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A heterogeneous agent model for assessing the effects of capital regulation on the interbank money market under a corridor system

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Abstract

Money markets play an important role in the implementation of monetary policy. Their structure and dynamics have, however, changed significantly in recent years. In particular, a number of new banking regulations will affect the behaviour of money market participants, and so have the potential to affect money market interest rates. This paper offers a model to examine how prudential regulation might affect interbank overnight interest rates where the central bank implements monetary policy using a corridor system. Combined with a set of assumptions as to the cost banks might incur in meeting regulatory capital requirements, it offers a framework with which to explore how such prudential regulation might affect the dynamics of overnight interest rates. The results — which are illustrative — estimate the interest rates at which banks might borrow and lend reserves overnight in the presence of prudential regulation. They suggest that risk-weighted capital requirements might increase the average level of overnight interbank interest rates, while the regulatory minimum leverage ratio might decrease it. If applied to real-world data on central bank reserves balances and regulatory metrics, this model also offers an insight into how central bank policymakers could — if they so choose — amend their operational frameworks to account for the effects of regulation.

Key words: Monetary policy implementation, money markets, bank regulation, central bank operations.

JEL classification: G12, E43, E43, E58.

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1 Introduction

Money markets play an important role in the implementation of monetary policy. They are the markets in which policymakers seek to influence short-term interbank market interest rates by setting a policy rate, which, in the case of the Bank of England, is Bank Rate. Changes in overnight interest rates, combined with market participants' expectations of their future level, influence longer-term interest rates and other asset prices in the wider economy.

Before the recent financial crisis, many central banks implemented monetary policy using a corridor system. Under this system, banks were able to borrow or deposit central bank reserves overnight with the central bank's standing facilities at interest rates set at a spread above and below the central bank's policy rate. The interest rates offered on these standing facilities provided a corridor within which overnight interbank interest rates trade because commercial banks were typically unwilling to trade in the market at rates more punitive than those available from the central bank. Importantly, because banks' incentives to use either facility were broadly balanced: as the interest rates on each standing facility were set at a symmetric spread to the policy and because banks were roughly equally like to face a shortage as an excess of reserves, overnight interest rates tended to remain at a level close to the policy rate.

But the structure and dynamics of money markets has changed substantially in recent years. Some of these changes are a result of market participants' response to the financial crisis. In particular, the crisis caused market participants to reconsider the likelihood that their counterparties might default. As a result, a range of financial institutions reduced their reliance on unsecured money markets as a means of meeting their short-term liquidity needs.

Other changes have come about as a result of policymakers' response to the crisis. This has taken the form firstly of changes to the framework through which central banks implement monetary policy. Several central banks embarked on large-scale asset purchase programmes financed by the issuance of central bank reserves or on longer-term refinancing operations. These operations increased the quantity of central bank reserves beyond those typically supplied before the crisis. Some central banks – including the Bank of England – also switched from a corridor to a floor system of monetary policy implementation, which allowed them to increase the aggregate supply of reserves whilst maintaining control over overnight interest rates.

Policymakers also responded to the financial crisis by introducing a range of new prudential regulations – including the Basel III reforms agreed by the Basel Committee on Banking Supervision – with the aim of strengthening banks' supervision, risk management and disclosure. One branch of these regulations aims to improve the quantity and quality of the capital that banks hold against their assets. This includes both risk-based capital requirements and the regulatory minimum leverage ratio.[1]

[1] Other capital regulations place limits on banks' exposures to individual institutions with the aim of containing the maximum loss they could face in the event of counterparty default.

Given the changes made to monetary policy implementation frameworks– and, in the case of the Bank of England, the suspension of its corridor system that operated before the crisis – central banks have limited experience of how new prudential regulations will affect their operations in normal times. In particular, it is possible that such regulations may alter banks' incentives to transact in money markets, and therefore the dynamics of interest rates under a possible future return to a corridor system. There is therefore a need for a framework that provides some insight into how the prudential regulation that followed the crisis might affect the dynamics of short-term interest rates under a corridor system, and central banks' ability to influence them.

The existing literature provides two sources of inspiration. One strand of literature models the dynamics of interest rates in a corridor system by examining a representative agent's decision to lend or borrow in the money market in order to meet a reserves target. These models, which include those of Poole (1968) and Whitesell (2006), have the advantage of firm micro foundations: the interest rates at which banks are willing to trade in the interbank money market are derived from banks' desire to minimise the expected opportunity cost of missing their reserves targets and so being forced to deposit or borrow reserves from central bank facilities at more punitive rates than those available in the market.

But these models focus on the actions of only a single representative agent, and on the single overnight interest rate at which they transact. They consequently have little to say on how market interest rates and volumes differ across the cross-section of market participants. A second line of research, which includes more recent work by Afonso and Lagos (2014) and Bech and Monnet (2013), seeks to incorporate a role for interbank trading between heterogeneous agents. In doing so, it is able to examine how the traded interest rate and volume varies across the cross-section of market participants. Models of this type do not as yet, however, include the effects of regulation that affects banks to differing degrees.

The novel contribution of the framework offered here is its combination of the advantages of both existing strands of literature to analyse the effects of various prudential regulations. The prices and quantities at which different individual banks borrow and lend are determined in a manner similar to that in the representative agent frameworks of Poole (1968) and Whitesell (2006), and arise through the minimisation of the loss they expect incur from using the central bank standing facilities. But, following the second strand of literature, the model incorporates a role for interbank trading and heterogeneous agents, with each agent representing a different money market participant. This allows it to incorporate heterogeneity among banks, due both to the effects of regulation and their reserves balances with the central bank.

Illustrative results from the model are produced using hypothetical data of central bank reserves balances. This is combined with assumptions as to the cost banks might incur in acquiring capital to meet prudential regulations, and the degree to which they factor in these costs when deciding the rates at which they are prepared to borrow and lend. These assumptions allow for the estimation of the overnight interest rates at which banks are willing to trade with each other.

Throughout, our intention is not to attempt to calibrate these effects precisely. Rather, we take as given certain assumptions about the cost banks incur in meeting regulation, which are based on rough estimates of the cost that UK banks might incur in raising capital. With these assumptions in hand, our work aims to provide some indicative analysis of the possible direction and relative magnitude of their effects on overnight money market interest rates under a corridor system.

This framework considers only banks' activity in unsecured interbank money markets. This is in part due to how, prior to the crisis, a large part of short-term borrowing took place in the unsecured interbank market. Since the crisis, however, banks' money market activity has shifted towards secured transactions.[2] The framework that follows could, however, be adapted to model the secured money market.

The results have two key policy implications. First, they provide some indication of how prudential regulation might affect interbank overnight interests for a given set of assumptions about the costs of capital incurred in meeting those regulations. Although both risk-weighted capital requirements and the regulatory minimum leverage ratio require banks to hold capital against their exposures, they bias average money market rates in different directions. This result arises because a marginal unit of borrowing or lending has different implications for banks' capital and leverage ratios, given how the resulting exposure to their counterparty is treated differently under each regulation.

- When a bank borrows in the money market, it acquires a new exposure to the central bank in the form of reserves. This exposure receives a zero risk weight under risk-weighted capital requirements, but must have capital held against it under the regulatory minimum leverage ratio. Assuming that the bank faces a certain cost in raising this capital, the framework presented here suggests that the minimum leverage ratio increases the marginal cost of borrowing reserves. This implies that the minimum leverage ratio could reduce banks' incentives to borrow in the market, and therefore reduces the overnight interest rate at which it will borrow in the market.
- In contrast, when a bank lends in the private money market, it swaps one form of exposure – that to the central bank, in the form of reserves – for another, in the form of an exposure to another private sector counterparty. These are treated the same under the regulatory minimum leverage ratio, so the required amount of capital a bank needs to hold is unchanged. But – under the assumption that exposures to private sector counterparties carry a higher risk-weight than exposures to the central bank – lending to other commercial banks increases the amount of capital a bank must hold to meet its risk-weighted capital ratio. To the extent that banks attach a cost to this higher capital

[2] This may in part be due to how the crisis increased banks' perceptions of credit risk (which is less of a concern in secured markets) and in part due to the incentives created by prudential regulation. For further discussion see Hauser (2013) and Jackson and Sim (2013).

requirement, this effect increases the interest rate banks require to induce them to lend reserves in the interbank money market.

The aggregate effect of both regulations will depend on the degree to which each type of regulation binds on banks, and the costs they face in meeting them.

Second, this framework can be used to investigate how changes to the design of the corridor system might change the effects of prudential regulation on overnight interest rates. One such adjustment would be to design a system that offers banks greater flexibility in managing day to day changes in their reserves balances. All else being equal, this might narrow the distribution of traded interest rates across banks and reduce the volatility of market interest rates observed over time. But the corollary would be a reduction in commercial banks' incentives to manage their reserves in the interbank market and therefore would reduce interbank money market activity. Moreover, such flexibility may not offset the bias to rates caused by costs associated with prudential regulation.

A second adjustment a central bank could make is to set an asymmetric corridor, in which the interest rate on the deposit and lending facility are not set equal distances apart from the policy rate. For instance, if overnight interest rates persistently trade above the policy rate, a decrease in the deposit rate or an increase in the lending rate would reduce average overnight interest rates.

Neither of these adjustments to central bank operating frameworks, however, is any panacea to a future volatility or biasing in overnight interest rates. Both would be likely to reduce private money market activity – because they would increase the probability that banks will respond to changes in their reserves balances by transacting with the central bank rather than with each other. And the analysis offered here also looks through other exogenous factors that might affect volatility of money market interest rates. This includes the effect of market stress due to banks' concerns around their counterparties' solvency or their own liquidity positions, as seen during the crisis.

The next section provides some background on money markets and central bank corridor systems. Section 3 introduces some of the regulations introduced in response to the crisis. Section 4 gives the setup of our baseline model of the money market, and some details of its parameterisation. The addition of prudential regulation into this framework is given in Section 5. Section 6 discusses the relevance of these results to policymakers. A final section concludes. Technical details and derivations are confined to the Annex.

2 Background on the overnight money market and the implementation of monetary policy

The sterling overnight money market plays an important role in the transmission of monetary policy in the United Kingdom. The Bank of England operates in the sterling money market in order to implement the interest rate decisions of the Monetary Policy Committee. It does so by seeking to maintain short-term interbank market interest rates between MPC meetings in line with Bank Rate, with little day-to-day or intraday volatility. In doing so, it seeks to establish the benchmark short-term risk-free rate, which forms the basis for other interest rates pertinent to the economy. Changes in overnight interest rates and changes in market participants' expectations of their future values affect longer-term interest rates. These in turn influence the cost of credit and prices of assets in the wider economy.

There are a number of ways in which central banks can seek to influence money market rates. We describe the system the Bank of England has chosen to do this before and after the start of the financial crisis, although many of these changes have been common to other central banks. For further details see Clews, Salmon and Weeken (2010).

The corridor system and reserves averaging (as operated by the Bank of England between 2006 and 2009)

Before the financial crisis, a number of central banks implemented monetary policy using a corridor system. Over each maintenance period, commercial banks had to meet reserves requirements or targets. Surplus reserves could be deposited at the central banks' standing facility where they were remunerated at a lower deposit rate. Banks with insufficient reserves to meet their target had to borrow the shortfall from the central bank lending facility, at a higher rate than the policy rate, in order to avoid a penalty. As commercial banks were typically unwilling to trade in the market at rates more punitive than those available from the central bank, these standing facilities provided a corridor within which overnight rates traded. So long as commercial banks' incentives to use either facility were, on average, broadly balanced overnight interest rates traded close to the middle of the corridor created by the borrowing and lending standing facilities. [3]

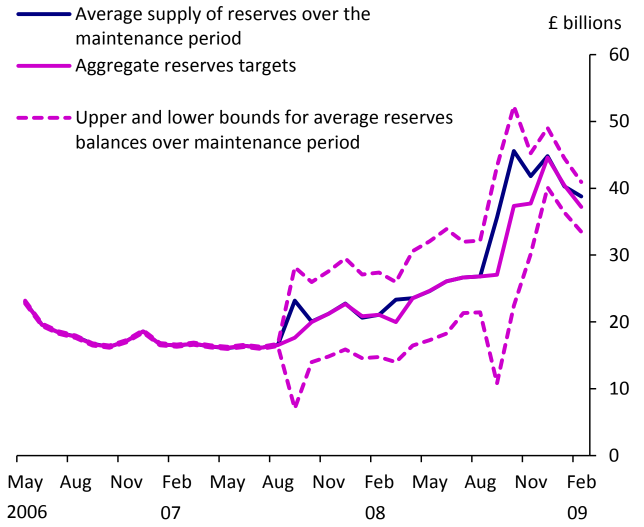
In the Bank of England's reserves averaging system, commercial banks set their own reserves targets for each month-long maintenance period between MPC meetings. The Bank of England aimed to supply an aggregate level of reserves equal to the sum of these individual targets. Banks could use a combination of the central bank's standing facilities and the private money market to manage their reserves balances to meet their targets. Reserves balances that were, on average, within a given range of these targets were remunerated at Bank Rate, but banks incurred a penalty rate on reserves balances above or below a range around their targets. Chart 1 shows a time series of commercial banks' aggregate total reserves target and the supply of reserves by the Bank of England between 2006 and 2009.

A stylised illustration of a commercial bank's demand schedule for reserves under a corridor system with reserves targets is shown in Chart 2. If, for example, a bank's reserves balance is low relative to target, it is willing to pay a higher rate in the private money market in order to gain additional reserves. But it would be unwilling to pay a rate higher than that at which it

[3] For a fuller discussion of the reserves averaging system, see Clews (2005).

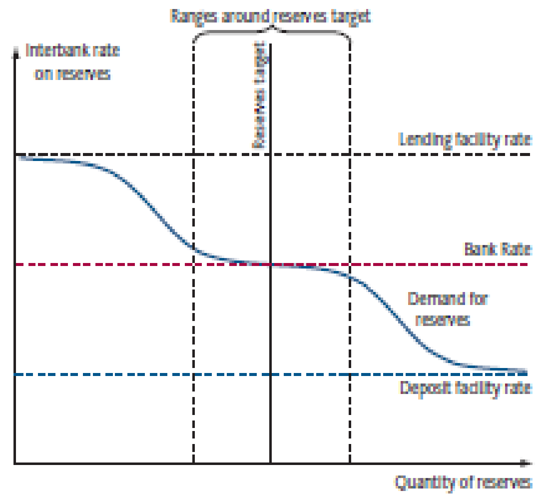
could borrow from the central bank's lending facility, shown by the higher of the three horizontal dotted lines in Chart 2. Similarly, if a bank has an excess of reserves relative to its target, it would be unwilling to lend at a rate below that which it could receive for placing reserves on the central bank's deposit facility (the lowest of the three horizontal dotted lines).

Chart 1 – Banks' aggregate reserves target and reserves supply by the Bank of England



Source: Bank of England.

Chart 2 – Commercial banks' demand schedule for reserves in a corridor system with reserves targets



Under the corridor system, banks are incentivised to trade with each other, rather than with the central bank, in order to meet their reserves targets provided interbank overnight interest rates traded within the corridor created by the standing facilities. The wider the corridor, the more costly it is for banks to meet their reserves targets using the central bank standing facilities and therefore the more banks are incentivised to use the market.

In the system of monetary policy implementation operated by the Bank of England pre-crisis, banks' reserves balances were remunerated at Bank Rate if they lay within a certain range around their reserves targets on average over the month. This range corresponds to the relatively flat portion of the demand curve in the centre of Chart 2. This section of the demand curve is flatter because, all else being equal, a wider target range reduces the likelihood of a bank needing to borrow from or lend to the central bank's standing facility.

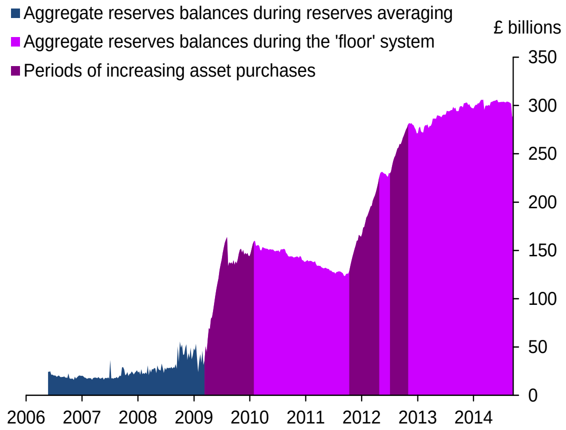
Widening the target range reduces the volatility of money market interest rates because banks' willingness to borrow or lend reserves is less sensitive to deviations in their individual reserves balances from target. But doing so also entails a reduction in banks' incentives to respond to fluctuations in their reserves balances by trading in the interbank market.

During the early phase of its reserves averaging system, the Bank of England operated with narrow ranges around reserves targets. But during the peak of the financial crisis, as the Bank supplied additional reserves on top of banks' voluntary reserves targets, the Bank significantly widened these target range from 1% up to 60% of banks' reserves targets (Chart 1).

The floor system (as operated by the Bank of England 2009-present)

With the onset of the financial crisis, many central banks revised their frameworks for implementing monetary policy. In particular, the Bank of England, along with other central banks, embarked on programmes of asset purchases financed by the creation of central bank reserves – or 'quantitative easing'. This resulted in a large and sustained increase in central bank reserves (Chart 3).

Chart 3 – Bank of England aggregate reserves balances



Source: Bank of England

Chart 4 – Commercial banks' demand schedule for reserves under a floor system

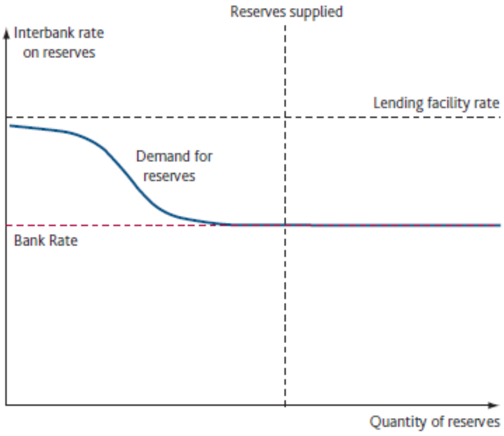
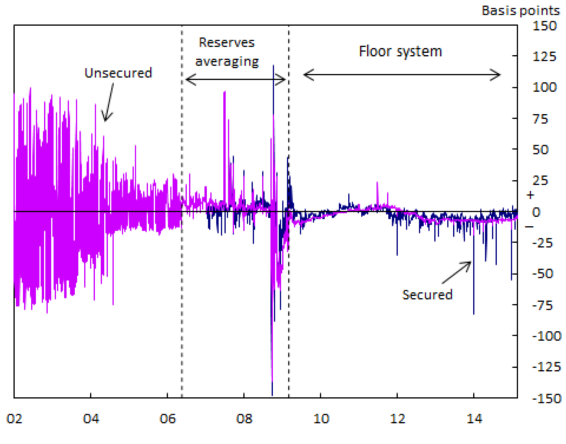


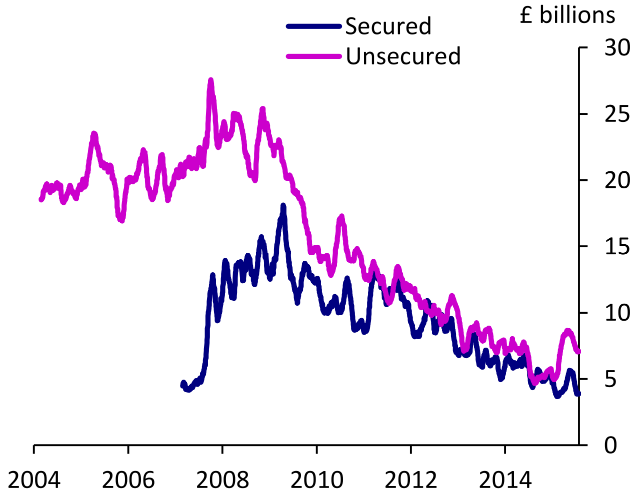
Chart 5 – The spread of unsecured and secured overnight interest rates to Bank Rate[(a)]



Sources: Wholesale Market Brokers' Association (WMBA) and Bank calculations.

(a) In the brokered secured market, interest rates are represented by the repurchase overnight index average (RONIA), which is the daily weighted average interest rate of transactions secured against UK government debt, brokered by members of the WMBA. Interest rates in the brokered unsecured market are represented by the sterling overnight index average (SONIA), which is the daily weighted average interest rate of unsecured overnight transactions brokered by WMBA members. For further details on RONIA and SONIA, see www.wmba.org.uk.

Chart 6 – Brokered unsecured and secured overnight money market turnover[(a)]



Sources: Wholesale Market Brokers' Association (WMBA) and Bank calculations.

(a) Secured is represented by turnover in the repurchase overnight index average (RONIA). Unsecured is represented by turnover in the sterling overnight index average (SONIA). For further details on RONIA and SONIA, see www.wmba.org.uk. 40-day moving averages of daily data.

At the same time, some central banks also suspended their corridor systems and instead implemented monetary policy through a floor system, in which either the deposit rate was set equal to the policy rate and/or all central bank reserves were remunerated at their policy rate.[4] In the case of the Bank of England, this was also accompanied by the suspension of banks' reserves targets. Such a floor system provides a minimum rate below which banks should be unwilling to lend reserves. In doing so, it allowed central banks to increase the aggregate supply of reserves without causing interest rates to deviate markedly from their policy rates. This 'floor' to interbank interest rates is shown by the flat portion of banks' demand for reserves at Bank Rate in Chart 4.

In the case of the Bank of England, the high level of aggregate reserves, combined with the introduction of this floor system, significantly reduced the volatility of sterling overnight interest rates (Chart 5). But the suspension of banks' reserves targets, combined with the high level of aggregate reserves, significantly reduced banks' incentives to trade reserves in the money markets in order to manage their day-to-day liquidity needs. This is one reason for the reduction in money market activity since 2009, as shown in Chart 6.[5]

Under the future normalisation of monetary policy, some central banks may ultimately decide to return to implementing monetary policy via a corridor system.[6] It is therefore important to consider what factors might cause the dynamics of interest rates to differ from those experienced under the corridor system that was operated pre- crisis.

3 The regulatory response to the financial crisis

The financial crisis led policymakers to introduce of a range of new prudential regulations designed to improve the resilience of the banking system. The reforms proposed by the Basel Committee on Banking Supervision – or Basel III – aim to improve the banking sector's ability to absorb shocks arising from financial and economic stress and so reduce the risk of spillovers from the financial sector to the real economy. The regulations have the potential to affect banks' incentives to borrow and lend in the interbank money market.

Two key components of the Basel III framework are its reforms to global capital and liquidity regulations. Early literature on the interaction of prudential regulation with the implementation of monetary policy focussed on the impact of liquidity regulation, and, in particular, the Liquidity Coverage Ratio (LCR). Bech and Keister (2013), for example, show

[4] The Bank of England suspended its reserves averaging scheme on 5 March 2009 when it started its purchase of assets financed by the creation of reserves. It suspended reserves targets and began remunerating all reserves at Bank Rate. The deposit facility rate was set to 0%, but was not used given all reserves were remunerated at Bank Rate.

[5] SONIA and RONIA measure only overnight trades made through brokers. The decline in the volumes of these measures is likely to exaggerate the overall decline in market activity, as contacts report that an increasing share of overnight money market activity takes place bilaterally rather than through brokers. See Jackson and Sim (2013).

[6] This issue is, for example, raised in Bank of England (2013) and Winters (2012).

how the LCR may influence banks' demand for reserves if banks are able to borrow reserves from the central bank – a high-quality liquid asset – against lower quality collateral. Where, however, the central bank standing facilities only offer reserves against high-quality collateral – as is the case with the Bank of England – banks' demand for overnight borrowing is unaffected.[7] Bonner and Eijffinger (2012) also provide empirical analysis of how the LCR might affect interbank markets by examining how banks responded to Dutch liquidity requirements. They find that the these liquidity requirements might cause banks to borrow and lend at higher interest rates on unsecured interbank transactions with a maturity greater than 30 days but have little/no effect on shorter-maturity interest rates.

The analysis offered here focuses on the potential impact of other new global regulatory requirements on banks' incentives for transacting in the overnight unsecured interbank money market. In particular, we examine the effects of:

- **Risk-based capital requirements:** the new Basel III reforms require banks to hold a higher quantity of capital against their assets, which are weighted by a measure of their perceived risk. In particular, banks can hold less capital against their exposures to the central bank than against their lending to other banks, as the latter are seen as riskier.[8]
- **The regulatory minimum leverage ratio:** leverage is the extent to which an institution chooses to fund itself through raising debt rather than capital. The Basel III reforms create a regulatory minimum leverage ratio that requires banks to hold Tier-1 capital equal to 3% of their assets and other exposures.[9]

4 The baseline model

4.1 Baseline model set-up

We first describe the behaviour of each individual bank in our baseline model, which is based on Poole (1968) and Whitesell (2006). Each bank must meet a target level of reserves at the end of the day. A bank is able to borrow and lend reserves in the private interbank money market to meet this target. But it is also subject to a payment shock late in the day, after the money market has closed. It is therefore only able to track its end-of-day reserves balance with the central bank with a margin of error. Although this is model of daily maintenance period, the incentives are likely to be broadly similar in a system in which banks' have to meet reserves targets over a longer maintenance period.

If, at the end of the day, the bank is above or below a given range of its reserves target, the bank must use the central bank standing facilities to decrease or increase its reserves balance

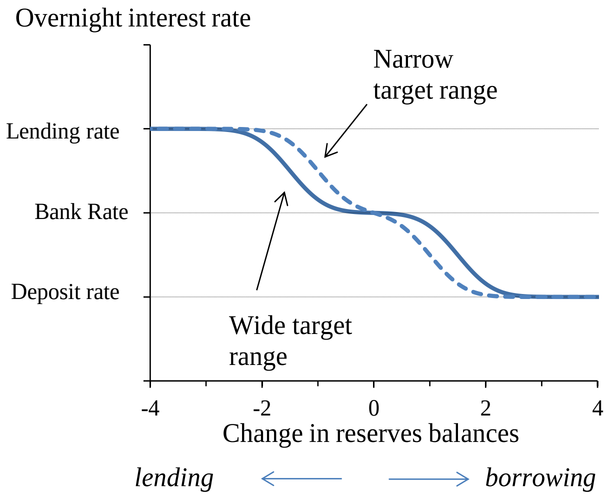
[7] This strictly applies when banks can borrow reserves overnight from the central bank against high-quality collateral with no haircuts. If the haircuts on high-quality of collateral are small, however, the effect of the LCR on incentives to borrow from the central bank may also be small.
[8] See http://www.bis.org/publ/bcbs189.pdf.
[9] International public disclosure of these ratios started in January 2015 and will come into force in January 2018 (see Bank of International Settlement (2013)). The Prudential Regulatory Authority in the United Kingdom has required the eight largest UK firms to meet minimum leverage ratios since January 2014.

such that it is within the target range. If the bank's reserves balance is within this range of its target, its reserves balances are remunerated at the main policy rate, Bank Rate.[10]

Faced with the uncertain payment shock after the end of interbank trading, the bank chooses its level of borrowing or lending in the money market in order to minimise the expected sum of two opportunity costs:

- The opportunity cost of ending the day with reserves in excess of its target range, and depositing those reserves at the central bank deposit facility. This opportunity cost is equal to the difference between what it would have earned from lending this amount in the market versus depositing it at the central bank.
- The opportunity cost of ending the day with a quantity of reserves short of its target range, and borrowing the difference from the central bank standing facility. This opportunity cost is equal to the difference between what it would have cost to borrow from the central bank versus from the money market.

Chart 7 – A single bank's demand schedule for borrowing/lending



Minimising the sum of these two expected opportunity costs gives the quantity of reserves a bank would want to borrow or lend at a given interbank interest rate. This schedule of interest rates and quantity of reserves is illustrated by the solid blue demand curve in Chart 7 (the technical details of its derivation are given in the Annex). The quantity of reserves a bank wishes to hold – and hence the amount of borrowing it wishes to perform given a certain reserves balance – is monotonically decreasing as a function of the market interest rate. This is because, at low interest rates, the opportunity cost to banks of not lending reserves in the market is low, so a bank chooses to hold more reserves. Conversely, banks choose to hold fewer reserves when interest rates are high because the opportunity cost of not having lent out reserves rises.

The flatter portion of the solid demand curve around the level of Bank Rate corresponds to the range around its reserves target within which a bank's reserves balance is remunerated at

[10] Implicitly, we assume there to be a large positive cost levied on banks failing to be within range of the reserves target. This cost is larger than that of the central bank's standing facilities; so banks always prefer using the central bank's standing facilities to missing their reserves targets.

Bank Rate (see Lee (2012)). Narrowing this target range decreases the width this flatter portion of the demand schedule (blue dotted line), for the reason set out in Section 2. This model is extended to incorporate multiple agents. It involves three stages:

i. Bank i starts with a reserves balances of $R_{i,0}$ equal to their individual reserves target K_i. There is then a shock, s, to the aggregate level of reserves. The effect of this shock on banks' reserves balances is proportional to each bank's target: banks with larger reserves balances are more affected by this shock than smaller ones. This shock reflects 'autonomous flows' (such as unexpected changes in commercial banks' demand for bank notes) that mean the central bank is only able to forecast commercial banks' aggregate demand for reserves with a degree of error.

ii. Each bank also experiences an idiosyncratic shock to their reserves balance, v_i. This reflects changes in their customer deposits that occur during the trading day. Unlike the previous shock to banks' aggregate reserves in (i), the idiosyncratic shocks do not affect the overall supply of reserves: one bank's unexpected loss of reserves is offset by other banks receiving positive payment shocks.

iii. Banks are then assigned to trade with another bank. Those that have fewer reserves than their target are matched to those that have an excess (if a bank cannot be matched - i.e. if there are more banks with a surplus than a deficit - then there is no trade). The matching of those with an excess to those with a deficit of reserves is random.[11] This system of 'directed search' - in which banks are assigned to other banks with which trade is feasible – can be seen as analogous to the brokered section of the money market (see Bech and Monnet (2013)).

iv. After trading an amount Δ_i, each bank receives an idiosyncratic late-in-the-day payment shock, ϵ_i. If after this shock their reserves balances does not equal their target, K_i, they must use the central bank's standing facilities either to borrow or lend reserves until their reserves balance is within a range of $\pm\, \alpha K$ of their target.

These steps are summarised in Figure 1.

When two banks meet, the quantity and interest rate at which they trade is determined by the point of intersection of the demand curve for borrowing (of the bank that is short reserves relative to its target) and the supply curve for lending (of that which holds an excess). Chart 8 provides an illustrative example:

- The bank represented by the blue line starts with its reserves balance on target and the red bank starts with a reserves balance £2 in excess of its target.

- The red bank is willing to lend some reserves at a rate below Bank Rate, while the blue bank would borrow some reserves at a rate below Bank Rate.

[11] A more complicated setup could match banks depending on the scale of the difference of their reserves balances and targets. We find that such a matching system does not make a significant difference to our end results.

- There are therefore gains from them trading. The amount they trade and the rate at which they do so is given by the intersection of the two curves. This occurs at the point at which the blue bank borrows £1 of reserves from the red bank. Though the blue bank is willing to borrow more than this amount, it would only do so at a lower rate than that at which the red bank is willing to lend.
- If the two banks' supply and demand curves do not intersect, then there is no interbank interest rate at which it is beneficial for both sides to trade. In this case, no trade occurs.

Chart 8 – Two illustrative banks' demand schedules for borrowing/lending

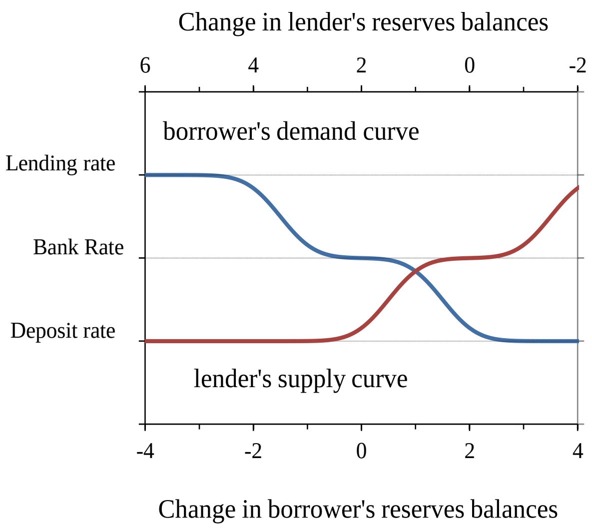


Figure 1 – A timeline of changes to bank *i*'s reserves balance

Time:	Start of day	Shock to aggregate reserve supply	Idiosyncratic reserves shock	Trades in interbank market	Late-in-day payment shock	End of the day
Reserves balance of bank i	$R_{i,0} = K_i$	$R_{i,0} + s_i$	$R_{i,0} + s_i + v_i$	$R_{i,0} + s_i + v_i + \Delta_i$	$R_{i,0} + s_i + v_i + \Delta_i + \epsilon_i$	$\{K_i(1+\alpha), K_i(1-\alpha)\}$

Note that by trading reserves at a price and quantity determined by the intersection of their demand and supply schedules, each pair of banks is left holding a quantity of reserves such that the marginal value they would ascribe to an extra unit of reserves is equalised.[12] The market therefore is a collection of bilateral markets, each of which gives rise to an equilibrium price. There is, however, no single equilibrium price that applies across the entire market simultaneously.

We assume for simplicity that banks are permitted only a single opportunity to trade. This could be seen as analogous to a system in which banks have to meet their target reserves balance over a short time horizon in which they have time to trade only once.

In reality, some central banks allowed banks to meet their reserves targets on average over a longer period of time. In the case of the Bank of England, banks had to meet their reserves

[12] This method of equalising marginal benefits of reserves yields the same equilibrium interest rate as that derived using a Nash bargaining approach, as in Bech and Monnet (2013), where both banks have equal bargaining power.

targets, on average, over the month-long period between meetings of the Bank's Monetary Policy Committee. This allowed banks greater flexibility in managing their reserves account balance than if they had to meet their reserves target every day. In particular, on any given day, banks were able to hold a reserves balance which was above or below their target and, in doing so, take advantage of any divergence between market interest rates and the rate expected on the remaining days of the maintenance periods. All else being equal, this might have decreased the volatility of money market interest rates. The treatment offered here, might, however, speak to the behaviour of interest rates on the final day of such a longer maintenance period.[13]

4.2 Parameterising the model

To illustrate the potential applications of the model, we apply it to a set of hypothetical data of commercial banks' reserves balances with the central bank.

On each simulated 'day', each bank receives a random idiosyncratic payment shock (see step ii above) to its reserves balance that moves that balance away from the bank's reserve target. These shocks across banks are also negatively correlated, reflecting how the total quantity of reserves in the system must remain the same after the shocks to individual banks' reserves account balances: if one bank experiences an outflow of reserves, other banks must experience an inflow of reserves.

The standard deviation of these shocks varies between banks and is proportional to the size of their initial reserves balances. This reflects how larger banks are likely to experience larger changes in their reserves balance given their exposure to a larger constellation of customer payment flows. Each bank is aware of the average volatility of the changes in their reserves account balance, and uses this to determine their demand and supply schedule for borrowing/lending reserves (see Annex for details).

Shocks to the *aggregate* level of banks' reserve balances – which reflect how the central bank may make errors in its supply of reserves (see step i above) – are assumed to be normally distributed, with mean zero and a standard deviation equal to 1% of the aggregate level of reserves. They are applied in proportion to each banks' reserves balance.

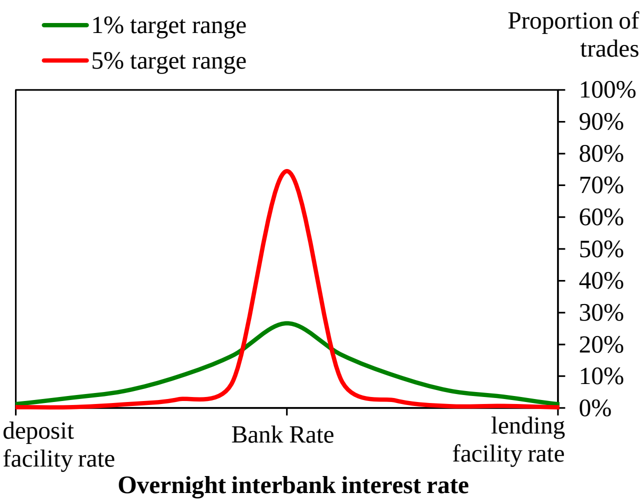
For the sake of illustration, in what follows, the interest rates on the central bank deposit and lending facilities are set 25 basis points above and below Bank Rate. This corresponds to the width of the corridor used by the Bank of England on the last day of each maintenance period when it operated a corridor system between 2006 and 2009.[14]

[13] See MacGorain (2005).
[14] Between 2008 and October 2008, on all other days of the maintenance period, the interest rate on the standing facilities operated by the Bank of England was set 100 basis points above and below its policy rate. Between October 2008 and March 2009, the corridor was set at 25 basis points at all time. For further details, see Clews, Salmon and Weeken (2010).

We first consider a baseline case without regulation that might affect banks' behaviour. Chart 9 shows a histogram of all traded interest rates generated over the 500 'days' of hypothetical data, across the cross-section of banks. This is shown for two different choices of the range around their target balance within which reserves are remunerated at Bank Rate: firstly, under a 1% target range (green line), interest rates are distributed widely across the interest rate corridor, but with a mean of a zero spread to Bank Rate. Note that this shows the cross-section of interest rates traded over every 'day'.

In the presence of a wider 5% target range (red line), the distribution of rates is more highly concentrated around Bank Rate. This reflects how the widening of this range reduces the probability with which banks need to use the central bank's standing facilities; that is, the proportion of shocks that might take a bank's reserves balance outside of the target range becomes smaller the wider is the target band.

Chart 9 – Histogram of traded interest rates across the cross-section of banks: Baseline case



Although widening the target range decreases the variance of the distribution of traded interest rates, doing so comes with the caveat that a wider target range reduces banks' incentives to use the interbank market to manage their reserves balance. This is because when the target range is wide the probability of a banks' reserves balance being outside this range is low, and so banks have less incentive to manage their reserves balance and keep it close to their targets. The central bank, however, may prefer banks to manage fluctuations in their liquidity through the private market rather than across its balance sheet. In choosing to widen its target range, a central bank therefore faces a trade-off between reducing the volatility of market interest rates and reducing the volume interbank money market activity.

5 Adding the effects of prudential regulation

This section examines how two pieces of regulation – risk-weighted capital requirements and the regulatory minimum leverage ratio– affect banks' incentives to trade in the interbank money market. Technical details and derivations of these effects are again confined to the Annex.

For each regulation, results take two forms. Firstly, we show the reserves demand schedule of a single representative bank and how this changes under the effect of the regulation in question. Second, we examine the distribution of estimated traded overnight interbank interest rates that results from banks' interactions in the multi-agent model. This involves a comparison of the distribution of traded interest rates across the cross-section of banks for the baseline case (described in Section 4, and shown in Chart 9) with that capturing the effect of prudential regulation.

Note that, in practice, some central banks have monitored not the distribution of the intra-day traded interest rates on a given day, but rather the distribution of the daily average of traded interest rate and how this changes over time. In what follows, however, we show the distribution of traded interest rates across the entire cross section of banks, as in Chart 9. This is in part in the interests of completeness, given that the model offered here affords insight into this distribution that would be masked by the reporting only of its average. Changes in the distribution of the cross section of traded interest rates will also be mirrored in changes to the distribution of their daily averages, even though the latter will typically be on a smaller scale.

5.1 Risk-weighted capital requirements

When a bank lends reserves in the interbank money market, it swaps one type of exposure – that to the central bank, in the form of reserves – for another, in the form of an interbank loan. Whereas the bank needs to hold capital against the latter exposure under risk-weighted capital requirements, it is assumed not to have to hold capital against its exposures to the central bank. The act of lending in the interbank market therefore increases the capital is it required to hold to meet its risk-weighted capital requirement.

Throughout what follows, it is assumed that this need for additional capital imposes a cost on banks, which they seek to recoup by adjusting the rate at which they are willing to lend. Banks' cost of capital – and the degree to which banks might seek to recoup this cost in adjusting the rates at which they are prepared to borrow/lend – is likely to vary considerably across institutions and across time. For example, banks that are closer to their minimum capital ratio might be more likely to pass on capital costs associated with new lending than banks that have capital ratios well in excess of their regulatory minimum.

Reflecting this uncertainty, and exploiting the heterogeneity between banks incorporated within this framework, the cost that banks are assumed to incur in raising the capital against their lending is allowed to vary across institutions. For the purposes of illustration, it is assumed that, in raising capital to meet their risk-weighted capital requirements, banks incur a random cost that is uniformly distributed within a range of 0 to 25 basis points. The upper end of this range is derived from recent estimates of the cost of capital of UK banks that are around 10%.[15] This, combined with an assumed minimum capital ratio of 8% and a risk-

[15] See Bank of England (2011).

weight on unsecured interbank lending of 30%,[16] produces a upper capital cost of around 25 basis points.

Chart 10 shows the effect this cost of meeting the risk weighted capital requirement has on a representative bank's reserves demand schedule (under the assumption that the bank's current reserves balance equals its reserve target). The cost a bank associates with risk-weighted capital requirements results in an upward shift in the portion of the bank's reserves demand curve corresponding to the rates at which it is prepared to lend (the left-hand portion of the solid line in Chart 10). The discontinuity in the reserves supply schedule, at the point of zero borrowing/lending, reflects the fact that risk-weighted capital requirements affect the rate at which a bank is willing lend, but not that at which it is willing borrow. This is because borrowing results in an additional exposure only to the central banks, which is assumed to carry a zero risk-weight.[17]

Widening the target range reduces the probability that a bank will require use of the central bank's standing facilities. This increases its willingness to increase or decrease its reserves balance relative to its target. In turn, this reduces the degree to which the interest rates must deviate from the central bank policy rate in order to incentivise banks to borrow or lend reserves. This results in a flattening of its reserves demand schedule (dotted line in Chart 10).

Chart 10 – The effect of risk-weighted capital requirements on a bank's reserves demand schedule

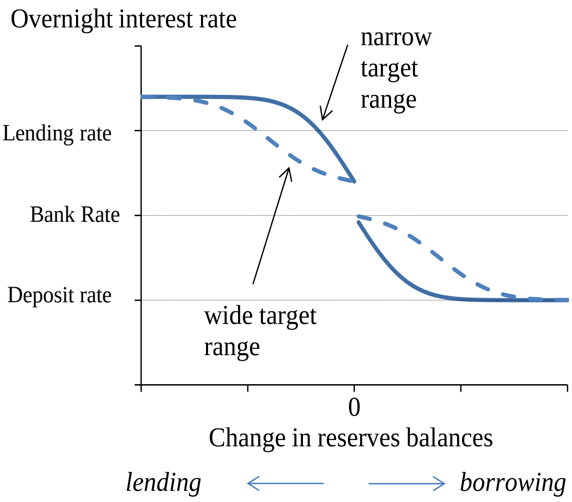
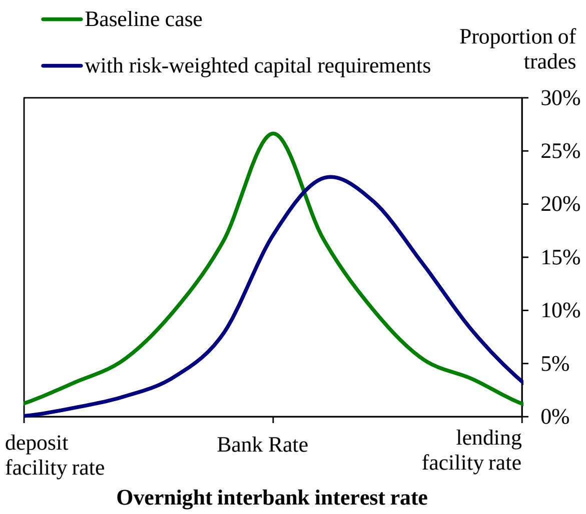


Chart 11 – Histogram of estimated traded rates: risk-weighted capital requirements



The effect of risk-weighted capital requirements on the cross-sectional distribution of simulated traded overnight interest rates is shown in Chart 11. This increases the average overnight interbank interest rate, causing the distribution of traded interest rates to shift

[16] See Bank for International Settlements (2011).

[17] This discontinuity introduces the possibility that a lender's and borrower's curve will not intersect. In this instance, it is in neither bank's interest to trade and so no trade occurs.

rightwards (blue line) relative to the baseline case without the effects of regulation (green line). Costs associated with the risk-weighted capital requirement also narrow the distribution of traded interest rates, as capital costs associated with lending increase the minimum rate at which a bank will lend.

Note, however, that although risk-weighted capital requirements lead banks to demand rates exceeding those the central bank's lending facility on their lending, no bank is willing to borrow at these rates – because it can borrow from the central bank more cheaply. This means that the range of traded interest rates remains bound by the central bank corridor, but that the introduction of regulation may decrease the volume of interbank trading.

5.2 Regulatory minimum leverage ratio

In contrast to the effects of risk-weighted capital requirements, the act of lending doesn't affect a bank's capital requirements under the regulatory minimum leverage ratio. This is because the act of lending reserves to another bank results in one exposure (i.e. central bank reserves) being replaced by another (i.e. a loan to another bank). As the regulatory minimum leverage ratio does not differentiate between these two exposures, this lending leaves banks' capital requirements unchanged.

Borrowing in the interbank market, however, expands a bank's balance sheet, creating a new exposure to the central bank. The regulatory minimum leverage ratio stipulates that a bank must hold capital against this exposure, thus introducing a potential additional cost to interbank borrowing. Note that throughout it is assumed that the regulatory minimum leverage ratio enters banks' decision-making as an exogenous cost independent of their reserves balance or reason for their borrowing. This may overstate its impact. Suppose, for example, that a bank suffers an unexpected fall in its reserves because a customer withdraws its deposits. All else being equal, this would increase its regulatory leverage ratio. If the bank were to borrow the interbank market to correct for this shock and increase its reserves balance, this would reduce its leverage ratio but only to the level before the unexpected withdrawal of customer deposits. In this case, the bank may choose not to factor in the cost of the leverage ratio on that interbank borrowing. A more sophisticated calibration or modelling of the leverage ratio effect might use this intuition to loosen the assumption that the leverage ratio cost is independent of the bank's reserves balance.

As before, we assume that this capital is costly to source, and that the cost experienced by individual banks in doing so is distributed uniformly distribution between 0 and 25 basis points, the same as for risk-weighted capital requirements. This may not be an unreasonable possible range: for instance, given that the internationally agreed regulatory minimum leverage ratio is currently set at 3%[18] - and, once again assuming banks to face a 10% cost of capital – the maximum cost would be around 30bps.

[18] See Bank for International Settlement (2014).

As interbank borrowing is now more costly, it reduces the interest rates required to incentivise a bank to borrow a given quantity of reserves. This leads to a downward shift in the right-hand portion of a bank's reserves demand schedule (solid line in Chart 12): a lower market interest rate is now required to incentivise a bank to perform a given level of borrowing in the interbank market.

The minimum leverage ratio also leads to an upwards shift in the left-hand portion of a bank's reserves demand schedule, corresponding to its willingness to lend reserves (Chart 12). This is because the minimum leverage ratio also makes borrowing from the central bank's standing facility more costly. In turn, this increases the expected cost of a bank ending the day with a shortage of reserves and so needing to use this facility. A bank therefore requires a higher interest rate to induce it to lend out its reserves. As the target range widens, the probability of needing to borrow from the central bank falls, implying that a bank would become more willing to lend out reserves. The widening of the target range therefore reduces this upwards bias to the bank's demand curve.

Chart 12 - The effect of the minimum leverage ratio on a bank's reserves demand schedule

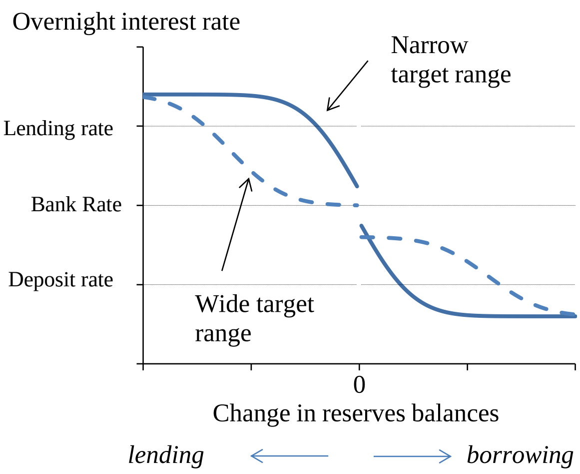
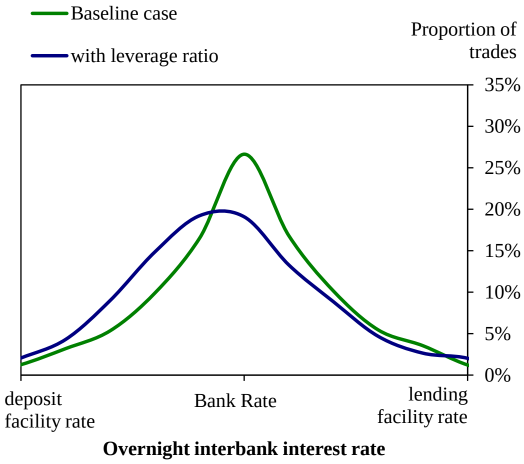


Chart 13 – Histogram of traded interest rates under the regulatory minimum leverage ratio



The overall impact of these two effects on traded overnight interbank interest rates is to bias them below the central bank policy rate, as shown in Chart 13. This is because while the cost from the minimum leverage ratio associated with interbank borrowing – which pushes down on interest rates – is certain, the probability of incurring the cost from the minimum leverage ratio associated with borrowing from the central bank – which pushes up on rates – is less than one. The former effect is therefore stronger and average overnight interest rates are biased below the central bank policy rate. This also implies that the effect of the minimum leverage ratio on banks' incentives both to borrow and lending is not symmetrical to that of the upward bias in interest rates associated with risk-weighted capital requirements, shown in Chart 11. This is because, while the minimum leverage ratio affects the cost of borrowing both from other banks and the central bank, risk-weighted capital requirements only affect the cost of lending to other banks. But, as the target range widens and reduces the probability that a bank will need to borrow from the central bank, the effects of the two regulations become more symmetric.

5.3 Summary of the effects of these prudential regulations

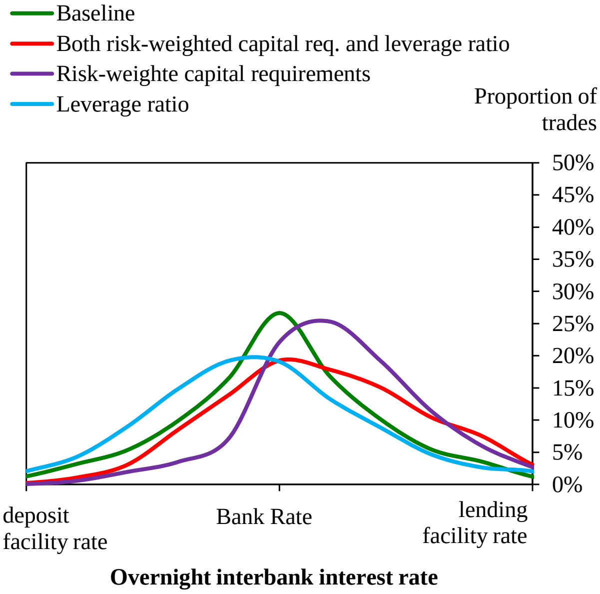
These results demonstrate how recent prudential regulations might affect the dynamics of traded overnight money market interest rates (for on a given set of assumptions about the costs they impose on banks). Together they suggest that:

- The extra costs that prudential regulation might introduce on banks' borrowing and lending might bias overnight interest rates away from central banks' policy rates, but in different directions:
  - Risk-weighted capital requirements *increase* the average traded interest rate relative to the central bank's policy rate. This is because – in extending an interbank loan – a bank swaps one exposure (to the central bank, in the form of reserves) for another - in the form of an exposure to a private bank, with the latter carrying a higher risk weight.
  - In contrast, the regulatory minimum leverage ratio *decreases* the average traded interest rate relative to the central bank's policy rate. This is because borrowing reserves in the interbank market increases a bank's total exposure, against which it may be required to hold more capital.

Both regulations – and their associated costs - also reduce the range of rates within which banks are willing to trade in the interbank market. Costs associated with lending imply that banks are no longer willing to lend in the private market at rates close to the bottom of the central bank corridor, while costs associated with borrowing reduce the maximum rate at which banks will borrow.

The discussion above treated the effect of each regulation in isolation. Chart 14 also compares the impact of each regulation (blue and purple lines) against the aggregate effect of both (red line).

Chart 14 – Histogram of traded overnight rates: combined effects of regulation



Two effects can be observed. First, the distribution of traded interest rates under the combined effect of regulation is slightly skewed towards the interest rate on the central bank lending facility. As discussed above, this reflects the fact that – for the same cost of capital –

risk weighted capital requirements have a slightly larger effect on overnight interests than does the regulatory minimum leverage ratio.

Second, the distribution of interest traded rates under the combined effects of both regulations is wider than that under the effect of only a single regulation (or in the baseline case). This reflects that the regulation introduces additional costs to both borrowing and lending, such that the distribution of traded rates is wider.

6 Policy Implications

The model offers some insights into how central bank policymakers could – if they so chose – vary the design of a corridor system in order to counteract (at least partially) the aggregate effects of prudential regulation on overnight interest rates. This section focuses on two such possible variations.

- First, an increase in the target range within which banks may meet their reserves targets. As described in Section 2, all else being equal, this reduces the volatility of overnight interest rates.
- Second, the introduction of an asymmetry into the central bank corridor, so that the interest rate at which the central bank is prepared to borrow/lend are at different distances from the policy rate. This could potentially counter any bias in the average interest rate introduced by the effects of prudential regulation.

6.1 Changing the target range

Chart 15 illustrates the effect of widening the target range from 1% to 5% in the presence of risk-weighted capital requirements. Increasing the width of the target range from 1% (blue line) to 5% reduces the dispersion of the cross-sectional distribution of traded interest rates (pink line). In contrast to the baseline case in Chart 9, however, the distribution of traded rates is now centred on a level equal to the policy rate plus the assumed cost to the bank of meeting the risk-weighted capital requirement.

Chart 16 considers the same adjustment to the target range but in the presence of the regulatory minimum leverage ratio. Widening the target range from 1% (blue line) to 5% (pink line) reduces the probability that a bank will require the use of the central bank's standing facilities. As in the case of risk-weighted capital requirements, this reduces banks' need to borrow or lend in the money market and hence reduces the dispersion of traded overnight interest rates.

Chart 15 – Histogram of traded interest rates under risk-weighted capital requirements and different target ranges

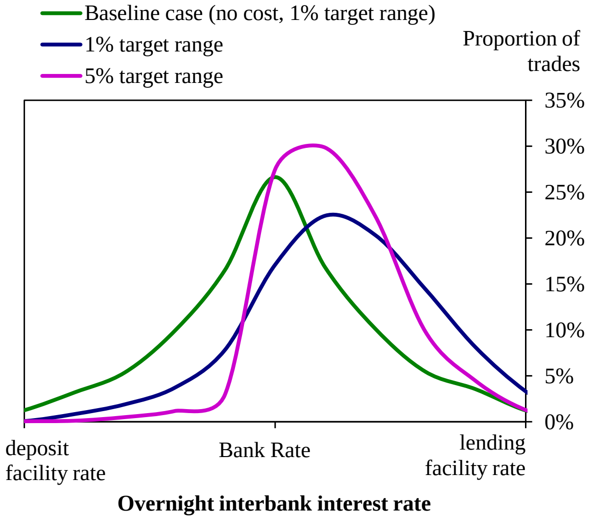
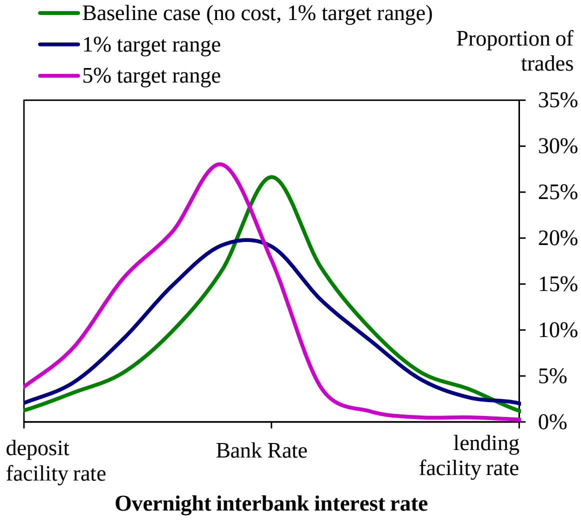
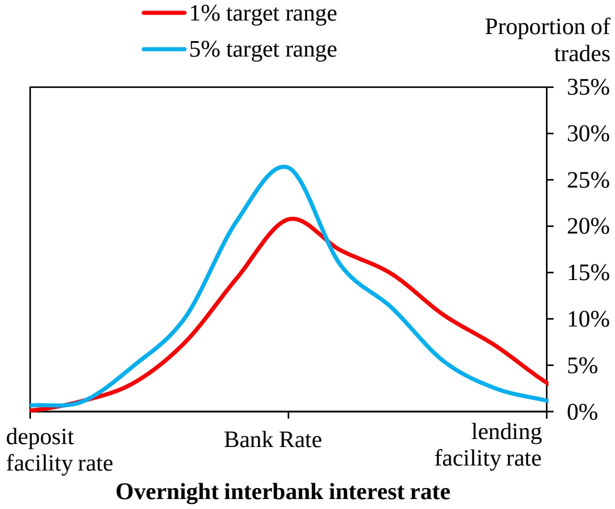


Chart 16 – Histogram of traded interest rates under the regulatory minimum leverage ratio and different target ranges



Finally, Chart 17 considers the impact of widening the target range in the presence of both risk-weighted capital requirements and the regulatory minimum leverage ratio. With a narrow target range, the effects of risk-weighted capital requirements are stronger than those of the leverage ratio. But with a wide target range, the effects of risk-weighted capital requirements and the leverage ratio are broadly balanced, and the resulting distribution centres more closely on the policy rate. This is because the minimum leverage ratio makes borrowing from the central bank more costly, reducing banks' willingness to lend out reserves. A wider target range, however, reduces the probability that a bank will need to borrow from the central, therefore making banks' more willing to lend reserves in the interbank market, which pushes down on overnight interest rates.

Chart 17 – Histogram of estimated traded rates: combined effects of regulation



6.2 An asymmetric corridor

Pre-crisis, central bank corridor systems – including that operated by the Bank of England – often set the interest rates on the lending and deposit facilities at an equal distance above and below the central bank policy rate. As the incentives for banks to hold reserves in a quantity less or greater than their targets were broadly balanced, this ensured that interbank interest rates traded around the policy rate at the middle of the corridor.

If prudential regulation were to affect the relative incentives for banks to hold a reserves balance below or above their target, then these incentives may no longer be balanced. One way to offset this – if central banks so chose – might be to introduce an asymmetry in the difference between the interest rates offered on the lending and deposit facilities.

Risk-weighted capital requirements increase the cost of lending reserves in the interbank market. This reduces the opportunity cost of a bank holding an excess of reserves relative to their target, causing interest rates to be biased to level above the central bank policy rate. This effect may be partly offset by either reducing the interest rate on either the deposit facility (in order to introduce an extra cost to holding an excess of reserves), or on the lending facility (reducing the cost associated with holding a quantity of reserves below target).

Chart 18 shows the effect on the distribution of traded interest rates of introducing an asymmetry into the corridor, in the presence of risk-weighted capital requirements. The effects of two asymmetries are shown: one in which the deposit rate is decreased by 10 basis points (purple line) and one where the lending rate is reduced by 10 basis points (green line). In either case, the bias of overnight interest rates introduced by the regulation is reduced, and the mean of the distribution returns to a level commensurate with the policy rate.

The effect on the overall distribution of interest rates is subtly different in either case, however. Reducing the interest rate on the deposit facility rate widens the range of interest rates at which banks find it economic to trade, increasing the negative skew of the distribution. In contrast, reducing the rate on the lending facility rate has the effect of compressing the distribution to a level closer to the policy rate. Correspondingly, a reduction in the rate on the deposit facility might incentivise greater interbank trading than would a reduction in that on the lending facility.

The regulatory minimum leverage ratio increases the cost of borrowing, as it requires banks to hold capital against all exposures. This reduces the average overnight interest rate. Chart 19 shows how this could be offset either by increasing the interest rate on the deposit or lending facilities. Both adjustments increase the average interest rate, offsetting the downwards bias. But, once again, each has different implications for the shape of the overall distribution. An increase in the deposit rate compresses the distribution, while the increase in the lending facility increases its skew, suggesting that the latter adjustment may incentivise a greater volume of money market transactions, albeit at the cost of greater interest rate volatility.

Chart 18 – Histogram of estimated traded rates in the presence of risk-weighted capital requirements, and under an asymmetric corridor

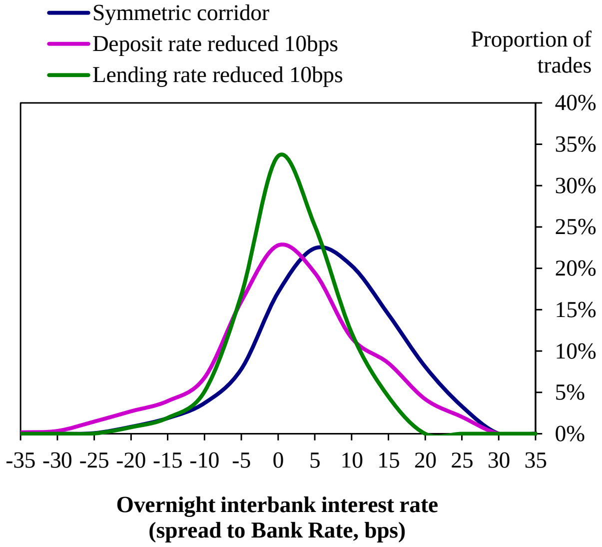
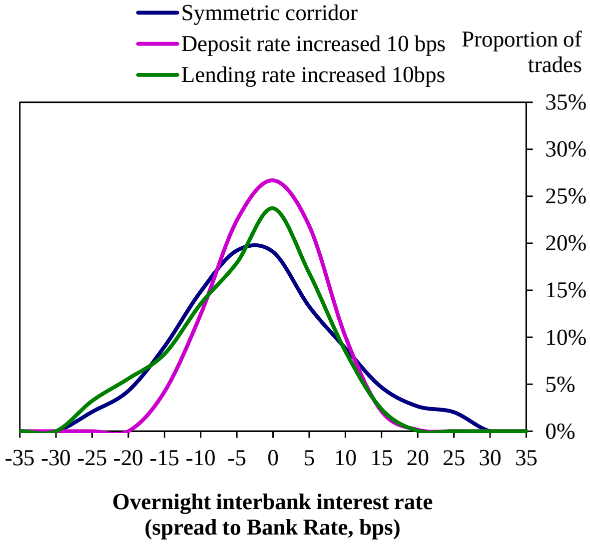


Chart 19 – Histogram of estimated traded rates in the presence of the minimum leverage ratio, and under an asymmetric corridor



7 Conclusion

This paper offers a framework through which to explore the possible effects of capital regulation on the dynamics of overnight interest rates, under a corridor system for implementing monetary policy. Its indicative results suggest that the combination of the risk-weighted capital requirements and the regulatory minimum leverage ratio can affect the range and volatility of interest rates that are traded in the interbank overnight money market.

These results have two key policy implications. First, they allow policymakers some insight into the possible dynamics of market interest rates under a potential future return to the corridor system in the presence of prudential regulation. Second, by calibrating the model to real-world data on banks' cost of capital and reserves balances, it may provide insights into how policymakers could – if they so choose – vary the design of a corridor system in order to counteract the effects of prudential regulation on overnight interest rates.

The work offered here gives rise to a number of possible future extensions. One example would be extending the model to include the possibility of multiple trading periods. This would allow the model to capture the dynamics of interest rates under a system of reserves averaging, where banks would have to meet reserves targets on average over each month. Such extensions are, however, left to further work.

References

Afonso, G, and Lagos, R (2014), 'An Empirical Study of Trade Dynamics in the Interbank Market', *Federal Reserve Bank of New York Staff Reports, No. 550*.

Bank of England (2011), *Financial Stability Report*, No. 30.

Bank for International Settlement (2011), 'Basel III: A global regulatory framework for more resilient banks and banking systems'.

Bank for International Settlement (2014), 'Basel III leverage ratio framework and disclosure requirements'.

Bank for International Settlement (2013), 'Supervisory framework for measuring and controlling large exposures: consultative document'.

Bech, M and Keister, T (2013), 'Liquidity regulation and the implementation of monetary policy', *BIS Working Paper No. 432*, Bank for International Settlements.

Bech, M and Monnet, C (2013), 'The Impact of Unconventional Monetary Policy on the Overnight Interbank Market', published in Heath, Lilley and Manney (ed.) (2013), *Liquidity and Funding Markets*, Reserve Bank of Australia.

Bonner, C and Eijffinger, S (2012), 'The Impact of the LCR on the Interbank Money Market', *DNB Working Paper No. 364*.

Clews, R (2005), 'Implementing monetary policy: reforms to the Bank of England's operations in the money market', *Bank of England Quarterly Bulletin*, pages 211–220.

Clews, R, Salmon, C and Weeken, O (2010), 'The Bank's money market framework", *Bank of England Quarterly Bulletin*, Vol.50, No.4, pages 292-301.

Hauser, A (2013), 'The five ages of (sterling) man: prospects for the UK money market', speech at London Money Market Association, 13 June 2013.

Jackson, C, and Sim, M (2013), 'Recent developments in sterling overnight money markets', *Bank of England Quarterly Bulletin*, Vol.53, No.3, pages 223-231.

Lee, J (2012), 'Corridor system and overnight interest rates: volatility and potential asymmetry', mimeo.

Poole, W (1968), 'Commercial bank reserve management in a stochastic model: implications for monetary policy', *Journal of Finance*, 23, pages 769-791.

Whitesell, W (2006), 'Interest rate corridors and reserves', *Journal of Monetary Economics*, 53, pages 1177-1195.

Winters, B (2012), 'The Bank of England's framework for providing liquidity to the banking system'.

Technical Annex

A1 Baseline model

We begin with an exposition of the standard model, as given in Whitesell (2006). Under this setup, a single representative risk-neutral bank i begins the day with reserves R_i. At the end of the day it must meet a reserves target K_i on which it is remunerated at Bank Rate r_R. During the day, the bank chooses to lend amount L_i in the money market (or borrow, if this amount is negative) at an interbank overnight interest rate of r, and does so to target an end-of-day balance K_i.

But because the bank is subject either to unexpected late payment shocks (that occur after the interbank market has closed), or delayed accounting information, it can determine its end-of-day position only within a margin of error given by the stochastic term, ε_i, where $E(\varepsilon_i) = 0$. The distribution of ε_i is given by the cumulative probability distribution function, F_i.

If the bank's end of day balance, $R_i - L_i + \varepsilon_i$ exceeds requirement K_i, that is $R_i - L_i - K_i + \varepsilon_i > 0$, then it earns interest at the central bank's deposit facility at rate $r_r - s_d$ on those reserves in excess of the requirement. If it falls short of this requirement, then the bank must borrow to meet this shortfall at the lending facility, at rate $r_r - s_l$. The corridor is symmetric when the interest rates on each standing facility are set are equal spreads to the policy rate, such that $s_d = s_l$.

With full information the bank would set its lending so as to meet its reserves target exactly; that is, set $L_i = R_i - K_i + \varepsilon_i$. But in the absence of full information, bank i chooses its level of interbank lending L_i to minimise its expected costs:

$$L_i = argmin \left\{ -rL_i - \int_{K_i - R_i + L_i}^{\infty} (r_R - s_d)(R_i - L_i - K_i + \varepsilon) dF_i(\varepsilon_i) - \int_{-\infty}^{K_i - R_i + L_i} (r_R + s_l)(R_i - L_i - K_i + \varepsilon_i) dF_i(\varepsilon_i) \right\}; \quad (1)$$

where:

- The first term represents the bank's cost from borrowing in the interbank money market;
- The second term is the expected return from reserves deposited in the central bank's deposit facility;
- The third term represents the expected cost of borrowing from the central bank's standing facility for a given choice of L_i.

Note that bank i's cost minimisation problem can also be rewritten as that involving the minimisation of the sum of the expected opportunity costs of being short and long reserves; that is as:

$$L_i = \arg\min \int_{K_i - R_i + L_i}^{\infty} \big(r - (r_R - s_d)\big)(R_i - L_i - K_i + \varepsilon_i) dF_i(\varepsilon_i) - \quad (2)$$

$$\int_{-\infty}^{K_i - R_i + L_i} \big((r_R + s_l) - r\big)(R_i - L_i - K_i + \varepsilon_i) dF_i(\varepsilon_i).$$

The first term integrand captures the bank's opportunity cost in the case where it ends the day with reserves in excess of its target (the payment shock ε is greater than $K_i - R_i + L_i$, the lower integration limit). The second term captures the bank's opportunity cost in the case where it ends the day with reserves less than its target (that is, the payment shock ε is less than $K_i - R_i + L_i$, the upper integration limit).

Taking the first order condition with respect to the bank's choice of lending, L_i, gives a first order condition expressing the resulting interest rate r as a function of the bank's optimal choice of lending, L_i*:

$$-(\mathrm{r} - (\mathrm{r_R} - s_d))[F_i(\infty) - F_i(K_i - R_i + L_i{}^*) \quad (3)$$
$$+((r_R + s_l) - r)[F_i(K_i - R_i + L_i{}^*) - F_i(-\infty)] = 0.$$

Rearranging terms, gives:

$$r - r_R = \mathrm{s_d} F_i(K_i - R_i + L_i{}^*) + \mathrm{s_l} F_i(K_i - R_i + L_i{}^*) - s_d. \quad (4)$$

If the corridor is symmetric, such that $s_d = s_l = s$, equation (4) can be simplified to:

$$r - r_R = 2sF_i(K_i - R_i + L_i{}^*) - \mathrm{s}$$

By way of intuition, note that if the market rate equals Bank Rate then, for a symmetric distribution of expected shocks F_i, $F_i(K_i - R_i + L_i^*)$ = 0.5, which can occur only if $L_i^* = K_i - R_i$; that is the representative bank begins the day with reserves exactly equal to their target (with no need to borrow/lend).

A2 The effects of the regulatory minimum leverage ratio and risk-weighted capital requirements

As described in Section 5, the regulatory minimum leverage ratio and risk-weighted capital requirements affect the relative opportunity costs a bank experiences if it ends the day with an excess/shortage of reserves relative to target. The minimum leverage ratio adds a fixed extra cost to all units of borrowing, regardless of whether this borrowing is from the private market or the central bank. Here we assume the cost of the minimum leverage ratio to bank *i* is a positive constant value c_{i1}.

Risk-weighted capital requirements impose an upfront cost to banks' lending in the interbank market, but not to that to the central bank. We assume that this capital cost associated with risk-weighted capital requirements is a constant value of c_{i_2}.

Each bank's reserves balance, distribution of payment shocks and costs of raising capital to meet the risk-weighted capital and minimum leverage ratio requirements also vary between banks.

Incorporating the effects of the regulatory leverage ratio and risk-weighted capital requirements into equation (1) gives the following minimisation problem for bank *i*:

$$\mathrm{L_i}^* = \arg\min -c_{i_1}\mathrm{L_i}_{[\mathrm{L_i}<0]} + \mathrm{c_{i_2}}\mathrm{L_i}_{[\mathrm{L_i}>0]} + \int_{\mathrm{K_i}-R_i+L_i}^{\infty}\big(r-(r_R-s_d)\big)(R_i-L_i-K_i+\varepsilon_i)dF_i(\varepsilon_i) - \int_{-\infty}^{K_i-R_i+L_i}\Big(\big(r_R+s_l+c_{i_1}\big)-r\Big)(R_i-L_i-K_i+\varepsilon_i)dF_i(\varepsilon_i); \quad (5)$$

The first term in equation (5) reflects of the cost c_1 associated with the meeting the regulatory minimum leverage ratio that applies to a bank's interbank borrowing (or negative lending, for which L<0).

The second term reflects the cost c_2 associated with risk-weighted capital requirements that applies to any positive amount lent in the interbank (for which $L_i > 0$). But because risk-weighted capital requirements do not apply to a bank's lending to the central bank, there is no cost associated with depositing reserves with the central bank (the third term). By contrast, the minimum leverage ratio does impose a cost to borrowing from the central bank. The cost to borrowing from the central increases by c_1, increasing the opportunity cost of ending the day with a shortage of reserves.

Taking the first order condition with respect to L_i gives:

$$-\mathrm{c_{i_1}}_{[\mathrm{L}<0]} + c_{i_2\,[\mathrm{L_i}>0]} - (r-(r_R+s_d))\big(1-F_i(K_i-R_i+L_i{}^*)\big) + (\big(r_R+s_l+c_{i_1}\big) - r)(F_i(K_i-R_i+L_i{}^*) = 0; \quad (6)$$

From which we get:

$$r - r_R = -s_d - c_{i_1\,[\mathrm{L_i}<0]} + c_{i_2\,[\mathrm{L_i}>0]} + (s_d+s_l+c_{i_1})F_i(K_i-R_i+L_i{}^*). \quad (7)$$

A3 Adding bands around the bank's reserves target

Now assume that banks are allowed to meet their reserves target *k* with some margin of tolerance, $\alpha > 0$; that is, as long as their end-of day reserves remain with the target range [(1-α)K, (1+ α)K], banks do not have to make use of standing facilities. But if reserves R_i - L_i – K_i + ε_i are larger than (1+ α)K, or smaller than (1- α)K_i, they would be forced to access the central banks deposit/lending facilities.

Now bank *i*'s minimisation problem becomes:

$$
\begin{aligned}
\mathrm{L_i} = \arg\min_{-L_j{}'' \leq L_i \leq L_i{}'} \quad & -c_{i1\{L_i<0\}}\mathrm{L_i} + c_{i2[L_i>0]}L_i \\
& + \int_{(1+\alpha)\mathrm{K_i}-\mathrm{R_i}+\mathrm{L_i}}^{\infty}\big(\mathrm{r} - (\mathrm{r_R} - \mathrm{s_d})\big)(\mathrm{R_i} - \mathrm{L_i} - (1+\alpha)\mathrm{K_i} + \varepsilon_\mathrm{i})\mathrm{dF_i}(\varepsilon_\mathrm{i}) \\
& + \int_{K_i-R_i+L_i}^{(1+\alpha)K_i-R_i+L_i}(r - r_R)((1+\alpha)K_i)dF_i(\varepsilon_i) \\
& + \int_{(1-\alpha)K_i-R_i+L_i}^{K_i-R_i-L_i}(r - r_R)\big((1-\alpha)K_i\big)dF_i(\varepsilon_i) \\
& + \int_{-\infty}^{(1-\alpha)K_i-R_i+L_i}\Big(\big(r_R - s_l + c_{i_1}\big) - r\Big)(R_i - L_i - (1-\alpha)K_i + \\
& \varepsilon_i)dF_i(\varepsilon_i).
\end{aligned}
\tag{8}
$$

Where, c_{i_1} $\mathrm{c_{i_2}}$ are defined as in equation (4).

Here:

- The first two terms reflect the costs associated with the minimum leverage ratio and minimum capital ratio requirements.
- The third and fourth terms reflect the opportunity cost of depositing excess reserves in the central bank deposit facility, in the case where end-of-day reserves balance exceeds (1+ α)K_i. In this case:
  - (1+ α)K_i of these reserves are remunerated at policy rate,
  - The remainder, $R_i - L_i - (1+\alpha)K_i + \varepsilon_i$, are remunerated at the rate of the deposit facility, $(r_R - s)$.
- The fourth and fifth terms are analogous to the first and second terms, but in the case where the bank borrows reserves necessary to meet the lower edge of the band around its reserves target

The first order condition of this optimisation problem now yields:

$$
r - r_R = F_i\big((1+\alpha)K_i - R_i + L_i{}^*\big)s_d + F_i\big((1-\alpha)K_i - R_i + L_i{}^*\big)\big(s_l + c_{i_1}\big) - \mathrm{s_d} - c_{i_1} + c_{i_2} \tag{9}
$$

This equation generates the supply/demand schedules used in our model.