a representative unit-linked fund; σ^{ULF} is the switching rate – the percentage of investors in a representative unit-linked fund switching their portfolio allocations from risky assets into risk-free following a fund loss of 1%; [19] and ${Losses_k}^{ULF}$ are the losses experienced by a representative unit-linked fund after shock k computed as in equation (2). We assume that in liquidating risky assets they do so in a way that maintains the pre-shock proportion of equity and corporate bonds within their risky asset portfolio.

Life insurance companies. Life insurance companies offer policyholders long-term savings and investment products under which the insurance company retains control of asset allocation

[18] As discussed in Bank of England (2016).
[19] For details on the calibration of this parameter see Annex 2.

decisions. Asset allocation decisions are therefore informed by a number of factors, including regulatory constraints defined under Solvency II regulations.[20] We model a representative life insurance company that targets a given solvency ratio above its regulatory minimum. We calculate the insurer's solvency ratio (SR) as follows:

$$SR = \frac{Capital\ Resources^{INS}}{Capital\ Requirement^{INS}} = \frac{A^{INS} - L^{INS}}{SCR^{INS}} = \varphi^{INS} \quad (5)$$

where A^{INS} and L^{INS} are the pre-shock market values of the insurance company's assets and liabilities, respectively; SCR^{INS} is the pre-shock regulatory solvency capital requirement; and φ^{INS} is the target solvency ratio as determined by the insurance company.

In line with Solvency II regulations, we assume that insurer's SCR^{INS} is equal to a one-year 99.5% Value-at-Risk measure (VaR) of the insurer's net worth[21] – that is, the difference between the values of insurer's assets and liabilities. We calculate the value of this VaR based on the market value of insurer's assets and liabilities, their respective VaR estimates and the correlations between them. In estimating the VaR for net worth we take into account how, in the face of certain exogenous shocks, changes in the value of the insurer's assets and liabilities can offset each other, thus reducing the VaR of the insurer's net worth and, hence, its SCR^{INS}. More formally, assuming that the insurance company invests in two types of assets – risky assets a_R and risk-free assets a_{RF} we have:

$$A^{INS} = {H^{INS}}_{a_R} + {H^{INS}}_{a_{RF}} \quad (6)$$

$$SCR^{INS} = (VaR_{a_R}^2 + VaR_{a_{RF}}^2 + VaR_L^2 + 2 * VaR_{a_R} * VaR_{a_{RF}} * \rho_{a_R,a_{RF}}$$

$$+ 2 * VaR_L * VaR_{a_{RF}} * \rho_{L,a_{RF}} + 2 * VaR_L * VaR_{a_R} * \rho_{L,a_R})^{0.5} \text{, where} \quad (7)$$

$VaR_{a_R}, VaR_{a_{RF}}, VaR_L$ are Value-at-Risk estimates for insurer's risky, risk-free assets and liabilities respectively; $\rho_{a_R,a_{RF}}$, $\rho_{L,a_{RF}}$, ρ_{L,a_R} are pair-wise correlations between the value of insurer's risky, risk-free assets and liabilities; ${H^{INS}}_{a_{RF}}, {H^{INS}}_{a_R}$ are insurer's holdings of risk-free and risky assets.

The Value-at-Risk of risky assets is evaluated as

$$VaR_{a_R} = \left(ER_{a_R} - \sigma_{a_R} * z_{99.5}\right) * w_{a_R} * (A^{INS} + L^{INS}) \quad (8)$$

[20] https://eiopa.europa.eu/regulation-supervision/insurance/solvency-ii

[21] Value-at-Risk (VaR) measures the worst expected loss under normal conditions over a specific time interval at a given confidence level. For example, if VaR is measured over a one-year period at a confidence level of 99.5% then this corresponds to the worst loss one would expect to occur in a single year over the next two hundred years.

$$w_{a_R} + w_{a_{RF}} + w_L = 1, \text{ where}$$

ER_{a_R} *and* σ_{a_R} are expected return and standard deviation of insurer's portfolio of risky assets; $w_{a_R}, w_{a_{RF}}$, w_L are the weights on the risky, risk-free assets and liabilities respectively in the portfolio of insurer's assets and liabilities.[22]

$VaR_{a_{RF}}$ and VaR_L are calculated in a similar way to VaR_{a_R}, as specified by equation (8).

The insurance company will adjust its asset portfolio after exogenous shocks that cause its solvency ratio to deviate from target. This deviation of the solvency ratio from the target is driven by changes in insurer's assets, liabilities and solvency capital requirements following the shock. [23] That is, the insurance company optimises the following problem:

$$\min_{w_{a_R}} \left(\frac{\widetilde{A^{INS}}_k - \widetilde{L^{INS}}_k}{\widetilde{SCR^{INS}}_k} - \varphi^{INS} \right), \tag{9}$$

where $\widetilde{A^{INS}}_k$ are insurer's total assets after a shock k, $\widetilde{L_k^{INS}}$ are insurer's liabilities after a shock k, and $\widetilde{SCR^{INS}}_k$ is insurer's regulatory solvency capital requirement after a shock k.

The post-shock value of insurer's liabilities $\widetilde{L_k^{INS}}$ is calculated as the sum of the post-shock value of its individual components:

$$\widetilde{L^{INS}} = L_{MA}^{INS}\left(1 - \frac{el_L\left(\widetilde{A_k^{INS}} - A^{INS}\right)}{A^{INS}}\right) + L_{RM}^{INS}\left(1 + \frac{yshock_{arf}}{yield} el_{RM}\right) + L_{TM}^{INS}\left(1 + \frac{yshock_{arf}}{yield} el_{TM}\right), \tag{10}$$

where L_{MA}^{INS} is the value of insurer's matching adjustment and some other liabilities, which cushion the impact of short-term asset fluctuations on insurer's solvency; L_{RM}^{INS} is the regulatory liability provision which reduces insurer's solvency following falls in risk-free interest rates; L_{TM}^{INS} is the temporary liability provision which partially offsets the impact of risk margin liability as Solvency II is gradually phased in;[24] el_L is the elasticity of L_{MA}^{INS} to changes in the value of insurer's assets; $yshock_{arf}$ is the exogenous shock to the risk free rate (zero for other types of shock); $yield$ is the current level of long-term government bond yield; el_{RM} and el_{TM} are elasticities of L_{RM}^{INS} and L_{TM}^{INS} w.r.t. shocks to the risk-free rate.

[22] More detail on the choice of parameters for insurance companies can be found in Annex 2.

[23] Shocks to yields affect not only assets, but also liabilities of insurers. For example, under Solvency II regulations, the so-called 'matching adjustment' allows insurers to partially 'look through' certain shocks to risky asset prices by adjusting the value of their liabilities. Also, the so-called 'risk margin', a new regulatory liability, is very sensitive to changes in risk-free rates and increases/decreases in value as risk-free rates fall/rise.

[24] Solvency II is expected to be fully implemented by 2032. After that point, temporary liability offset L_{TM}^{INS} will no longer exist.

The insurer chooses the optimal weight on the risky asset $w^*_{a_R}$ – that is, the proportion of the insurer's portfolio invested in the risky asset – to minimise the difference between its actual post-shock solvency ratio and its target ratio, φ^{INS}. We solve the optimisation problem in equation (9) numerically. Intuitively, if insurer's solvency ratio falls below the target following the shock, the insurer will be incentivised to reduce its holdings of risky assets (a_R) and increase its holdings of the risk-free asset (a_{RF}) to lower the VaR of its net worth and hence its SCR^{INS}, which will help bring the solvency ratio back to target.[25]

Hence, the insurer's sale of the risky asset or purchase of the risk-free asset in response to an adverse shock *k*, Q^{INS}_{ak}, is computed as:

$$Q^{INS}_{ak} = \left(\widetilde{A^{INS}}_k + \widetilde{L^{INS}}_k\right) * (\widetilde{w_{ak}} - w^*_{ak})$$

$$\widetilde{A^{INS}}_k = A^{INS}(1 - Losses^{INS}_k) \quad (11)$$

where $Losses^{INS}_k$ are the percentage losses (expressed as a decimal) the insurer experiences on its total assets following shock *k*; $\widetilde{w_{ak}}$ is the weight of asset a in the portfolio of insurer's assets and liabilities immediately following shock *k* (i.e. before the insurer has adjusted its asset allocations); and w^*_{ak} is the insurer's optimal weight in asset class a, calculated under equation (9) above.[26]

We assume that the time that the insurer takes to react to a deterioration in solvency – that we denote by $\tau^{INS,fall}$ – is short. This creates a demand for liquidity in risky asset markets. In contrast, we assume that the time the insurer takes to react to an increase in solvency above target – that we denote by $\tau^{INS,rise}$ – is more prolonged (e.g. over the course of a month). This follows the fact that regulators and market analysts, who monitor the insurer's solvency ratio closely, are likely to exert more pressure on the insurer following a deterioration in solvency and less (or no) pressure following a solvency improvement. In other words, the solvency constraint binds tightly following a deterioration in solvency, and less tightly following the improvement in solvency.[27]

Defined-benefit pension funds. Defined-benefit pension funds offer their members income streams (which are typically indexed to inflation) during their retirement. To meet these

[25] This is consistent with some of the behaviours found in the empirical/theoretical papers (e.g. Ellul et al (2011) and Rousova, Giuzio (2018)).

[26] We assume that post-shock the value of insurer liabilities $\widetilde{L^{INS}}_k$ and their weight in the asset/liability portfolio is fixed and not affected by re-balancing in the insurer's asset portfolio.

[27] See p. 4 of http://ec.europa.eu/internal_market/insurance/docs/solvency/solvency2/faq_en.pdf

obligations, pension funds invest periodic payments made by corporate sponsors – who are typically the employer of the scheme members – into financial assets.

The asset allocation decisions of UK defined-benefit pension funds are primarily controlled by boards of independent trustees, which seek to ensure that scheme members receive what is owed to them. But because pension funds are financed by corporate sponsors, the asset allocation decision may also be influenced by the sponsors' desire to minimise the adverse impact of volatile pension deficits on their shareholders' value.[28]

We, therefore, model two types of representative pension funds.

The first pension fund is supported by a ***financially unconstrained sponsor*** that doesn't seek to influence the asset allocation decision. In particular, the pension fund is assumed to have the flexibility to target long-term asset allocations and mechanically rebalance towards those targets in the face of shocks to asset prices (i.e. buying the asset whose value has fallen and vice versa) when asset allocations deviate from the tolerance range.[29] Hence, the unconstrained pension fund's net sale/purchase of asset a in response to shock k, Q_{ak}^{UPF}, can be computed as:

$$Q_{ak}^{UPF} = \begin{cases} 0, & if\ \overline{w_a}^{LB} \leq \widetilde{w_{ak}} \leq \overline{w_a}^{UB} \\ A^{UPF}(1 - Losses_k^{UPF})(\widetilde{w_{ak}} - \overline{w_a}) & otherwise \end{cases} \tag{12}$$

where A^{UPF} is the pre-shock value of the pension fund's total assets; $Losses_k^{UPF}$ are the losses the pension fund experiences (as a proportion of its initial total assets) following the shock of type k; $\widetilde{w_{ak}}$ is the weight in asset a immediately following shock k (i.e. before the pension fund has adjusted its asset portfolio), $\overline{w_a}$ is the pension fund's target weight in asset class a; $\overline{w_a}^{LB}$ and $\overline{w_a}^{UB}$ are lower and upper bounds of the tolerance range for weights on asset class a, with $\overline{w_a}$ equal to $\overline{w_a}^{LB}$ if the asset class weight falls below the lower bound of the tolerance range; and to $\overline{w_a}^{UB}$ if it goes above the upper bound of the tolerance range. For more detail on the calibration of the tolerance range see **Annex 2.**

Given the flexible nature of the unconstrained pension fund's objective function (i.e. target weight constraints binds less tightly), we assume that the fund rebalances its asset portfolio gradually over time. In particular, the assumed time horizon for the unconstrained pension fund's response function – denoted by $\tau^{UPF} -$ is set to one month.

[28] See Sweeting (2005).
[29] These assumptions are supported by findings from the FSB's survey of institutional investors.

The second pension fund is supported by a ***financially constrained sponsor*** that does influence the asset allocation decision. In particular, the corporate sponsor is sensitive to adverse changes in the pension fund's funding level. This is because large and volatile pension deficits (i.e. where the value of the pension fund's liabilities significantly exceeds the value of its assets) adversely impact the attractiveness of the sponsor's equity. Hence, this type of pension fund will face a different constraint. In particular, the pension fund's sponsor will not let the volatility of its pension deficit, σ^{CPF}, to surpass some maximum level, σ_{MAX}^{CPF}. More formally, the fund faces the following constraint:

$$\sigma^{CPF} = \sqrt{w_A^2 \sigma_A^2 + w_L^2 \sigma_L^2 + 2 w_A w_L \sigma_A \sigma_L \rho_{A,L}} \leq \sigma_{MAX}^{CPF}, \qquad (13)$$

where $\mathrm{w_A}$ and $\mathrm{w_L}$ are the fund's weights in assets and liabilities (and these sum to 1); σ_{A} and σ_{L} are the volatilities of the fund's assets and liabilities; and $\rho_{\mathrm{A,L}}$ is the correlation between the value of fund's assets and liabilities.

The volatility of the pension fund's assets, σ_{A}, is in turn influenced by the proportions of total assets invested in the risky asset, $\mathrm{w_{a_R}}$, and the risk-free asset, $\mathrm{w_{a_{RF}}}$:

$$\sigma_A = \sqrt{w_{a_R}^2 \sigma_{a_R}^2 + w_{a_{RF}}^2 \sigma_{a_{RF}}^2 + 2 w_{a_R} w_{a_{RF}} \sigma_{a_R} \sigma_{a_{RF}} \rho_{a_R, a_{RF}}}, \qquad (14)$$

where $\sigma_{\mathrm{a_R}}$ and $\sigma_{\mathrm{a_{RF}}}$ are the volatilities of the risky asset and risk-free asset; and $\rho_{\mathrm{a_R, a_{RF}}}$ is the correlation between the value of the fund's risky and risk-free assets.

If σ_{MAX}^{CPF} is exceeded after the shock, the fund is assumed to rebalance from risky assets a_R (i.e. equities) to risk-free assets a_{RF} (i.e. fixed-income securities). This reduces the volatility of the pension fund deficit, as fixed-income securities are less volatile and are better hedges for the pension fund's liabilities. If instead σ_{MAX}^{CPF} is not breached, the fund is assumed to do nothing. Hence, the constrained pension fund's net sale/purchase of asset a in response to shock *k*, Q_{ak}^{CPF}, is computed as follows:

$$Q_{ak}^{CPF} = \begin{cases} A^{CPF}(1 - Losses_k^{CPF})(\widetilde{w_{ak}} - \overline{w_{ak}}), & if\ \sigma^{CPF} > \sigma_{MAX}^{CPF} \\ 0, & otherwise \end{cases} \qquad (15)$$

where A^{CPF} is the pre-shock value of the pension fund's total assets, $Losses_k^{UPF}$ are the losses the pension fund experiences (as a proportion of the value of initial total assets) following the shock of type k; $\widetilde{w_{ak}}$ is the weight in asset a immediately following shock *k* (i.e. before the pension fund has adjusted its asset portfolio); $\overline{w_{ak}}$ is the weight in asset class a consistent with the pension fund's deficit volatility of σ_{MAX}^{CPF}.

As under UK pension regulations pension funds are only required to recalculate their deficit position on a triennial cycle, we assume that a representative pension fund responds and rebalances over a prolonged period of time. Hence, we set the assumed time horizon for the constrained pension fund's response function – denoted by τ^{CPF}– equal to 1.5 years.

Market intermediaries

Market intermediaries provide liquidity to accommodate the sales of assets by other investors. Unlike 'buy-side' investors, their business models do not involve holding material long exposure to financial assets for an extended period of time, but instead focus on meeting the shortfalls in the demand for/supply of securities by other investors. Hence, we assume that their capital positions are not materially impacted by the initial shock.

In what follows, we set out our approach to modelling the intermediation mechanism specific to the corporate bond market, which is the focus of this simulation framework.[30] In modelling the behaviour of market intermediaries, namely hedge funds and dealers, we follow closely the approach in Baranova et al (2017b).

Hedge fund.[31] In the framework, the hedge fund chooses the proportion of the overall quantity of assets (corporate bonds) being sold – denote by Q – that it wishes to buy. We denote this quantity by Q^{HF}. In doing so, the hedge fund seeks to maximise its profit by weighing the costs of financing the purchase against the expected return from the arbitrage opportunity. The arbitrage opportunity arises as the market-clearing price, set by the dealer (see below), deviates from the fundamental asset value following the sale of assets by 'buy-side' investors. We assume that the hedge fund can observe/anticipate both Q, as well as the likely post-sale market-clearing price.

The hedge fund needs to finance its purchase of bonds via repo borrowing, which is provided by the dealer. Hence, the hedge fund's ability to purchase corporate bonds is constrained by the amount of repo funding that the dealer is willing to provide and the terms of this funding, such as the repo haircut and the repo rate. Further, the ability of the hedge fund to buy assets is also constrained by the amount of unencumbered liquid assets that it has to meet repo haircuts.

[30] To simplify the notation, in this section we drop the subscript a referring to different asset classes.
[31] Modelling the hedge fund as a market intermediary is consistent with Ferguson and Laster (2007) who argue that hedge funds add liquidity to markets and are broadly stabilising.

Putting all of the above together, the hedge fund chooses Q^{HF*} to maximise its expected profit

$$\max_{\mathrm{Q}^{HF}}\{\mathrm{Q}^{HF}(\mathrm{D}(\mathrm{Q}^{D}) - \mathrm{R} \times \mathrm{HP}^{HF})\} \tag{16}$$

subject to the constraint

$$\mathrm{Q}^{\mathrm{HF}} \times \mathrm{h}^{\mathrm{HF}} \leq \mathrm{LA}^{\mathrm{HF}},$$

where $\mathrm{D}(\mathrm{Q}^{D})$ is the expected percentage discount from the fundamental asset value as set by the dealer; Q^{D} is the amount of assets purchased by the dealer; R is the rate charged by the dealer on hedge fund's repo borrowing; HP^{HF} is the hedge fund's expected holding period for purchased assets; h^{HF} is the haircut on hedge fund's repo borrowing and LA^{HF} is the amount of unencumbered liquid assets held by the hedge fund.

We assume that the dealer behaves competitively. Hence, the repo rate R that it charges the hedge fund is set so that it fully covers dealer's funding and regulatory costs associated with this transaction. Specifically,

$$R = FC + LR \times C \tag{17}$$

where FC is dealer's own funding cost, LR is the amount of capital, as dictated by the regulatory leverage ratio, required for this transaction, and C is the dealer's cost of capital.

Dealer. The dealer plays a key role in supplying liquidity in the corporate bond market in this framework. In particular, the dealer clears the corporate bond market (i.e. buys the rest of the assets not purchased by the hedge fund). In clearing the market, it does two things.

First, the dealer chooses the amount of spare balance sheet capacity – denoted by SC – to provide for accommodating corporate bond sales. If this balance sheet capacity is insufficient to accommodate sales, we assume that the corporate bond market 'breaks'. By this we mean that the dealer runs out of the intermediation capacity and market liquidity becomes severely impaired. Transactions could still occur (e.g. if a dealer could directly match a seller and a buyer), but those are likely to happen at highly dislocated prices.

This spare balance sheet capacity *SC* at any given point in time is modelled as:

$$SC = E \times OL - BS \tag{18}$$

where E is dealer's equity capital; OL is dealer's optimal level of leverage; and BS is dealer's current balance sheet size.

Both the dealer's equity capital and optimal leverage are modelled to be decreasing functions of the exogenously determined level of market stress, which we proxy by the VIX index.

Intuitively, during the periods of high market turmoil, the dealer is likely to incur losses on its positions, which reduces its equity capital (i.e. a fall in E) and therefore its ability to make markets. This relationship between dealer equity and the level of market stress is modelled empirically by regressing the return on equity for major global banks on the VIX index.[32]

Dealer's optimal leverage (for any given level of E) and hence its willingness to make markets is also likely to fall as the level of market stress goes up. Following Baranova, Liu, and Noss (2016), we model dealer's optimal leverage theoretically using a knock-out barrier option framework. Under it – for any given level of market stress – the dealer chooses an optimal level of leverage that maximises its shareholders' value. We assume that the dealer is subject to a regulatory constraint on its minimum leverage ratio that – if breached – leads to its default and the claims of its equity holders being reduced to zero. As market stress – and hence asset volatility – increases, the threat of breaching the regulatory requirement causes the dealer to maintain larger voluntary capital buffers on top of its minimum leverage ratio requirement. This implies that dealer's optimal leverage declines as the level of market stress goes up, which reduces its willingness to intermediate markets. More detail on modelling dealer's optimal leverage is provided in **Annex 3**.[33]

Given that the dealer's business model generally involves the provision of a range of financial services, we further assume that any firm-level spare balance sheet capacity of the dealer SC is allocated to different business lines, including the provision of repo funding and market-making, proportionately to their relative sizes in the current balance structure. We denote the share of spare balance sheet capacity allocated to repo and corporate bond market-making as $share_{repo}^{BS}$ and $share_{MM}^{BS}$ respectively. When there is spare balance sheet capacity at the market-making desk (i.e. $Q^D \leq share_{MM}^{BS} \times SC$), the dealer will apply the marginal cost of capital $-$ denoted by C_{desk} $-$ to cover the associated regulatory costs when providing market-making services. When the market-making desk balance sheet capacity is exceeded (i.e. $share_{MM}^{BS} \times SC < Q^D \leq SC$), the dealer can accommodate the sale by re-allocating capital from other business lines, but will

[32] In the past, small to moderate increases in the level of market stress have had a minor (or even positive impact) impact on dealers' equity capital. Whilst large increases in the level of market stress have had a much more material impact on their capital positions. Given this, we model changes in dealer's equity as a quadratic function of the changes in the level of market stress. See Annex 2 for more detail on the exact calibration.

[33] This type of behaviour is consistent with the empirical evidence found by Adrian, Boyarchenko, and Shachar (2017), who show that institutions that face more regulations after the crisis have less ability to intermediate customer trades.

apply a higher cost of capital for doing so – denoted by C_{alloc}.[34] Once the dealer runs out of balance sheet capacity at the firm-level (i.e. $Q^D \geq SC$), we assume the market is "broken".

Second, the dealer sets the new market-clearing price ('secondary shock price) at a discount from the primary shock asset price. This discount D is set so that it fully compensates the dealer for the costs of warehousing inventory on its balance sheet and, in nominal terms, can be calculated as:

$$D\,(Q^D) = Q^D \times Cost(Q^D) \times HP^D(Q^D) \tag{19}$$

where Q^D is the amount of assets purchased by the dealer; $Cost(Q^D)$ is the cost of holding a unit of inventory on balance sheet for a unit of time; $HP^D(Q^D)$ is the dealer's expected inventory holding period.

$Cost(Q^D)$ reflects the funding, hedging and regulatory costs incurred by the dealer when warehousing corporate bond inventory on its balance sheet. Specifically,

$$Cost(Q^D) = H \times \big(LR \times C(Q^D) + FC(VIX) + HC(Q^D, VIX)\big) + (1 - H) \times (RWA(VIX) \times C(Q^D) + FC(VIX)) \tag{20}$$

where H is the proportion of dealer inventory that is hedged; LR is the amount of equity capital, as dictated by the regulatory leverage ratio, required for this transaction; $C(Q^D)$ is the dealer's cost of equity; $HC(Q^D, VIX)$ is the cost of hedging interest and credit risk of corporate bond inventory; $FC(VIX)$ is the dealer's funding cost; and $RWA(VIX)$ is the risk-weighted capital requirement associated with the transaction.

Funding cost is the cost of funding corporate bond inventory in repo markets. We assume that the dealer pays the risk-free rate on the repo borrowing (given that it is over-collateralised), but needs to pay the unsecured funding cost on the over-collateralisation. We further assume that the unsecured funding cost just covers the expected loss on an unsecured loan to the dealer. Hence dealer's funding cost function can be described as:

$$FC(VIX) = r_f + h^D(VIX) \times (PD(VIX) * LGD) \tag{21}$$

where r_f is the risk-free interest rate; $h^D(VIX)$ is the haircut on dealer's repo borrowing; $PD(VIX)$ is the dealer's probability of default; LGD is the dealer's expected loss given default.

[34] For repo provision, we assume that once balance sheet capacity at the repo desk is exhausted, the dealer does not re-allocate capital from other businesses. This is due to how market contacts describe the provision of repo funding to clients as an ancillary business, provided in conjunction with other financial services.

As can be seen from equation (20), the hedging and capital costs of warehousing inventory are assumed to increase with the amount of assets that the dealer needs to purchase. Intuitively, hedging a large bond position is likely to move the price of hedging, increasing the cost per unit of inventory hedged. Also, as described above, $C(Q^D)$ takes different values depending on whether the balance sheet capacity for purchasing corporate bonds is available at the market-making desk level (C_{desk}) or needs to be re-allocated from other business lines (C_{alloc}). Further, $Cost(Q^D)$ is also partly affected by the overall level of market stress, which we proxy with the VIX index. For example, haircuts and hence the cost of repo funding increase with the level of market stress.

Finally, the discount from the fundamental asset price is also partly determined by the time period over which the dealer expects to hold inventory on its balance sheet before offloading it to other investors $HP^D(Q^D)$. This time period increases with the quantity of corporate bonds purchased and decreases with the speed with which the dealer expects to sell those bonds to other investors. More specifically, following initial shocks to asset prices the dealer anticipates the reaction functions of the slower-moving investors whose constraints bind less tightly (e.g. pension funds) and adjusts its expected holding period accordingly, depending on whether and how quickly such investors are buying or selling corporate bonds. Exact calculation of $HP(Q^D)$ is described below.

The price discount can also be expressed as the percentage of the value of assets bought by the dealer.

$$D\,(Q^D)/Q^D \;=\; C(Q^D)\;\times\;HP^D(Q^D) \qquad (22)$$

As this percentage discount is a quadratic function of Q^D, the schedule of discounts from the fundamental asset value will increase non-linearly with the amount of assets purchased by the dealer.

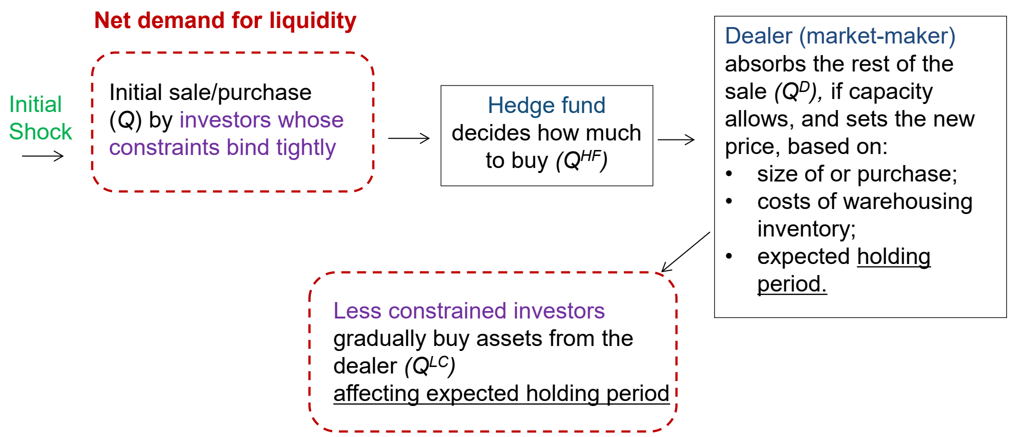
Important to note that we assume prices are at their fundamental values before the initial shock. This does not mean that no trading, including that in corporate bonds, occurs before the shock. However, we assume that any pre-shock trading is random and can be easily offset (matched) across market participants by the dealer, who, thus, can avoid warehousing inventory on its balance sheet and the costs associated with this.

More detail on the parametrisation of the dealer and the hedge fund is presented in **Annex 2.**

Interaction between 'buy-side' investors and market intermediaries and the price impact of asset sales

The interaction between 'buy-side' investors and market intermediaries in the framework is illustrated in **Diagram 2.** The type and sequencing of the interaction between 'buy-side' investors and market intermediaries depends on the degree to which their constraints bind.

Diagram 2 – Interaction between 'buy-side' investors and market intermediaries



When initial exogenous shocks to asset prices cause investors' constraints to bind more tightly (e.g. as is the case for open-ended and unit-linked funds, as well as for the insurer when its solvency falls below the target), they are forced to rebalance their portfolios promptly. Hence, we sum up the amount of corporate bonds that they wish to buy or sell, as estimated in equations (3), (4) and (11), to find the net demand for liquidity:

$$Q = \begin{cases} Q^{OEF} + Q^{ULF} & if\ SR > \varphi^{INS} \\ Q^{OEF} + Q^{ULF} + Q^{INS} & otherwise \end{cases}. \quad (23)$$

Market intermediaries will need to absorb this net demand for liquidity (top left-hand side red box in **Diagram 2**). By framework set up, $Q = Q^{HF} + Q^{D}$.[35]

Investors subject to flexible constraints (e.g. pension funds) or for whom exogenous shocks cause constraints to bind less tightly (e.g. insurers when their solvency goes above the target) are likely to rebalance their portfolios more slowly. When this is the case, we assume that such rebalancing does not directly affect the net demand for liquidity that market intermediaries need

[35] Subject to the availability of dealer spare capacity.

to absorb. Instead, as mentioned above, this changes dealer's expectations regarding its inventory holding period – that is, how long it will take the dealer to sell assets to other investors without putting downward pressure on market prices (bottom red box in **Diagram 2**). Hence:

$$HP^{D}(Q^{D}) = \frac{Q^{D}}{Q^{LC}+Q^{NT}} \tag{24}$$

where Q^{NT} is the amount of corporate bonds that the dealer could sell on a normal trading day (i.e. in the absence of any shocks) without exerting downwards pressure on market prices; Q^{LC} is the daily buying/selling of corporate bonds by less constrained investors triggered by the exogenous shock. We evaluate Q^{LC} as:

$$Q^{LC} = \begin{cases} \frac{Q^{UPF}}{\tau^{UPF}} + \frac{Q^{CPF}}{\tau^{CPF}} + \frac{Q^{INS}}{\tau^{INS,rise}} & if\ SR > \varphi^{INS} \\ \frac{Q^{UPF}}{\tau^{UPF}} + \frac{Q^{CPF}}{\tau^{CPF}} & otherwise \end{cases} \tag{25}$$

where Q^{INS}, Q^{UPF} and Q^{CPF} are the amounts of corporate bonds sold and bought by less tightly constrained investors, as estimated in equations (11), (12) and (15) respectively; and $\tau^{INS,rise}$, τ^{UPF}, τ^{CPF} are their assumed rebalancing speeds in days.[36]

This distinction between more and less constrained investors implies that even though less constrained investors might be able and willing to buy assets sold by other investors, unless they react quickly, large net demand for liquidity may still emerge and cause sharp moves in asset prices.

5. *Model application*

We apply the framework described above to explore the potential amplification of instantaneous shocks in the investment-grade UK corporate bond market – a key funding market for the UK real economy.[37]

In this application we do not attempt to pin down the single most likely type/size of shock and assess its impact. Instead, for each type of shock to corporate bond yields (i.e. that to the risk-free rate, credit and liquidity risk premia) we assess the impact of a range of shock sizes. This is equivalent to running a 'reverse' stress test that seeks to explore which types and sizes of the shock could test the resilience of the UK corporate bond market.

[36] See Annex 2 for the exact value of parameters specifying the re-balancing speed.

[37] From here onwards, UK corporate bond market refers to investment-grade corporate bonds issued by UK-domiciled corporates, both financial and non-financial.

To convert the shocks to the components of corporate bond yields into corresponding asset price falls, we use the following approach:

$$shock_{ak} = \begin{cases} -\,yield_k \times MD_a, & if\ a = goverment\ bonds, corporate\ bonds \\ 0\,, & if\ a = equity, cash, other\ assets \end{cases} \quad (26)$$

where $yield_k$ is the size of the exogenous shock to corporate bond yields of type k in percentage points; MD_a is the modified duration of a given fixed-income asset class.[38]

In applying the framework, we try to capture those agents that would be most important for understanding stress amplification in this market. Our approach is to include as few representative agents as possible for each sector, whilst still capturing the most material nuances between business models that drive the differences in behaviour. For more detail on the scope and agents in the model see **Table 1.**

For open-ended funds we capture UK-domiciled funds and funds domiciled in the EU jurisdictions that have large fund industries and invest and market their shares heavily across Europe, including in the UK.[39] For unit-linked funds, life insurers and pension funds, we focus on UK-domiciled entities as there tends to be a high degree of 'home bias' in their investment strategies (i.e. they tend to invest in assets of home currency and/or domicile).[40] By choosing this scope, we capture around two thirds of investors in UK investment-grade corporate bonds.

The remaining share of the market is held by a variety of overseas investors (such as investment funds domiciled outside of UK/Luxembourg/Ireland, non-UK insurers and pension funds, sovereign wealth funds), as well as other domestic investors (such as UK commercial banks). We do not capture those overseas investors as UK corporate bonds are likely to play only a minor role in their portfolios, and modelling them will materially increase the complexity of the framework. Further, at this stage we omit UK commercial banks from the framework due to the relatively low share of the UK investment-grade corporate bond market that they hold. Also, such holdings are small relative to the size of their capital positions, so shocks to corporate bond prices are unlikely to trigger material deleveraging behaviour by banks.[41]

[38] Shocks to the risk-free rate will affect the prices of both corporate and government bonds, whilst shocks to the credit and liquidity risk premia will affect the prices of corporate bonds only.
[39] This is based on the analysis of asset allocations of open-ended funds domiciled in Europe, using Morningstar data.
[40] See 'MQ5: Investment by insurance companies, pension funds and trusts Statistical bulletins' by Office for National Statistics.
[41] Major UK banks appear to hold c. 8% of the outstanding sterling investment-grade corporate bonds, which is equivalent to slightly more than 4% of their total Tier 1 capital (not risk-weighted). We believe their share of the broader UK investment-grade corporate bond market (as defined above) is similar to that of the sterling segment.

Table 1 – Representative agents in the framework

Agent type	*Scope*	*Number of agents*
Open-ended funds	UK funds plus funds domiciled in Ireland and Luxembourg	Four key agents corresponding to different fund investment profiles (e.g. equity funds, corporate bond funds, other fixed-income funds, mixed funds).
Unit-linked funds	UK-domiciled entities only	One agent corresponding to the whole sector.
Life insurers		Two agents corresponding to two main types of life insurers: a non-profit insurer (e.g. annuity writer) investing primarily in corporate bonds (risky asset) and government bonds and a with-profits insurer (e.g. provider of savings products) investing primarily in equity (risky asset) and fixed income securities (less risky assets).
Defined-benefit pension funds		Two agents corresponding to funds supported by: (i) financially constrained; and (ii) financially unconstrained corporate sponsors.
Hedge funds	Global, fixed income strategies only	One representative agent.
Dealers	Global largest dealers (G-16)	One representative agent.

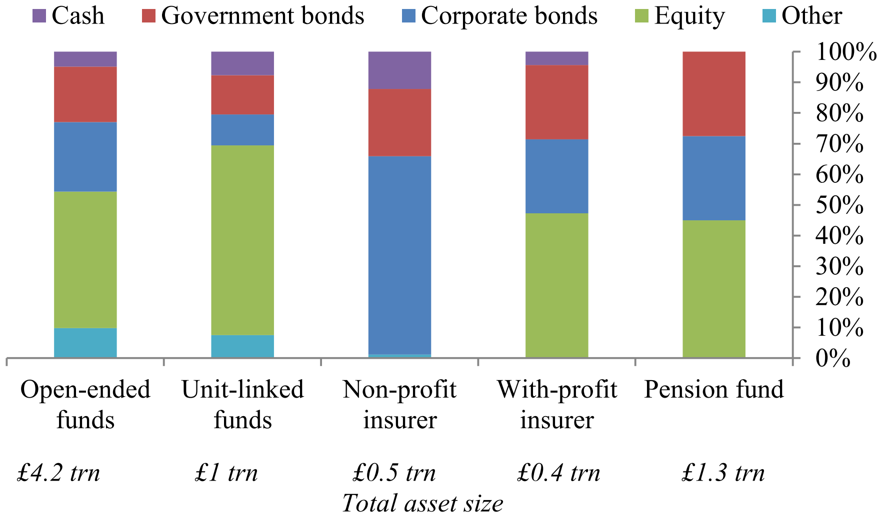
For some sectors, such as unit-linked funds, we model a single representative agent. [42] For others, the differences in business models and behaviours require greater granularity. For example, for open-ended investment funds we consider four types of funds pursuing different investment strategies. For insurers, we distinguish between a non-profit insurer (provider of annuity products) and with-profits insurer (provider of savings products) given that they have distinct business models and balance sheet structures. For pension funds, as described above, we distinguish between funds supported by a financially constrained and a financially unconstrained sponsor.

'Buy-side' agents in our framework vary in size and the composition of their balance sheets, and hence their importance for corporate bond markets (**Chart 1**). For example, unit-linked funds have a relatively small proportion invested in corporate bonds, whilst non-profit insurers have more than half of their assets invested in this asset class.

Given the focus of the simulation is on the UK investment-grade corporate bond market, we split asset holdings of all 'buy-side' investor into the following asset classes: UK investment-grade corporate bonds, other investment-grade corporate bonds, high-yield corporate bonds, government bonds, equity, cash and equivalents, and other assets.

[42] This choice is driven by data constraints. However, we think that having one representative agent is sufficient for unit-linked funds, as such funds generally invest in a mix of asset classes, with policyholders switching their investments across funds with different risk profiles.

Chart 1 – Balance sheet size and structure of 'buy-side investors'[43]



Source: Morningstar, Solvency II regulatory data, ONS.

For liquidity providers, following Baranova et al (2017a), we focus on largest global dealers (so-called G-16) and global hedge funds pursuing fixed-income strategies. This is because largest global dealers and hedge funds intermediate all major corporate bond markets. We also largely follow the parametrisation of the global hedge fund and the dealer from Baranova et al (2017b). However, given that our focus is on a particular segment of the corporate bond market (i.e. UK investment-grade corporate bonds, as opposed to the global corporate bond market as in Baranova et al (2017b)), we adjust the balance sheet capacity that global hedge funds and dealers might be willing to allocate for intermediating the UK segment of the market. More specifically, before applying the hedge fund/dealer pricing mechanism parametrised for the global corporate bond market, we scale up the net sales of UK investment-grade corporate bonds by dividing them by the share of UK investment-grade corporate bonds in the global corporate bond market ($Share_{UKIG}$).

As described in **Section 4**, both dealer spare balance sheet capacity and the price discount that it sets are a function of the VIX index, which is an exogenous variable. For internal consistency we map the value of exogenous initial shocks to the components of corporate bond yields to the values of the VIX index. We do so by regressing the level of the VIX index on changes in credit spreads; and separately the level of the VIX index on changes in the risk-free rate, with the latter proxied by government bond yields.[44]

[43] The chart shows 'buy-side' investors' holdings of global corporate bonds.

[44] More specifically, we regress three-month average level of the VIX index on monthly changes in global investment-grade corporate bond spreads; and the three-month average level of the VIX index on monthly changes in 10-year UK government bond yields for

Full detail on the parametrisation of the model for the UK investment-grade corporate bond market is provided in **Annex 2**.

6. Framework outputs

The framework described in this paper allows us to produce the following outputs:

- The quantity of corporate bonds bought/sold by different types of market participants for a given type and size of shock to asset prices.
- How moves in corporate bond prices can be amplified by the buying/selling behaviour of different investors.
- Market breaking points – the magnitudes of different types of shocks that trigger net asset sales that could test the ability of dealers to absorb them. We explore two types of market breaking points: one where corporate bond sales start to exceed the spare balance sheet capacity of the dealers' market-making desk; and the other where firm-level spare balance sheet capacity is exhausted.

In what follows, we present the results of the application of the framework for exploring stress dynamics in the UK investment-grade corporate bond market.

Single-factor initial shocks to corporate bond yields

Chart 2 shows the amount of UK investment-grade corporate bonds bought and sold by constrained investors (**Chart 2a**) and less constrained investors (**Chart 2b**) for a range of initial shocks to the credit risk premia component of corporate bond yields. The net demand for liquidity from constrained investors is mainly driven by open-ended investment funds' selling behaviour in response to investor redemptions. As insurers' solvency positions deteriorate, the non-profit insurer sells riskier corporate bonds and buys government bonds, whilst the with-profit insurer sells riskier equities and buys fixed income assets (including corporate bonds). In aggregate, this results in roughly zero net demand for liquidity in corporate bond markets by life insurers. The pension fund supported by a strong (i.e. financially unconstrained) sponsor gradually provides liquidity to the dealer when shocks are large enough to cause asset class

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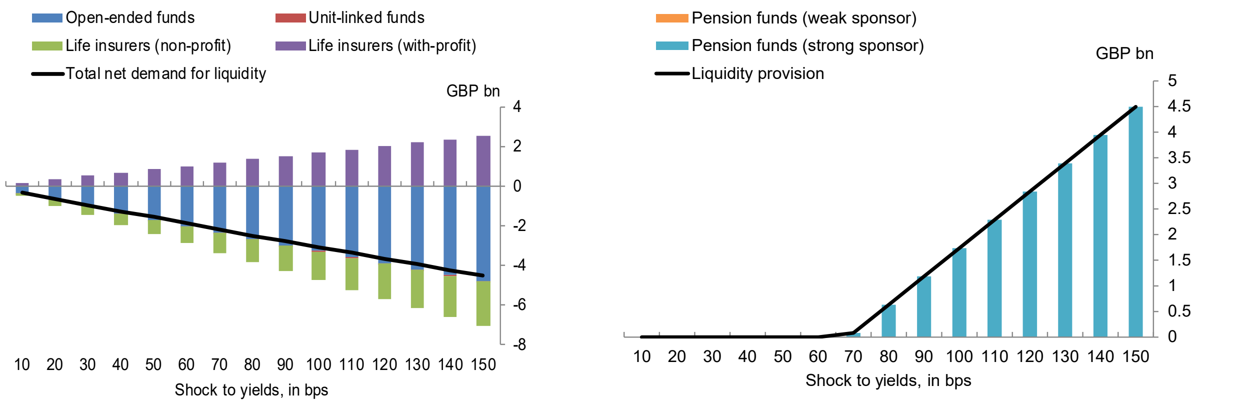
shocks to the risk-free rate. Essentially, we are estimating the likelihood of sharp adverse moves in corporate bond yields occurring amidst prolonged elevated level of financial market stress. This is done for consistency with Baranova et al (2017b) that we draw on, where the behaviour of the dealer is assumed to vary in response to prolonged episodes of market stress (as measured by the quarterly average of the VIX index), as opposed to short-term volatility spikes. For changes in the risk-free rate the relationship with the VIX index is not statistically significant. Hence, for this type of shock we do not vary the level of market stress with the shock size and keep the level of the VIX index fixed at its historical average.

weights to deviate from the target range. The pension fund supported by a weak (i.e. financially constrained) sponsor does not re-balance, as the credit shock does not cause the volatility of the pension fund deficit to exceed the maximum permitted level.

Chart 2 – Buying and selling behaviour of more tightly and less tightly constrained investors for a range of initial shocks to the credit risk component of corporate bond yields[45]

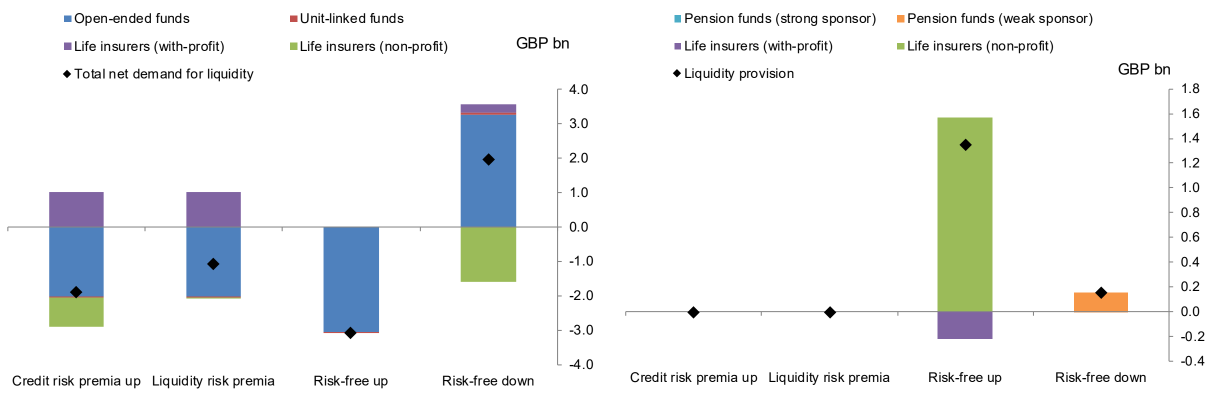
a. More tightly constrained investors **b. Less tightly constrained investors**



Note: Re-balancing behaviour for unconstrained investors is shown on a monthly basis (i.e. how much corporate bonds they would buy/sell over a period of a month).

Chart 3 – Relative magnitudes of selling/buying behaviours in the UK corporate bond market by type of market participant for an initial shock of 60bps

a. More tightly constrained investors **b. Less tightly constrained investors**



Note: Re-balancing behaviour for unconstrained investors is shown on a monthly basis (i.e. how much corporate bonds they would buy/sell over a period of a month).

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[45] In these charts positive numbers reflect purchases of corporate bonds, negative numbers sales.

Chart 3 summarises the estimated selling/buying behaviours in the UK investment-grade corporate bond market for four types of shocks to asset prices, when the size of the initial shock takes a value of 60bps. More detailed results for the buying and selling behaviour of different investor types are shown in **Annex 1.**

We find that shocks to credit risk premia generate a strong selling pressure, mainly driven by open-ended funds and offset somewhat by the aggregate behaviour of life insurers. By comparison, the selling pressure following shocks to liquidity risk premia is smaller.[46] This is because, under Solvency II, non-profit insurers are more able to look through the impact of liquidity shocks on their capital positions (as compared to credit shocks), which causes them to de-risk by selling corporate bonds to a lesser extent.[47] An increase in the risk-free rate generates significant selling pressure in aggregate, mostly due to large redemptions from open-ended investment funds. Shocks to the risk-free rate result in larger redemptions from funds than shocks to credit spreads, since they cause losses on funds' both government and corporate bond holdings, whilst shocks to the components of credit spreads (i.e. credit and liquidity) impact corporate bond prices only. An increase in the risk-free rate is a positive shock for insurers, as it reduces the value of their liabilities by more than the value of their assets, thus improving their solvency positions. This incentivises their gradual rebalancing towards riskier assets (i.e. towards corporate bonds for the non-profit insurer, and towards equity for the with-profits insurer). Finally, a decrease in the risk-free rate results in a net supply of liquidity in the UK corporate bond market, as open-ended funds' buying behaviour is able to fully absorb the selling pressure from life insurers.

Although material in size, unit-linked funds sell only a limited quantity of corporate bonds. This is due to the low sensitivity of policyholder switching requests to losses, as well as the relatively low share of corporate bonds in their portfolios.

In general, the pension fund supported by a financially unconstrained ('strong') sponsor will be incentivised to gradually buy fixed income assets, including corporate bonds, as the weight on this asset class in the portfolio falls below the target range following shocks to credit and liquidity risk premia. All types of shock equal to 60 bps do not cause the asset weights to

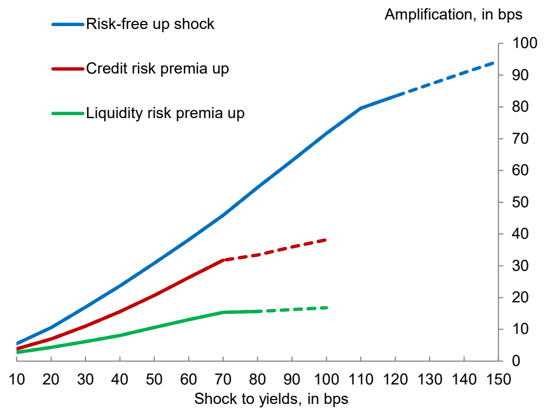
[46] The selling pressure by open-ended funds is the same for shocks to credit and liquidity risk premia, as in the framework fund investors focus on losses/gains when deciding whether to redeem/subscribe and abstract from the fundamental drivers of those losses.
[47] Solvency II 'matching adjustment' provision allows for a greater reduction in insurer's liabilities when asset prices fall as result of liquidity shocks, as compared to credit shocks. In practice, when corporate bond spreads move it is not straightforward to determine whether the driver of the move is credit or liquidity risk. That said, given that liquidity shocks cause a lesser impact on insurers' solvency, insurers develop models that help distinguish between the two and secure less stringent regulatory treatment.

deviate outside the target range and, hence, trigger no re-balancing behaviour by this type of pension funds.

The pension fund supported by a financially constrained ('weak') sponsor adjusts its asset allocations only if the volatility of its deficit increases beyond the maximum tolerance level. This tolerance level is breached for falls in the risk-free rate of 60bps and above, which encourages the funds to buy fixed income assets, including corporate bonds. The tolerance level is not breached for any other type of shock examined.

Chart 4 shows estimates of the potential amplification effect, expressed as the additional increase in UK corporate bond yields, over and above the initial shock. Results are shown for different types and sizes of the initial shock. In line with the magnitude of the selling pressure described earlier, initial increases in credit risk premia and the risk-free rate (blue and red lines) are amplified significantly, whilst the amplification of liquidity shocks (green line) is more moderate.

Chart 4 – Amplification of shocks in the UK corporate bond market



Notes: Where solid lines end reflects the point where dealers run out of desk-level capacity; dashed lines end where dealers run out of spare capacity at the firm level.

More specifically, an initial 60 bps shock to credit risk premia is likely to be amplified by an extra 26 bps, as compared to 13 bps amplification for a similar-sized shock to liquidity risk premia. Given that shocks to the risk-free rate affect all fixed income assets and cause largest losses for investors, they also cause the largest amplification. In particular, a 60 bps shock to the risk-free rate can be amplified by another 38 bps.

Putting this in the context of historical moves in UK investment-grade corporate bond spreads and yields, for all types of shock the sum of the initial shock and the amplification is somewhat higher than the largest historical weekly increase in spreads/yields, but lower than the largest historical monthly move.[48]

For large shocks, less constrained investors, such as pension funds, face incentives to rebalance, which moderates the amplification of initial shocks (as manifested in the slope of all lines flattening for larger shock sizes). For example, the amplification effect for the credit risk shock

[48] Here we take the moves in sterling investment-grade corporate bond spreads/yields as a proxy for the UK market as whole. Largest weekly increases in spreads and yields were observed in Sep 2008 and amounted to 74 and 67 bps respectively. Largest monthly increases in spreads and yields were observed in Sep-Oct 2008 and amounted to 122 and 132 bps respectively.

flattens after the shock size of 70 bps, the point at which the pension fund with the 'strong' sponsor starts having incentives to rebalance.

As illustrated in **Chart 4**, shocks to credit and liquidity risk premia of 70-80 bps, which are roughly in line with the largest historical weekly moves in investment-grade corporate bond spreads, could exhaust the capacity of the dealer's market-making desk to absorb corporate bond sales (the point on the horizontal axis where solid red and green lines end). If the dealer can re-allocate spare capital from other business lines, shocks to credit and liquidity risk premia of up to 100 bps can be absorbed without a 'market dislocation' (the point on the horizontal axis where red and green dashed lines end).

We find that for increases in the risk-free rate, dealers are likely to be able to intermediate the market for larger shock sizes (blue line). This is because in the parametrisation of the framework increases in the risk-free rate are assumed to occur against a backdrop of low levels of market stress, proxied by the VIX index. Historically, risk-free interest rates have tended to rise amidst an improving macro outlook and low overall market volatility (when dealer's business models are typically under less pressure).[49] However, this assumption might overstate the ability of dealers to make markets should a rise in the risk-free rate be driven by a snap-back in term premia or inflation expectations and not be accompanied by improvement in the macro outlook.

Multifactor initial shocks to corporate bond yields

The results above are based on single-factor shocks to corporate bond yields. However, our framework is flexible and can also be used to explore the implications of multifactor shocks to yields. Below we present the results for a multifactor shock equal to 60 bps, split equally across the risk-free, credit and liquidity components of corporate bond yields. We also compare these results to those for single-factor shocks of the same magnitude (i.e. 60 bps). For comparability, for the multifactor and single-factor shocks, we assume that the level of the VIX index is fixed and equal to its historical average of 20 per cent.

Chart 5 shows the buying and selling behaviour in the UK investment-grade corporate bond market for a multifactor shock and a single-factor credit risk shock, both equal to 60bps.
In both cases, the net demand for liquidity by constrained investors is mainly driven by open-ended funds. The magnitude of the buying and selling behaviour of with-profit and non-profit insurers respectively is smaller following a multifactor shock, as compared to a credit shock.

[49] For more information on the role that the VIX index plays in the framework, see Sections 3, 4 and Annex 2.

This is due to how, under the multifactor shock, the moves in the risk-free rate component improve insurers' solvency positions (as such shocks reduce the value of insurers' liabilities by more than that of their assets) and incentivise them to buy risky assets. This partially offsets the sales of risky assets prompted by the shock to the liquidity and credit components of corporate bond yields. In both cases the shock of 60 bps is not large enough to trigger rebalancing behaviour by pension funds.

Chart 5 – Buying and selling behaviour in the UK IG corporate bond market of investors for a single-factor (credit risk) and a multifactor shock of 60 bps.

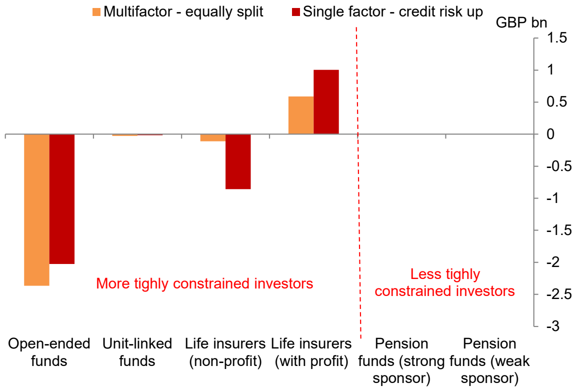


Chart 6 – Amplification of shocks in the UK IG corporate bond market for a single-factor and a multifactor shock of 60 bps.

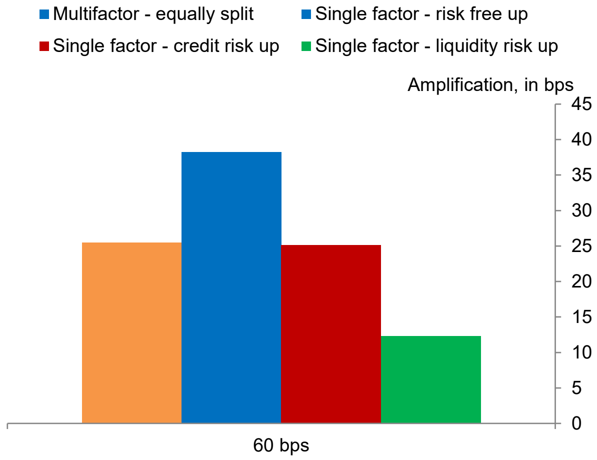


Chart 6 compares the amplification effects in the UK investment-grade corporate bond market under a 60 bps multifactor shock and the three single-factor shocks of the same size. The multifactor shock of 60 bps triggers a smaller amplification than a single-factor risk-free rate shock, similar amplification to a single-factor credit shock, and larger amplification than a single-factor liquidity shock.

7. *Sensitivity analysis*

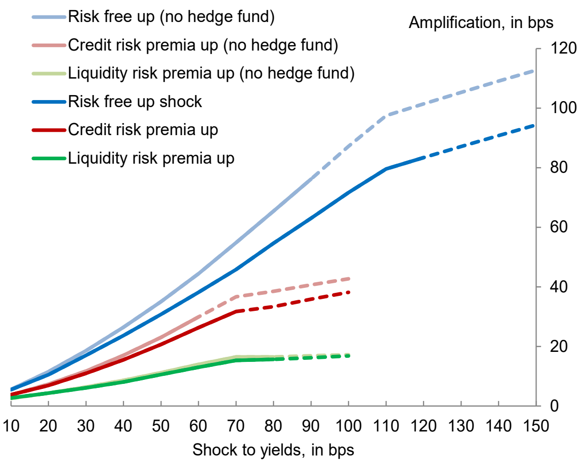
In this section we investigate how sensitive our results are to some of the key modelling assumptions: (i) the assumption that the hedge fund provides liquidity alongside the dealer; (ii) the calibration of the relationship between the initial shock and the level of the VIX index, that we use as a proxy for market stress, and (iii) the speed with which institutional investors, such as insurers, respond to the initial shock.

Sensitivity 1: Hedge fund as a liquidity provider

Results presented above assume that the hedge fund, acting in a profit-maximising manner, purchases some of the corporate bonds sold by the 'buy-side' investors, thus providing liquidity to the market. However, empirical evidence on the behaviour of hedge funds under stress is mixed. [50] We therefore test the alternative assumption that hedge funds act neutrally and neither buy nor sell in response to the initial shock and asset sales by 'buy-side' investors.

Chart 7 shows the comparison of model results when the hedge fund provides liquidity in the market and when it does not. When the hedge fund does not purchase some of the bonds sold by 'buy-side' investors, the dealer has to accommodate more assets on its balance sheet. This implies that, for a given type of shock, the price impact of asset sales will be higher and the balance sheet capacity of the market-making desk will be exhausted for smaller shock sizes. In particular, for a 60 bps credit and liquidity shocks the amplification effect is 14% and 7% higher respectively, when the hedge fund does not provide liquidity. Also in this scenario credit shocks of 70 bps could exhaust the balance sheet capacity of the market-making desk, as compared to 80 bps in the baseline case (**Chart 7**).

Chart 7 – Sensitivity of model outputs to assumptions on hedge fund behaviour



Notes: Where solid lines end reflects the point where dealers run out of desk-level capacity; dashed lines end where dealers run out of spare capacity at firm-level.

Sensitivity 2: Mapping between exogenous initial shocks and market stress

As mentioned in **Section 3**, dealer's ability and willingness to intermediate markets are assumed to decline as the overall level of market stress goes up. Also, dealer's costs of warehousing corporate bond inventory are assumed to increase with the level of market stress. Hence, we explore the sensitivity of the results to the assumed strength of the relationship between different types of initial shocks and market stress (as proxied by the VIX index).[51]

For the relationship between the VIX index and credit spreads (used for shocks to credit and liquidity risk premia), we test the sensitivity of the results to increasing/decreasing the beta from the regression of the VIX index on credit spreads by one standard deviation.

[50] In particular, Ferguson and Laster (2007) argue that hedge funds add liquidity to markets and are broadly stabilising. In contrast, Choi and Shachar (2013) find that, during the 2007–09 financial crisis, hedge funds demanded liquidity in the corporate bond market.
[51] The estimation of the baseline relationship between the level of the VIX index and initial shocks is described in Section 5, with more detail provided in **Annex 2.**

For the risk-free rate shock, we apply a different sensitivity check.[52] In particular, we run a separate regression between the level of the VIX index and changes in inflation expectations, as inferred from the ten-year UK breakeven inflation rates.[53]

We further test the sensitivity around this estimate, by increasing/decreasing the coefficient from this regression by one standard deviation. Results of this sensitivity analysis are presented in **Table 2**.

In general, for all types of shock a stronger relationship between the initial shock and the level of market stress decreases the size of the shock that could test the ability of dealer's market-making desk to absorb asset sales and marginally increases the price impact of sales.

Table 2 – Sensitivity of model outputs to the mapping between initial shocks and the level of the VIX index

Scenario	*Amplification for 60 bps shock*	*Desk-level market-breaking point*
Credit spread vs. VIX (baseline)	26.3	80
Credit spread vs. VIX (+ 1 st. dev)	26.6	70
Credit spread vs. VIX (- 1 st. dev)	26.0	90
Risk-free rate vs. VIX (baseline, based on 10-year gov. bond yield)	38.2	130
Risk-free rate vs. VIX (based on 10-year inflation break-even)	38.6	90
Risk-free rate vs. VIX (based on 10-year inflation break-even, + 1 st.dev.)	39.0	80
Risk-free rate vs. VIX (based on 10-year inflation break-even, - 1 st.dev.)	38.2	110

Note: results for the credit spread mapping refer to credit shock only.

Sensitivity 3: Speed of response of institutional investors

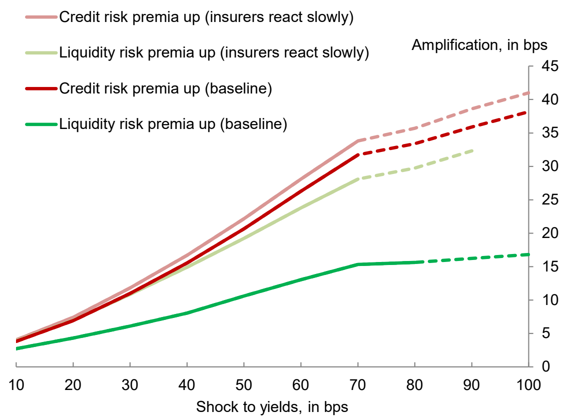
Here we vary the assumption regarding the speed with which insurers rebalance their portfolios, including holdings of corporate bonds, following a deterioration in solvency. In particular, instead of assuming that they react quickly and contribute to the net demand for liquidity that the dealer needs to absorb (as shown in **Chart 3**), we assume that they rebalance gradually (i.e. over a one-month period).[54] Such an alternative assumption means that the dealer will factor in insurers' rebalancing behaviour when determining its expected holding period for corporate bond inventory.

Chart 8 shows the results of the simulation for credit and liquidity shocks[55] under this alternative assumption and compares them to the baseline results (i.e. as shown in **Chart 4**).

[52] This is due to the beta from the baseline regression of the VIX index on changes in the risk-free rate not being statistically significant.
[53] This relationship is statistically significant at 5%.
[54] This assumption is similar to that when insurer solvency position improves following the shock.
[55] We do not explore an upwards shock to the risk-free rate here. For this type of shock insurers' solvency positions improve and we already assume that they rebalance more slowly.

For a credit shock (when insurers in aggregate are very marginal net buyers of corporate bonds[56]) their slower rebalancing leads to higher net demand for liquidity that dealers need to absorb and lower expected holding period per unit of inventory. This in turn results in a somewhat higher price impact for all shock sizes. For a liquidity shock, we see more difference in results as insurers are more material net buyers of corporate bonds. The price impact is much larger as insurers' aggregate behaviour no longer directly offsets the selling by open-ended investment funds. Also, the size of the shock that could test the capacity of the dealer to make markets is smaller.

Chart 8 – Sensitivity of model outputs to assumption on the speed of response of insurance companies



Notes: Where solid lines end reflects the point where dealers run out of desk-level capacity; dashed lines end where dealers run out of spare capacity at firm-level.

Other key model parameters

In addition to the assumptions tested above, model results are also driven by a large number of parameters, as detailed in **Annex 2**. However, some of those have a more material impact on model outputs than others. More specifically, the key parameter driving the behaviour of the open-ended investment funds is the sensitivity of fund flows to fund losses (σ_i). For insurers, it is the level of their target solvency ratio (φ^{INS}) relative to their current solvency position (SR),[57] as well as the sensitivity of insurers' liabilities to changes in the value of insurers' assets (el_L). For the pension fund with a 'strong' sponsor, it is the width of the tolerance range for asset class weights ($\overline{w_a{}^{LB}}, \overline{w_a{}^{UB}}$). For the dealer, it is the distance between the actual pre-shock leverage ratio (*E/BS*) and that required by the regulations (LR^{reg}), as well as the share of the dealer's balance sheet allocated to market-making corporate bonds ($share_{MM}^{BS}$) and the daily amount of corporate bonds that the dealer can offload to other investors in normal market conditions without impacting the price (Q^{NT}).

[56] The sale of corporate bonds by a non-profit insurer is less than the purchase by a with-profit insurer.
[57] In the baseline model calibration we assume that pre-shock solvency ratio is equal to the target.

8. Conclusion

The framework described in this paper is a useful tool for exploring the amplification of asset price shocks in the financial system. In particular, it allows us to 'zoom in' on one type of amplification channel (i.e. fire-sales) and its impact on a financial market (i.e. corporate bonds) that plays an important role in facilitating funding to the real economy.

Although the framework is based on simple models of representative market participants, it still yields useful insights for systemic risk assessment.

In particular, the magnitude of the amplification of shocks to corporate bond prices depends on the origin of the shock, and the extent to which a given type of shock negatively affects other assets classes and different types of investors.

The likelihood of market dislocation (i.e. the case when the demand for liquidity in corporate bond markets begins to exceed the capacity of dealers to absorb it) depends on the speed of reaction of buy-side investors that are forced to sell assets to avoid breaching their constraints. It also depends on the ability and willingness of the dealer to allocate capital to market-making corporate bonds, which in turn are influenced by the extent to which shocks to corporate bond prices coincide with the wider market stress that the dealer is exposed to.

We also find that the buying behaviour of long-term institutional investors, such as pension funds, could partly mitigate the amplification effects, especially in the case of large shocks. That said, even in the presence of such buying behaviour, large-scale moves in asset prices are possible if those investors are slower-moving and cannot directly offset the immediate demand for liquidity arising from the behaviour of constrained investors.

This framework is not without limitations and can be thought of as an intermediate step towards building a more granular and realistic simulation of system-wide stress. More specifically, this work could be extended along several dimensions. One extension could involve adding to the current framework a representative agent corresponding to commercial banks. Other possible extensions include increasing the granularity and heterogeneity of agents, representing different types of market participants, and asset classes, including to better capture the strength of contagion via common asset holdings.[58] However, these extensions will likely materially increase the complexity of the framework.

[58] This is particularly relevant if we were to incorporate additional rounds of behavioural responses into our framework.

In the meantime, this framework could be a useful tool for central banks and other policymakers. It could be used to quantify the potential amplification of fundamental shocks to asset prices driven by market participant behaviour. It could also be used for exploring the 'market-breaking points' – the types and magnitudes of shock that could test the ability of corporate bond markets to absorb asset sales and cause disorderly moves in corporate bond prices and corporate funding costs. Finally, it could be a useful tool when seeking to develop macro-prudential policies targeted at making market-based finance more resilient.

References

Adrian, T., N. Boyarchenko, and O. Shachar. (2017). Dealer balance sheets and bond liquidity provision. *Journal of Monetary Economics, 89, 92-109.*

Almeida, H., M. Campello, B. Laranjeira and S. Weisbenner (2009). Corporate debt maturity and the real effect of the 2007 credit crisis. *NBER Working Paper No. 14990.*

Anderson, N., L. Webber, J. Noss, D. Beale and L. Crowley-Reidy (2015). The resilience of financial market liquidity. *Bank of England Financial Stability Paper, 34.*

Bank of England (2016), Financial Stability Report, November 2016.

Bank of England (2018), Financial Stability Report, June 2018.

Baranova, Y., Z. Liu, and J. Noss. (2016).The role of collateral in supporting liquidity. *Staff Working Paper No. 609.* Bank of England.

Baranova, Y., J. Coen, P. Lowe, J. Noss, and L. Silvestri (2017a). Simulating stress across the financial system: the resilience of corporate bond markets and the role of investment funds. *Bank of England Financial Stability Paper, 42*.

Baranova, Y., Z. Liu, and T. Shakir (2017b). Dealer intermediation, market liquidity and the impact of regulatory reform. *Bank of England Staff Working Paper No. 665.*

Blake, D. (2003). UK pension fund management after Myners: The hunt for correlation begins. *Journal of Asset Management, Vol. 4. 1, 32-72.*

Bookstaber, R., and M. Paddrik (2015). An Agent-based Model for Crisis Liquidity Dynamics. *Office of Financial Research, 1–34.*

Bookstaber, R., M. Paddrik, and B. Tivnan (2017). An agent-based model for financial vulnerability. *Journal of Economic Interaction and Coordination, 1-34.*

Calimani, S., G. Halaj and D. Żochowski (2017). Simulating fire-sales in a banking and shadow banking system. *European Systemic Risk Board Working Paper Series, No. 46.*

Campello, M., J.R. Graham, and C.R. Harvey (2010). The real effects of financial constraints: Evidence from a financial crisis. *Journal of Financial Economics, Vol. 97, Issue 3.*

Cetorelli, N., F. Duarte, and T. Eisenbach (2016). Are Asset Managers Vulnerable to Fire Sales? *Liberty Street Economics.*

Choi, J., and Y. Huh (2017). Customer Liquidity Provision: Implications for Corporate Bond Transaction Costs. *Finance and Economics Discussion Series 2017-116*. Board of Governors of the Federal Reserve System (U.S.).

Choi, J., and O. Shachar (2013). Did liquidity providers become liquidity seekers? *Federal Reserve Bank of New York Staff Report No. 650.*

Committee on the Global Financial System (2010). The role of margin requirements and haircuts in pro-cyclicality. *CGFS Papers No. 36*

Cont, R., and E. Schaanning (2017). Fire sales, indirect contagion and systemic stress testing, *Working Paper 2017/2*, *Norges Bank.*

Czech, R. and M. Roberts-Sklar (2017). Investor Behaviour and Reaching for Yield: Evidence from the Sterling Corporate Bond Market. *Bank of England Staff Working Paper 68*5.

Douglas, G., J. Noss, and N. Vause (2017). The impact of Solvency II regulations on life insurers' investment behaviour. *Bank of England Staff Working Paper 664*.

Ellul, A., C. Jotikasthira, and C.T. Lundblad (2011). Regulatory pressure and fire sales in the corporate bond market. *Journal of Financial Economics 101, 596-620.*

Ferguson, R., and D. Laster (2007). Hedge funds and systemic risk. *Banque de France Financial Stability Review, No. 10..*

Financial Stability Board (2018). Global Shadow Banking Monitor 2017.

Fricke, C., and D. and Fricke (2017). Vulnerable Asset Management? The Case of Mutual Funds. *Discussion Papers 32, Deutsche Bundesbank.*

Gehde-Trapp, M., Y. Gündüzc, Y. and J. Nasevd (2015). The liquidity premium in CDS transaction prices: Do frictions matter? *Journal of Banking & Finance, Volume 61, pp. 184–205.*

Goldstein, I., H. Jiang, and D. T. Ng (2017). Investor flows and fragility in corporate bond funds. *Journal of Financial Economics, 126 (3), pp. 592–613.*

Greenwood, R., A. Landier, and D. Thesmar (2015). Vulnerable banks. *Journal of Financial Economics , 115 (3), pp. 471–485.*

Gruic, B., M. Hattori, and H.S. Shin (2014). Recent changes in global credit intermediation and potential risks. *BIS Quarterly Review, September 2014.*

Hałaj, G. (2018). Agent-based model of system-wide implications of funding risk, *Working Paper Series 2121*, European Central Bank.

King, M. (2009). The cost of equity for global banks: a CAPM perspective from 1990 to 2009, *BIS Quarterly Review, September 2009.*

Mallaburn, D., M. Roberts-Sklar, and L. Silvestri (forthcoming). The resilience of trading networks: evidence from the sterling corporate bond market. *Bank of England Staff Working Paper.*

Manconi, A., M. Massa, and A. Yasuda (2012*).* The role of institutional investors in propagating the crisis of 2007–2008. *Journal of Financial Economics 104 (3), 491–518.*

Merton, R. C. (1974). On the Pricing of Corporate Debt: The Risk Structure of Interest Rates. *Journal of Finance, 29, 449-70.*

Morris, S., I. Shim, and H.S.Shin (2017). Redemption risk and cash hoarding by asset managers. *BIS Working Papers No 608.*

Rousova, L.F., and M. Giuzio (2018). Insurers' investment strategies: pro-cyclical or counter-cyclical. *European Central Bank (forthcoming).*

Sweeting, P. (2005). Funding and Asset Allocation Strategies - Why Firms and Trustees Behave as They Do. *Working Paper presented to the 2005 U.K. Finance and Investment Board Conference.*

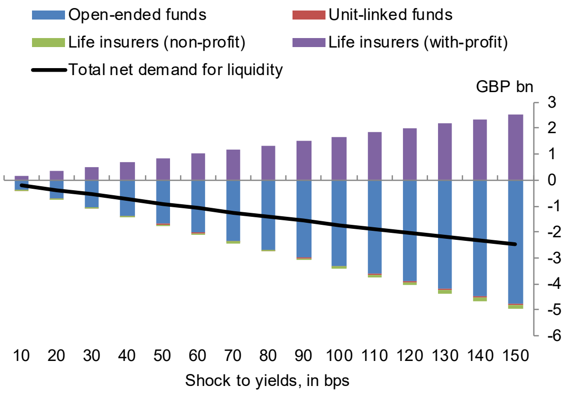
Timmer, Y. (2018). Cyclical investment behaviour across financial institutions. *Journal of Financial Economics, 129 (2018), pp. 268-286.*

Annex 1 – Buying and selling behaviour of investors in the UK corporate bond market for different types of shocks

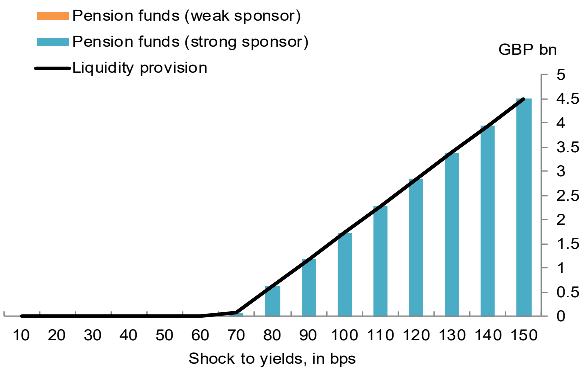
Charts in **Table A** summarise the buying and selling behaviour of different market participants in the UK investment-grade corporate bond market for different types of exogenous shocks. In the charts we show separately the behaviour of constrained investors that rebalance quickly and drive the net demand for liquidity; and less constrained/unconstrained investors that rebalance by gradually trading with the dealer and thus influence the dealer's expected inventory holding period.

Table A – Buying/selling behaviour of constrained and less constrained investors for different types of shocks*

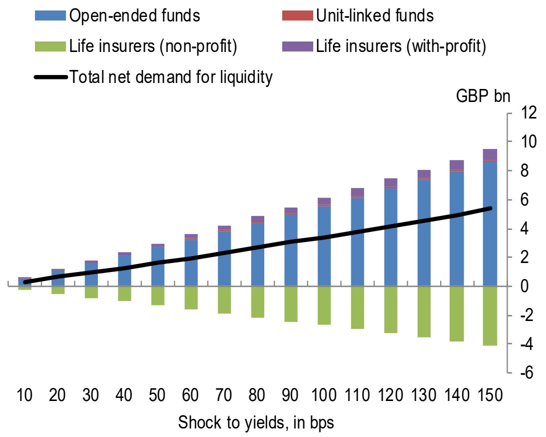
Liquidity shock – immediate net demand for liquidity from constrained investors



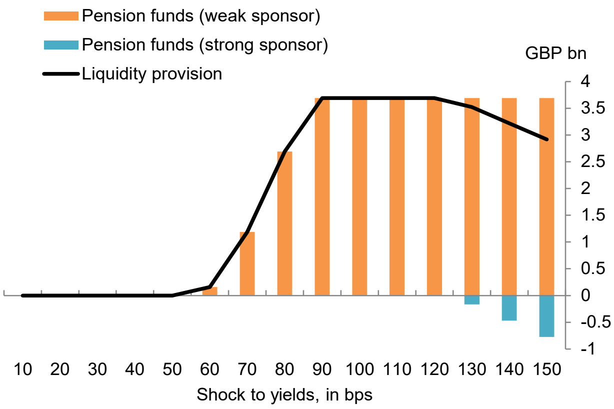
Liquidity shock – gradual liquidity provision by less constrained/unconstrained investors



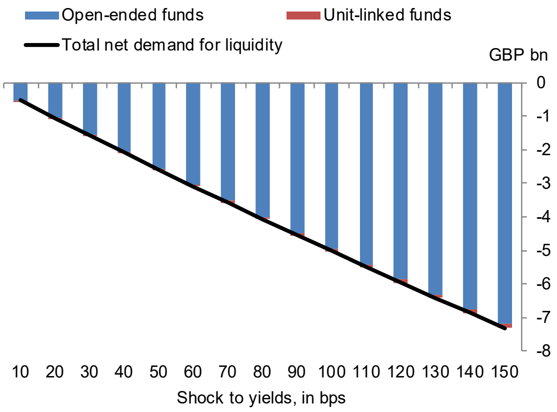
Risk-free rate down shock – immediate net demand for liquidity from constrained investors



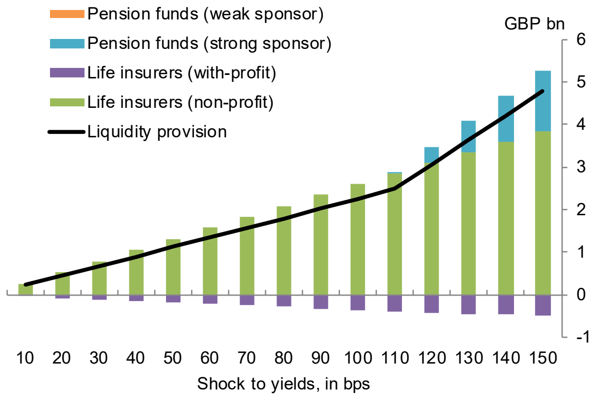
Risk-free rate down shock – gradual liquidity provision by less constrained/unconstrained investors



Risk-free rate up shock – immediate net demand for liquidity from constrained investors



Risk-free rate up shock – gradual liquidity provision by less constrained/unconstrained investors



*Rebalancing behaviour for unconstrained investors is shown on a monthly basis (i.e. how much corporate bonds they would buy/sell over a period of a month).

Annex 2 – Parametrisation of key model variables

Variable	Description	Calibration	Data source
Initial shock (section 5)			
k	Type of shock	Risk free, credit and liquidity	Assumption
$shock_{ak}$	Fall in price of asset a following a shock to yields of type k	$shock_{ak} = -yield_k \times MD_a$ where: MD_{IGcorp}=5.9; MD_{HYcorp}=3.5; MD_{Gov}=8.4. No impact on equities, cash and other assets.	BofAML Global Index System, Bloomberg.
$yield$	Change in risk-free, credit and liquidity components of bond yields	From 1 to 150 basis points	Exogenous
Mapping between the initial shock to yields and the level of the VIX index	To capture the extent to which initial shocks tend to be associated with broader market stress	Credit/liquidity shock: $VIX = 18.6 + 0.21 \times yield$ Risk-free shock: *VIX* = 20 (fixed at its historical average).	Credit/liquidity shock: based on a linear regression of three-month average level of the VIX index on monthly changes in global investment-grade corporate bond spreads. Risk-free shock: the relationship between VIX and changes in UK government bond yields is not statistically significant.
Open-ended investment funds(section 4)			
A^{OEF_i}	Total initial assets of fund category i	$A^{OEF_{equity}}$ = £1,445 bn; $A^{OEF_{allocation}}$= £1,108 bn; $A^{OEF_{corp\ bonds}}$= £850 bn; $A^{OEF_{gov\ bonds}}$= £600 bn.	Morningstar. Data as of end-2015.
H_a^{OEFi}	Initial holdings of asset a by fund category i	$H_{UKIG,equity}$ = £1bn; $H_{nonUKIG,equity}$ = £2bn; $H_{HY,equity}$ = £1 bn; $H_{EQ,equity}$ = £1,385 bn; $H_{GOV,equity}$ = £2 bn; $H_{CASH,equity}$ = £26 bn; $H_{OTHER,equity}$ = £28 bn; $H_{UKIG,allocation}$ = £42 bn; $H_{nonUKIG,\ allocation}$ = £ 88 bn; $H_{HY,allocation}$ = £82 bn; $H_{EQ,allocation}$ = £464 bn; $H_{GOV,allocation}$ = £233 bn; $H_{CASH,allocation}$ = £103 bn; $H_{OTHER,allocation}$ = £96 bn;	Morningstar. Data as of end-2015. *UK IG* and *nonUKIG* refer to UK and non-UK investment-grade corporate bonds respectively. *HY* refers to global high-yield corporate bonds, *EQ* to global equity, *GOV* to global government bonds, *CASH* to cash and cash equivalents, *OTHER* to other assets not covered above.

		$H_{UKIG,\ corp\ bonds}$ = £128 bn; $H_{nonUKIG,\ corp\ bonds}$ = £271 bn; $H_{HY,\ corp\ bonds}$ = £189 bn; $H_{EQ,\ corp\ bonds}$ = £1 bn; $H_{GOV,\ corp\ bonds}$ = £121 bn; $H_{CASH,\ corp\ bonds}$ = £26bn; $H_{OTHER,corp\ bonds}$ = £114 bn; $H_{UKIG,\ gov\ bonds}$ = £38 bn; $H_{nonUKIG,\ gov\ bonds}$ = £80 bn; $H_{HY,\ gov\ bonds}$ = £20 bn; $H_{EQ,\ gov\ bonds}$ = £1 bn; $H_{GOV,\ gov\ bonds}$ = £384 bn; $H_{CASH,\ gov\ bonds}$ = £24 bn; $H_{OTHER,gov\ bonds}$ = £54 bn.	
σ_i^{OEF}	Pro-cyclicality of investors of fund category i (i.e. investor redemptions in response to a 1 % loss).	Calibrated using panel regression as in Baranova et al. (2017a). σ_{equity} = 0.1; $\sigma_{allocation}$ = 0.2; $\sigma_{corp\ bonds}$ = 0.6; $\sigma_{gov\ bonds}$ = 0.3.	Monthly Morningstar data on fund returns and redemptions covering 2005-2015.
Unit-linked funds(section 4)			
H_a^{ULF}	Initial holdings of asset a by unit-linked fund ULF	$\sum H_a^{ULF}$ = £1,000 bn; H_{UKIG}^{ULF} = £29 bn; $H_{nonUKIG}^{ULF}$ = £40 bn; H_{HY}^{ULF} = £32 bn; H_{EQ}^{ULF} = £618 bn; H_{GOV}^{ULF} = £127 bn; H_{CASH}^{ULF} = £77 bn; H_{OTHER}^{ULF} = £76 bn.	Based on Bank of England survey of unit-linked insurers (findings discussed in Bank of England (2016)). Data as of end-2015.
σ^{ULF}	Switching rate of policyholders in unit linked funds in response to a 1% loss.	σ^{ULF} = 0.13.	Estimated based on Bank of England survey of unit-linked insurers (findings discussed in Bank of England (2016)).
Life insurance companies(section 4)			
A^{INS}	Value of insurers' total initial assets	Non-profit insurer A^{INS} = £474bn. With-profit insurer A^{INS} =£397 bn.	Solvency II regulatory data. As of H1 2016.
L^{INS}	Values of insurers' total initial liabilities	Non-profit insurer L_{MA}^{INS}= £350 bn; L_{RM}^{INS} = £24 bn; L_{TM}^{INS} = - £22 bn. With-profit insurer L_{MA}^{INS}= = £360 bn; L_{RM}^{INS} = £6.3 bn; L_{TM}^{INS} = - £5.9bn.	Solvency II regulatory data. As of H1 2016.
SCR^{INS} (pre-shock)	Values of insurers' regulatory capital requirements	Non-profit insurer SCR^{INS} =£87 bn. With-profit insurer	Calibrated in line with Solvency II guidance and set so

		SCR^{INS} = £27bn.	that SR is equal to target φ^{IC}.
SCR^{INS} (post-shock calibration)	Values of insurers' regulatory capital requirements	<u>Non-profit insurer:</u> ER_{a_R} = 3.6%; σ_{a_R} = 8.8%; $ER_{a_{RF}}$ = 1.7%; $\sigma_{a_{RF}}$ = 4.4%; ER_L = -2.1%; σ_L = 6.7%; $\rho_{a_R,a_{RF}}$ = 0.67 $\rho_{L,a_{RF}} = \rho_{a_R,L}$ = -0.22 (free parameter, set so that initial estimated SR is equal to the target). <u>With-profit insurer:</u> ER_{a_R} = 7%; σ_{a_R} = 18%; $ER_{a_{RF}}$ = 2.2%; $\sigma_{a_{RF}}$ = 4.9%; ER_L = -2.1%; σ_L = 7.3%; $\rho_{a_R,a_{RF}}$ = -0.1; $\rho_{L,a_{RF}} = \rho_{a_R,L}$ = -0.71 (free parameter, set so that initial estimated SR is equal to the target).	Bloomberg and Bank of England. For <u>non-profit</u> insurer, the risky asset is corporate bonds and the risk-free asset is government bonds. For <u>with-profit</u> insurer, the risky asset is equity and the risk-free asset is fixed-income assets (government, corporate bonds).
φ^{INS}	Insurers' target solvency ratios (that is, capital resources divided by the regulatory capital requirement)	140% (same for non-profit and with-profits insurers)	Bank of England.
H_a^{INS}	Values of insurers' initial holdings of asset a	<u>Non-profit insurer:</u> H_{UKIG}^{INS} = £158 bn; $H_{nonUKIG}^{INS}$ = £107 bn; H_{HY}^{INS} = £47 bn; H_{EQ}^{INS} = £0 bn; H_{GOV}^{INS} = £162 bn; $H^{INS}{}_{a_R} = H_{UKIG}^{INS} + H_{nonUKIG}^{INS} + H_{HY}^{INS}$; $H^{INS}{}_{a_{RF}} = H_{GOV}^{INS}$. <u>With-profit insurer:</u> H_{UKIG}^{INS} = £48 bn; $H_{nonUKIG}^{INS}$ = £33 bn; H_{HY}^{INS} = £14 bn; H_{EQ}^{INS} = £188 bn; H_{GOV}^{INS} = £113 bn. $H^{INS}{}_{a_R} = H_{EQ}^{INS}$; $H^{INS}{}_{a_{RF}} = H_{GOV}^{INS} + H_{UKIG}^{INS} + H_{nonUKIG}^{INS} + H_{HY}^{INS}$.	Solvency II regulatory data. As of H1 2016.

$\widetilde{H_{ak}^{INS}}$	Values of insurers' holdings of asset a after a shock k	$\widetilde{H_{ak}^{INS}} = H_a^{INS}(1 - shock_{ak})$	Mechanical calculation.
$\widetilde{A_k^{INS}}$	Values of insurers' total assets after a shock k	$\widetilde{A_k^{INS}} = \sum_a \widetilde{H_{ak}^{INS}}$	Mechanical calculation.
el_L	Percentage change in the value of insurer's matching adjustment liabilities and some other liabilities (L_{MA}^{INS}) for 1% change in value of insurer assets driven by shock to yields of type k	$el_L^{liquidity}$ = - 0.96; el_L^{credit} = - 0.94; $el_L^{risk-free}$ = -1.	Bank of England.
el_{RM}, el_{TM}	Percentage change in the values of other regulatory liabilities under Solvency II (i.e. the 'Risk Margin' (RM) and 'Transitional Measures on Technical Provisions' (TM)) for a given basis point change in interest rates	$el_{RM}^{risk-free}$ = - 0.6; $el_{TM}^{risk-free}$ = - 0.56.	Bank of England.
$\widetilde{w_{ak}}$	Insurers' portfolio weights of asset a after a shock k	$\widetilde{w_{ak}} = \frac{\widetilde{H_a^{INS}}}{\widetilde{A^{INS}}}$	Mechanical calculation.
$\tau^{INS,fall}$	Time for insurance companies to respond to falls in solvency below target	instantaneous (i.e. 1 day)	Applying intuition from recent FSB survey.
$\tau^{INS,rise}$	Time taken for insurance company to respond to a increase in solvency above target	1 month	
Unconstrained pension funds(section 4)			
A^{UPF}	Value of unconstrained pension fund's initial total assets	A^{UPF} = £625 bn.	Purple Book (produced by the Pensions Regulator/Pensions Protection Fund).
H_a^{UPF}	Initial holdings of asset a by unconstrained pension fund	H_{UKIG}^{UPF} = £75 bn; $H_{nonUKIG}^{UPF}$ = £77 bn; H_{HY}^{UPF} = £27 bn; H_{EQ}^{UPF} = £269 bn; H_{GOV}^{UPF} = £178 bn.	
$\widetilde{H_{ak}^{UPF}}$	Unconstrained pension fund's holdings of asset a	$\widetilde{H_{ak}^{UPF}} = H_a^{UPF}(1 - shock_{ak})$	Mechanical calculation.

	after a shock k		
w_a	Unconstrained pension fund's portfolio weight of asset a before the shock	$w_{ak} = \frac{H_a^{UPF}}{A^{UPF}}$	Mechanical calculation.
$\widetilde{w_{ak}}$	Unconstrained pension fund's portfolio weight of asset a after a shock k	$\widetilde{w_{ak}} = \frac{\widetilde{H_{ak}^{UPF}}}{\widetilde{A^{UPF}}}$	Mechanical calculation.
$Losses_k^{UPF}$	Unconstrained pension fund's losses after a shock k (as a fraction of total initial assets)	$Losses_k^{UPF} = \sum_a \frac{H_a^{UPF}}{A^{UPF}} shock_{ak}$	Mechanical calculation.
τ^{UPF}	Time taken for unconstrained fund to rebalance asset portfolio following shocks	1 month	Applying intuition from FSB survey.
$\overline{w_a{}^{LB}}, \overline{w_a{}^{UB}}$	Upper and lower bounds for permitted portfolio weights of asset a	$\overline{w_a{}^{LB}} = w_a * (1-0.05)$; $\overline{w_a{}^{UB}} = w_a * (1+0.05)$; Where 0.05 is the pension fund tolerance range.	
Constrained pension funds (section 4)			
A^{CPF}	Value of constrained pension fund's initial total assets	$A^{CPF} = £\ 665$bn.	Purple Book (produced by the Pensions Regulator/Pensions Protection Fund).
H_a^{CPF}	Initial holdings of asset a by constrained pension fund	H_{UKIG}^{CPF} = £74 bn; $H_{nonUKIG}^{CPF}$ = £76 bn; H_{HY}^{CPF} = £26 bn; H_{EQ}^{CPF} = £312 bn; H_{GOV}^{CPF} = £176 bn.	
L^{CPF}	Value of constrained pension fund's initial total liabilities	L^{CPF} = £882 bn.	
w_A, w_L	Constrained pension fund's initial weights on asset and liabilities	w_A =43%; w_L = 57%.	
σ_A, σ_L	Volatilities of constrained pension fund's assets and liabilities	$\sigma_A = \sqrt{w_{a_R}^2\sigma_{a_R}^2 + w_{a_{RF}}^2\sigma_{a_{RF}}^2 + 2w_{a_R}w_{a_{RF}}\sigma_{a_R}\sigma_{a_{RF}}\rho_{a_R,a_{RF}}}$; σ_L = 15%.	Bloomberg and Bank of England.
$\sigma_{A,L}$	Correlation between pension assets and liabilities	$\rho_{A,L}$ = 0.34	Bank of England.
$w_{a_R}, w_{a_{RF}}$	Constrained pension fund's initial weights on risky and risk free	$w_{a_R} = \frac{H_{a_R}^{CPF}}{A^{CPF}}$; $w_{a_{RF}} = \frac{H_{a_{RF}}^{CPF}}{A^{CPF}}$;	Bank of England.

	assets	$H^{CPF}_{a_R} = H^{CPF}_{EQ}$ = £312 bn; $H^{CPF}_{a_{RF}} = H^{CPF}_{UKIG} + H^{CPF}_{nonUKIG} + H^{CPF}_{HY} + H^{CPF}_{GOV}$.	
$\sigma_{a_R}, \sigma_{a_{RF}}$	Volatilities of risk-free and risky assets	σ_{a_R} = 16% (equity); $\sigma_{a_{RF}}$ = 6% (fixed-income).	Bloomberg.
$\rho_{a_R,a_{RF}}$	Correlation between risk-free and risky assets	$\rho_{a_R,a_{RF}}$ = -0.1.	Bloomberg.
$Losses^{CPF}_k$	Constrained pension fund's losses from shock k (as a fraction of total initial assets)	$Losses^{CPF}_k = \sum_a \frac{H^{CPF}_a}{A^{CPF}} shock_{ak}$	Mechanical calculation.
σ^{CPF}_{MAX}	Maximum pension fund volatility permitted	110% * current volatility	Applying intuition from recent FSB survey.
τ^{CPF}	Time taken for constrained fund to rebalance asset portfolio following shocks	18 months	Triennial pension fund valuations are required under the Pensions Regulator's (tPR) rules. Hence, the average response time is half that.
Hedge fund (section 4)[59]			
h^{HF}	Haircut on hedge fund repo borrowing	VaR +0.094	Estimated based on Committee on the Global Financial System (2010).
VaR	Value-at-Risk (10-day 99%) for a standard diversified corporate bond portfolio	0.001 * VIX − 0.0021	Regression of estimated VaR for a European corporate bond index on the VIX index. VaR is calculated as $D \times \sigma \times 2.33$, where D is the modified duration of the bond index and σ is the standard deviation of 10-day changes in bond yield (expressed as decimal).
LA^{HF}	Unencumbered liquid assets of fixed-income hedge funds	£31.7 bn	FCA Hedge Fund Survey and SEC Private Fund Statistics .
HP^{HF}	Hedge funds' expected holding period for purchased assets	$HP^{HF} = HP^D(Q^D)$	Assumption.
*Other hedge fund variables are covered in the dealer section below.			

[59] Calibration for the global corporate bond market, as in Baranova et al (2017b).

Dealer (section 4)[60]			
BS	Balance sheet size of major global dealers (G-16)	£8760 bn	SNL.
E	Tier 1 equity capital of major global dealers (G-16)	£467 bn Changes with VIX: ΔE/E= ((ΔVIX×0.0223-ΔVIX^2×0.0115) /100	As inferred from weighted average leverage ratio of 5.5%. Bank of England (2018) The relationship b/w dealer return on equity (RoE) and market stress (VIX) is estimated using quarterly historical data from SNL and Bloomberg.
OL	Dealer's optimal level of leverage	For modelling and parametrisation, see **Annex 3**	
$share_{repo}^{BS}$	Share of dealer balance sheet allocated to corporate bond repo	0.15%	Based on regulatory returns for major UK banks.
$share_{MM}^{BS}$	Share of dealer balance sheet allocated to making markets in corporate bonds	3.1%	Based on regulatory returns for major UK banks.
C_{desk}	Cost of capital applied to transactions if it is available at the desk level	10%/(1-0.3)	10% (based on King (2009)) divided by (1-tax rate) where tax rate is 30%.
C_{alloc}	Cost of capital (pre-tax) applied to transactions when it is reallocated from other business lines	16.7%	Based on historical average RoE of Morgan Stanley and Goldman Sachs (SNL).
LR	Leverage ratio requirement applied to the transaction	LR = 1/OL	
LR^{reg}	Minimum regulatory leverage ratio requirement	4%	Weighted average of requirements in corresponding jurisdictions of global dealers.
H	Hedging ratio for corporate bond inventories.	40%	Market intelligence.
$HC(Q^D, VIX)$	Dealer's hedging cost per unit of corporate bond inventory	$hedgePrem(VIX) + hedgePI * H * Q^D$	Mechanical calculation.

[60] Calibration for the global corporate bond market, as in Baranova et al (2017b).

$hedgePrem(VIX)$	CDS premium paid for hedging credit risk of corporate bonds	(65.2 + 1.4 * VIX)/10000	Based on regression estimates between the average of CDX.NA.IG and iTraxx Europe CDS indices and the VIX index.
$hedgePI$	Price impact of hedging	54 bps per €1bn notional	Based on Gehde-Trapp et al (2015).
r_f	Risk-free interest rate	0.5%	Bank Rate post-crisis.
h^D	Haircut on dealer repo borrowing	VaR + 2.2 * PD	Estimated based on CGFS (2010).
PD	Probability of dealer default.	*PD* is estimated based on a simple Merton model of a representative dealer bank with equity equal to *E*, total assets equal to *BS*, and return on assets following a normal distribution with mean *roaMean* and standard derivation *roaVol.*	
roaMean	Dealer return on assets	0.66%	Historical RoA from pure dealer banks - i.e. Morgan Staley and Goldman Sachs (SNL).
roaVol(VIX)	Volatility of dealer return on assets	(VIX * 0.0114 + 0.08)/100	Calibrated based on a regression between historical RoA from Morgan Staley and Goldman Sachs (SNL) and the VIX index.
1-LGD	Recovery rate for dealer unsecured debt	0.4	Moody's.
VaR	Value-at-Risk (10-day 99%) for a standard diversified corporate bond portfolio	0.001 * VIX − 0.0021	Regression of estimated VaR for a European corporate bond index on the VIX index. VaR is calculated as $D \times \sigma \times 2.33$, where D is the modified duration of the bond index and σ is the standard deviation of 10-day changes in bond yield (expressed as decimal).
RWA	Risk-weighted capital requirement	$MRC \times 12.5 \times capitalRatio$	Based on Basel III rules for calculating market risk capital requirements, as set by BCBS.
MRC	Market risk charge	$(\text{VaR} \times 3) \times 3 \times 0.64 + 0.056$	The capital charge in the fundamental

			review of the trading book is ES (expected shortfall) + DRC (default risk charge). ES is assumed to be 64% of 3 × (VaR + $Stressed\ VaR$). $Stressed\ VaR$ is assumed to be 2 times the VaR. DRC is estimated based on Basel QIS.
capitalRatio	Tier 1 capital ratio requirement	11%	Appropriate amount of Tier 1 capital for the UK banking system, as set in its "Framework of capital requirements for UK banks" (2015).
$Share_{UKIG}$	The share of the UK investment-grade corporate bond market in the global corporate bond market.	7.9%	Reuters DBI.
Q^{NT}	The amount of corporate bonds that the dealer could sell to other investors on a normal trading day, without negatively affecting the price.	£0.3 bn.	Evidence from Begalle (2013), adjusted to cover the global corporate bond market

Annex 3 – Modelling dealer's optimal leverage

This annex describes the approach to modelling the level of dealer's optimal leverage for a given level of market stress, as proxied by the VIX index.

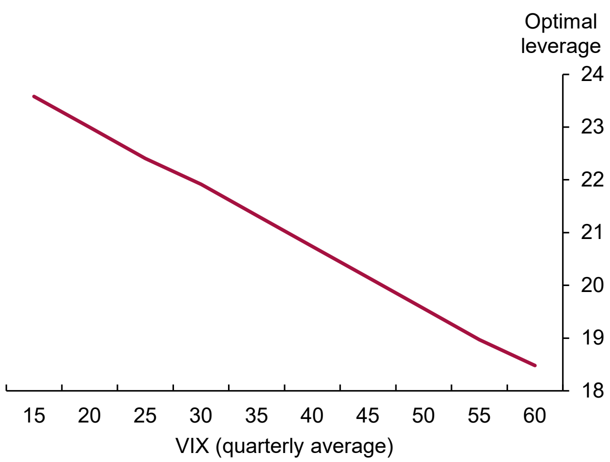
To do so we use a variant of the 'structural' credit risk model, introduced by Merton (1973). Under it, the value of firm's equity is modelled as the value of a call option on firm's assets, struck at the face value of the firm's debt. The value of such an option can be determined using option-pricing techniques.

For the application described in this paper, we model the value of dealer's equity as a 'down-and-out' call option that expires worthless if the value of dealer's assets falls below a 'barrier' level commensurate with its regulatory minimum leverage ratio requirement, at any time prior to the maturity of dealer's debt. This is intended to reflect the possibility that a regulator intervenes to wind down the dealer's business if its assets fall below this value (or, in other words, its leverage exceeds the maximum permitted level), even if the dealer is still solvent (i.e. dealer's assets are still greater than its liabilities).

We further assume that the dealer's balance sheet – and, in particular, its choice of optimal leverage – is constructed to maximise the payoff to its shareholders; and that for any given book value of dealer's equity, any desired change in dealer's leverage (i.e. expansion/contraction of the balance sheet) is achieved via the issuance/redemption of debt.

Under these assumptions, there exists a level of dealer's assets – or, correspondingly, a level of leverage – that maximises the value of the dealer's equity for each level of asset volatility (which we assume depends on the overall level of market stress, proxied by the VIX index). This optimal level of leverage could be estimated numerically using the closed-form formula for the price of a 'down-and-out' call option, which in our application reflects the value of the dealer's equity.

Chart A – Dealer's optimal leverage



To calibrate the dealer's optimal leverage we use the volatility of major global dealers' return on assets as a proxy for their asset volatility, which we then map to the level of the VIX index. We also assume that the dealer faces a regulatory minimum leverage ratio of 4%,[61] an average debt maturity of 2.5 years, and the risk-free interest rate of 0.5%.

This optimal level of leverage – and how it varies with the VIX volatility index (and hence dealer's asset volatility) – is shown in **Chart A.**

[61] Weighted average of individual leverage ratio requirements for largest global dealers.