Funding Liquidity Risk: Definition and Measurement *

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Abstract:
In this paper we propose definitions of funding liquidity and funding liquidity risk and present a simple, yet intuitive, measure of funding liquidity risk based on data from open market operations. Our empirical analysis uses a unique data set of 135 main refinancing operation auctions conducted at the ECB between June 2005 and December 2007. We find that our proxies for funding liquidity risk are typically stable and low, with occasional spikes, especially during the recent turmoil. We are also able to document downward spirals between funding liquidity risk and market liquidity.

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Non-technical summary

This paper addresses an important gap in the literature as we show that funding liquidity risk of banks can be measured using publicly available information. This also allows us to assess the interactions of market liquidity and funding liquidity risk in an empirical way, adding to previous theoretical finding supporting downward spirals between both. First, we define funding liquidity and funding liquidity risk as measuring without a definition is difficult if not impossible.

Funding liquidity is defined as the ability to settle obligations immediately when due. Consequently, a bank is illiquid if it is unable to settle obligations on time. Given this definition, it can be said that funding liquidity risk is driven by the possibility that, over a specific horizon, the bank will become unable to settle obligations when due.

Funding liquidity is essentially a zero-one concept, i.e. a bank can either settle obligations, or it cannot. Funding liquidity risk, on the other hand, can take on infinitely many values reflecting the magnitude of risk. Moreover, funding liquidity is a point-in-time concept, while funding liquidity risk is forward-looking. As long as the bank is not in an absorbing state, both liquidity and illiquidity are possible. The likelihood of either depends on the time horizon considered and on the nature of the funding position of the bank. In this respect, concerns about the future ability to settle obligations or to raise cash at short notice, i.e. future funding liquidity, will impact on current funding liquidity risk.

Considering the implementation of the aforementioned definitions, a more operational definition would be helpful. To this end, the definition of a settlement asset is narrowed down to central bank money, since in the vast majority of cases; the latter is one of the most important settlement assets from an aggregate point of view. Hence, the ability to settle is crucially linked to the ability to satisfy the demand for central bank money. Therefore, a more narrow definition of funding liquidity can be the ability to settle obligations with central bank money immediately when due.

In practice, a bank is able to satisfy the demand for central bank money, and is thus liquid, as long as outflows of central bank money are smaller than, or equal to, inflows at each point in time. However, the net amount of central bank money needed to remain liquid is uncertain from an ex-ante perspective and depends on the stochastic volume of liquidity required and the stochastic prices of acquiring it. Such uncertainties generate funding liquidity risk. We draw on the relevant literature and argue that in equilibrium there is a relationship between banks' bids and liquidity risk, i.e. banks submit informed bids in the OMO taking into account information about future liquidity needs and future prices they have to pay to obtain it from other sources. Moreover, the theoretical literature shows that higher funding liquidity risk implies more aggressive bidding behaviour, in an environment with frictions in interbank and asset markets. Although submitted bids may not perfectly reflect the marginal value for funding liquidity, they should provide an ordinal proxy measure of funding liquidity risk.

The proposed funding liquidity risk measure takes into account information on both the price of liquidity (i.e. the bid rate minus the ECB policy rate or the marginal rate) and the volume of liquidity obtained (i.e. the volume allotted), normalised by the total volume of liquidity provided, in order to maintain consistency across auctions of differing size. Summing up this information across bids and banks gives an aggregate proxy of funding liquidity risk, which equals the weighted average bid rate minus the policy rate, i.e. variables routinely reported by the ECB when main refinancing operations are conducted through variable rate tenders.

Our empirical analysis is based on a unique data set of 135 main refinancing operation (MRO) auctions conducted between June 2005 and December 2007 in the euro area. We effectively have information on the bidding schedules of each of the 877 participating banks in the relevant auctions. Using these data we are in a position to construct and analyse, for the first time, a proxy for funding liquidity. We find that funding liquidity risk has similar properties as market liquidity risk in that it shows persistence at low levels with occasional spikes, particularly after the beginning of the turmoil in August 2007.

We then use this proxy to investigate empirically the link between funding and market liquidity. Theoretical research has rationalised strong interactions between funding liquidity risk and market liquidity in periods of crisis. Shocks to funding liquidity can lead to asset sales and may depress asset prices, with dire consequences for market liquidity. The loop is established when lower market liquidity leads to higher margin calls, which increase funding liquidity risk as outflows rise. A downward liquidity spiral begins, as a new round of asset sales begins so that banks can remain liquid.

Whilst the theoretical exposition is clear, and many observers consider it relevant to the recent turmoil, a lack of measures of funding liquidity risk has delayed empirical validation. Using our risk measure, it is possible to empirically support these interactions by looking at the inter-relationships between the proposed funding liquidity risk proxy measure and the ECB’s index of financial market liquidity. In so doing, we able to provide, for the first time, empirical evidence that there are strong negative interrelationships between our measure of funding liquidity risk and a measure for market liquidity. In this sense higher funding liquidity risk implies lower market liquidity.

Overall our paper provides a useful contribution in the research field of liquidity not only because it opens up ways of further empirical research on liquidity, an area of research hindered by the unavailability of proxies, but also because it can be used as a very efficient tool for policy analysis and monitoring.

1. Introduction

Many historical episodes have highlighted the crucial role of funding liquidity for banking crises. The events since August 2007 have been no different. They bore all the hallmarks of a funding liquidity crisis as interbank markets collapsed and central banks around the globe had to intervene in money markets at unprecedented levels. Nonetheless, a concrete measure of funding liquidity risk using accessible data remains so far elusive. This paper addresses this gap by developing a measure based on banks' bids during open market operations. Our empirical analysis uses a unique data set of 135 main refinancing operation auctions conducted at the ECB between June 2005 and October 2008. Similar to measures of market liquidity, we find that our proxies for funding liquidity risk are typically stable and low, with occasional spikes, especially during the recent turmoil. Our measure also allows us to assess the interactions of market liquidity and funding liquidity risk. Even though downward spirals between both have been a key concern for most policy makers during this and previous crises, we are the first to provide robust empirical evidence.

Measurement without definition is, however, difficult if not impossible. In this paper we define *funding liquidity* as *the ability to settle obligations with immediacy.* Consequently, a bank is illiquid if it is unable to settle obligations in time. In this case the bank defaults, resulting in losses to shareholders and possibly depositors. Given this definition, it can be said that *funding liquidity risk is driven by the possibility that over a specific horizon the bank will become unable to settle obligations with immediacy*. In particular we show that funding liquidity risk has two components: future (random) in- and outflows of settlement assets such as money and future (random) prices of obtaining funding liquidity from different sources. In contrast to other definitions used by academics and practitioners we show in the first part of the paper that our definitions have important properties, shared by definitions of other risks. First, like solvency, funding liquidity is point-in- time and a binary concept as a bank is either able to settle obligations or not. Funding liquidity risk on the other hand can take infinitely many values depending on the underlying funding position of the bank. As any other risk, it is forward looking and measured over a specific horizon.

Our analysis also highlights that funding liquidity is best understood as a flow concept, i.e. a bank is liquid as long as outflows of money are less or equal to inflows and the stock of money. In a modern economy many different forms of money - or settlement assets more broadly - exist. For our analysis we focus on the most important settlement asset in the economy. In the Eurosystem, but also in most other economies, large value payment and settlement systems rely on central bank money as the ultimate settlement asset (see CPSS, 2003). Hence, the ability to settle is crucially linked with the ability to satisfy the demand for central bank money, which banks can obtain directly from the central bank at open market operations (OMO), the interbank market, by selling assets or by raising costumer deposits.

Ideally and in line with other risks, we would want to measure funding liquidity risk by the distribution summarising the stochastic nature of in- and outflows and random prices banks need to pay to obtain the necessary funds. However, this information is unavailable. Instead, we observe banks' bids during open market operations. In the second part of the paper we draw on the relevant literature and argue that in equilibrium there is a relationship between banks' bids and liquidity risk, i.e. banks submit informed bids in the OMO taking into account information about future liquidity needs and future prices it has to pay to obtain it from other sources. Based on the model of Nyborg and Strebulaev (2004) as a basis, we argue that if there are frictions in interbank and asset markets, banks with higher funding liquidity risk will bid more aggressively, the more so the higher their funding liquidity risk. Hence, a higher spread indicates higher risk. This is intuitive as banks with higher funding liquidity risk are willing to pay a higher price to obtain funds from the central bank to hedge this risk.

Our measure significantly improves on other measures used for funding liquidity risk so far. Banks' own funding liquidity risk measurement such as gap analysis or stress testing is essentially equivalent to a very detailed analysis of the stock flow constraint we suggest in the first part of the paper (see Matz and Neu, 2007, or Banks, 2005). This is very data intensive and relies entirely on confidential information. Whilst we also use confidential data from the ECB, other central banks have similar data available. And our proposed measure of aggregate funding liquidity risk can be easily derived from public data provided by the ECB after each OMO. Therefore our method allows for a frequent and timely assessment of funding liquidity risk in an environment characterised by limited data availability.

Aggregate funding liquidity risk has also been measured by the spread between interest rates in the interbank market and a risk free rate (e.g. see IMF, 2008). This is the average price for obtaining liquidity in the interbank market. In this sense it reflects a key component of funding liquidity risk. However, the spread is not only determined by the average funding liquidity risk but impacted by several other factors (e.g. see Michaud and Upper, 2008). Gyntelberg and Wooldrige (2008) also show that during the recent turmoil the interbank market rate has become less representative of actual funding conditions because of increased uncertainty, dispersion in the credit quality across banks and greater incentives to strategically misreport funding costs.[1]

[1]. Interbank rates such as LIBOR are fixed by surveying a set of banks each day about their own funding costs. Findings by the Wall Street Journal indicated that actual interbank interest rates have

But most importantly, the spread between interest rates in the interbank market and a risk free rate is purely a price measure and it does not reveal anything about market access, which maybe severely impaired during crisis, nor the volume of net-liquidity demand – the second component of funding liquidity risk.

Our empirical analysis is based on a unique data set of 135 main refinancing operation (MRO) auctions conducted between June 2005 and December 2007 in the euro area. We effectively have information on the bidding schedules of each of the 877 participating banks in the relevant auctions. We find that our proxies have intuitive properties. Namely, they show persistence at low levels with occasional spikes that funding liquidity risk is supposed to have according to market practitioners (see Matz and Neu, 2007). Moreover, these properties are also shared by measures for market liquidity (e.g. see Amihud, 2002; Chordia et al., 2000, 2002; Pastor and Staumbaugh, 2003). As already discussed, we are also able to show that there are strong negative interrelationships between our measure of funding liquidity risk and a measure for market liquidity. In this sense higher funding liquidity risk implies lower market liquidity. We are able to show that this effect is only present during the turmoil. This is exactly what theory (e.g. Brunnermeier and Pedersen, 2007) would suggest as interactions should only occur once banks face funding liquidity risk.

The remainder of the paper is structured as follows. In Section 2 we introduce our definition of funding and funding liquidity risk. After providing a short overview of OMOs in the euro areas in Section 3, we analyse the sources of funding liquidity risk and show that higher funding liquidity risk will result in higher bids during OMOs in Section 4. Section 5 introduces our measures and Section 6 presents the bidding data on which our measures rely. In Section 7 we present the empirical measures and empirical evidence on their relationship with market liquidity risk. Finally, Section 8 concludes.

2. Definition of funding liquidity and funding liquidity risk

2.1. Funding liquidity and funding liquidity risk

We define *funding liquidity* as *the ability to settle obligations with immediacy.* Consequently, a bank is illiquid if it is unable to settle obligations in time. In this case the bank defaults, and shareholders and possibly also depositors incur losses. Given this definition it can be said that *funding liquidity risk is driven by the possibility that over a specific horizon the bank will become unable to settle obligations with*

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been even higher than indicated by LIBOR during the recent turmoil. See *The Wall Street Journal,* "Bankers cast doubt on key rate amid crisis", 16 April 2008.

immediacy. In particular we show that funding liquidity risk has two components: future (random) in- and outflows of money and future (random) prices of obtaining funding liquidity from different sources.

It is worth to highlight important differences between funding liquidity and funding liquidity risk: Funding liquidity is essentially a binary concept, i.e. a bank can either settle obligations or it cannot. Funding liquidity risk on the other hand can take infinite many values as it is related to the distribution of future outcomes. Implicit in this distinction is also a different time horizon. Funding liquidity is associated to one particular point in time. Funding liquidity risk on the other hand is always forward looking and measured over a particular horizon. In this respect, concerns about the future ability to settle obligations, i.e. future funding liquidity, will impact on current funding liquidity risk.

The distinction between liquidity and liquidity risk is straightforward and similar to other risks. For example, a similar distinction can be made between credit risk and default. For example a borrower can be in default or not. Whilst default is a binary concept measured at one particular point in time, credit risk is not. The credit risk associated with a loan is determined by the likelihood that the borrower will default over a particular horizon.[2] Therefore, credit risk is always used as a forward looking measure and can take infinite many values, depending on the underlying credit worthiness of the borrower.

Surprisingly a distinction in the definition of funding liquidity and funding liquidity risk is not made by practitioners and academics. In terms of funding liquidity, the IMF defines it as "the ability of a solvent institution to make agreed-upon payments in a timely fashion" (p. xi, IMF, 2008). This is very similar to ours, even though we argue that it may well be the case that an institution is liquid but solvent. Borio (2000), Strahan (2008) or Brunnermeier and Pedersen (2007) define funding liquidity as the ability to raise cash at short notice either via asset sales or new borrowing. Whilst it is the case that banks can settle all their obligations in a timely fashion if they can raise cash at short notice, the reverse is not true as a bank may well be able to settle its obligations as long as its current stock of cash is large enough. As the ability to raise cash can vanish (Borio, 2000) this definition is implicitly forward looking and therefore closer associated to funding liquidity risk. The definition of the Basel Committee of Banking Supervision is close to our definition even though it mixes the concepts of funding liquidity and funding liquidity risk. In their view liquidity is "the ability to fund increases in assets and meet obligations as they come due" and they argue that "within this definition is an assumption that obligations will be able be met

[2] A broader definition of credit risk also accounts for the stochastic nature of loss given default, changes in the underlying credit quality and changes in exposure at default.

at a 'reasonable cost' " (p.2, BCBS, 2008).[3] While the first part is essentially equivalent to our definition of funding liquidity, the second part is in our view more related to funding liquidity risk even though it is unclear what 'reasonable' really means.

Our definition raises the question how banks settle obligations. As discussed in the introduction, many different settlement assets exist in an economy (see CPSS, 2003). Generally this is not realised as for example different forms of money in one currency are close substitutes and can be converted into each other at par. The most visible money constitutes of banknotes and coins, but this only plays a minor role as settlement asset. On the other hand, liabilities of commercial banks – which are also referred to as commercial bank money – represent the largest stock of money in the economy. Most transactions, especially those involving private agents, are settled in commercial bank money. However, for banks funding liquidity risk management central bank money plays a crucial role as this is the one of the most, if not the most, important settlement asset. In the Eurosystem, but also in most other economies, large value payment and settlement systems rely on central bank money as the ultimate settlement asset (see CPSS, 2003).[4] Hence, the ability to settle is crucially linked with the ability to satisfy the demand for central bank money. Central bank money, in turn, consists mainly of deposits held by commercial banks with the central bank.[5] In Annex 2 the role of central bank money as a settlement asset is elaborated further.

2.2 Funding liquidity as a stock-flow concept

As has been pointed out by Drehmann, Elliot and Kapadia (2007) funding liquidity is related to flows. The authors also show that the theoretical literature on liquidity can be expressed as a flow constraint.[6] Given our definition, a bank is able to satisfy the demand for money, and hence is liquid, as long as at each point in time outflows of money are smaller or equal to inflows and the stock of money held by the bank. Following this reasoning, a stock flow constraint provides an easy and straightforward representation:

$$Outflows_t \leq Inflows_t + Stock\ of\ Money_t \qquad (1)$$

Annex 1 provides a more detailed breakdown of in- and outflows and explains in depth that the key settlement asset for all components is central bank money. For our purposes, money in constraint (1) can therefore be thought of as central bank money.

[3] Even though it is implicit that the BCBS is defining funding liquidity it is interesting that this definition talks about liquidity in general.
[4] For a history of central banks' role in interbank payment systems see Norman et al (2006).
[5] Cash and central bank reserves have also be labelled as high powered money in the monetary economics literature (e.g. see Friedman and Schwarz, 1963).
[6] See also Drehmann (2007).

For measuring funding liquidity risk, we focus on the net volume of liquidity (i.e. central bank money) needed in order to avoid illiquidity. This can be represented by a new variable which we call the net-liquidity demand (*NLD)*. We construct this variable from the stock flow constraint. Namely we take the difference between all outflows (*Outflows)* and contractual (i.e. known) inflows (*$Inflows^{due}$)* net of the stock of central bank money *(M):*

$$\begin{aligned} NLD_t &= Outflows_t - \left(Inflows_t^{due}\right) - M_t \\ &\leq p_t^D L_{new,t}^D + p_t^{IB} L_{new,t}^{IB} + p_t^A A_{sold,t} + p_t^{CB} CB_{new,t} \end{aligned} \tag{2}$$

NLD is the net amount of central bank money the bank needs to remain liquid. In case of a deficit (i.e. outflows are larger than inflows and the stock of money), the inequality highlights that NLD_t has to be financed either by new borrowing from depositors (L_{new}^D), from the interbank market (L_{new}^{IB}), selling assets (A_{sold}) or accessing the central bank (CB_{new}). All these sources have different prices *p*. If there is a positive net liquidity demand which cannot be funded with new inflows, the bank will become illiquid and default. Conversely, if the bank has an excess supply of liquidity, no borrowing is necessary and the bank can sell the excess liquidity on the market. [7]

Whilst NLD_t is the funding liquidity constraint faced by the bank in each period, funding liquidity risk is related to future developments of *NLD*. For example, if funding liquidity risk is assessed over a one period horizon, then it could be analyzed by the distribution of NLD_{t+1}. Equation 2 shows that funding liquidity risk has two random components: volumes and prices.

Random volumes of *NLD* are the first component of funding liquidity risk. Although contractual obligations (whether in- or outflows) and their maturities are known, the possibility of defaulting counterparties can lead to some randomness. Moreover, other sources of outflows can be rather volatile. For example, off-balance sheet commitments can induce large swings in cash flows as seen during the recent crisis. Also note that outflows are partly endogenously determined. Indeed, under severe stress the bank may decide to cut back on new lending or reduce asset purchases. However, to ensure that franchise value is not lost, banks are generally reluctant to cut established credit relationships, unless absolutely necessary. Finally, some inflows are also endogenously and others exogenously determined. As we discuss in detail below, banks choose optimally from which source they want to obtain funding in case they face a shortfall and therefore endogenously affect inflows. Nonetheless, other inflows

[7] Ex-post inflows always equal to outflows as long as the bank does not fail. High inflows are always absorbed by asset purchases or new lending, for example in the interbank market. If at the end of the period banks have excess inflows of central bank money they will deposit them with the marginal deposit facility at the central bank.

are exogenous, as depositors not only withdraw but also deposit money in the bank in a random fashion.

Random prices are the second component of funding liquidity risk. Ex-ante, prices of obtaining liquidity from different sources are, to some extent, uncertain. As we discuss in detail below, prices in the central bank auction and in the interbank market depend on the realisation of unknown shocks. The same holds for the price of liquidity from selling assets, especially in periods of turmoil. Nevertheless, certain prices are predetermined. These are the prices for customer deposits, as they are endogenously set by the bank. The prices for obtaining money from the central bank via the marginal facilities are also given.

The question for this paper is how to measure liquidity risk given the stochastic nature of *NLD*. Ideally and in line with other risks, we would want to measure funding liquidity risk by the distribution summarising the stochastic nature of in- and outflows and the random prices banks need to pay to obtain the necessary funds. However, even banks with access to far more data are unable to construct the full distribution. We circumvent this problem by focusing on an important liquidity source as shown in equation 2, e.g. central bank auctions, (CB_{new}) and the banks' bids in terms of price and volume we observe during open market operations. While doing that, we have to bear in mind that in equilibrium there is a relationship between prices for liquidity in different markets, i.e. a bank submits informed bids in the main refinancing auctions (MRO), after taking into account information about its own liquidity needs and about the price and volume of liquidity it can get from other sources. In Section 4 below we show that bids, or more precisely the (adjusted) spread between the bid and the minimum bid rate, contain information about funding liquidity risk and can therefore be used as a proxy measure. There we also discuss price fluctuations in greater detail. However, before we discuss the theoretical background for our measure it may be useful to provide a more thorough discussion on the institutional background of open market operations in the euro area for those who are less familiar with OMOs.

3. Open Market Operations in the euro area

In the euro area OMOs are mainly carried out as either main financing operations (MROs), which are conducted weekly and have a maturity of one week or as long term refinancing operations (LROs), which are conducted less frequently and have a maturity of 3months. Additionally the ECB conducts fine tuning operations, if there is a need for an additional and extraordinary injection or absorption of central bank money.

As MROs form the basis of our measure we discuss them in more detail. From March 2005 until 7 October 2008 MROs were typically conducted as standard flexible rate tenders until. This means that during each MRO auction eligible banks can submit bids (volume and price) at up to ten different bid rates at the precision of one basis point (0.01%). Prices and volumes are unconstrained, except for the minimum bid rate, which equals the policy rate set by the Governing Council. Banks are only required to submit sufficient collateral for the allotted liquidity. The auction is price-discriminating, i.e. every successful bidder has to pay her bid. At the marginal rate, depending on the aggregate bid schedule, bids may be rationed, so that everyone takes the same pro rata amount of the remaining liquidity. An example of an aggregate bid curve is shown in Chart A1 in the Appendix, which also shows the marginal rate and the total allotment for this particular auction.

To calibrate the allotment volume in the weekly MROs, the ECB takes the sum of the outstanding autonomous factors (such as banknotes, government deposits and net foreign assets) and banks' reserve requirements.[8] The allotment volume that satisfies exactly these needs for central bank money in aggregate is called the "benchmark allotment". An ECB forecast of the autonomous factors on which basis the benchmark allotment is calculated is published prior to the bidding of the banks in the MRO.

In the period since August 2007, however, the ECB followed “frontloading” practices in deciding the allotted volume. In order to respond to the increased demand for liquidity for banks and help them to fulfil their reserve requirements earlier in the maintenance period, the ECB allotted significant amounts over the benchmark amount at the beginning of the maintenance period, linearly decreasing this amount towards the end, always trying to maintain balanced liquidity conditions at the end of the maintenance period (through absorbing the extra liquidity during the maintenance period with FTOs). As we discuss later, this development, however, is unlikely to reflect on our measure, given the adjustment we included for auctions of different sizes.

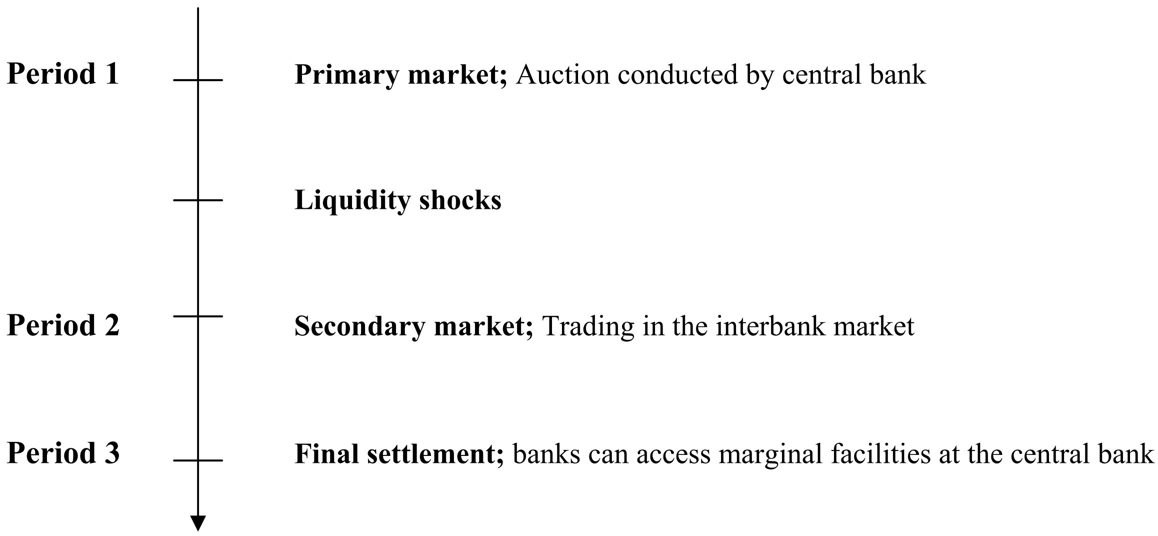
[8] In the Euro area individual banks have to fulfil reserve requirements. Banks are allowed to hold positive or negative (relative) reserve balances with the CB within a specified period (i.e. relative to their requirements banks can hold more or less. Negative current accounts, so-called intraday credit, have to be collateralised and will be referred to the marginal lending facility at the end of the day). However reserve requirements have to be fulfilled on average across the maintenance period (usually between 28 and 35 days). At the start of the maintenance period the reserve requirements are determined by the Eurosystem for each bank and remain fixed during the period. The settlement day of the first MRO marks the start of the maintenance period. In addition, since April 2004, this is the day on which interest rate decisions of the Governing Council of the ECB become effective.

4. Funding liquidity risk and bidding behaviour at OMOs

In this section we show that higher funding liquidity risk can be measured by the spread between the submitted bid and the minimum bid rate, by first analysing a stylised world where banks can only obtain liquidity from the central bank or the interbank market with or without frictions. In the last part of this section we broaden the discussion to analyse bidding behaviour when all sources of liquidity are considered.

Following the seminar paper by Poole (1968), the literature has analysed a stylised time line focusing on the central bank and the interbank market when analysing bidding behaviour in open market operations. For expositional purposes we will use the simplest case throughout the discussion in this section shown in Figure 1.

Figure 1: Stylised time line



The stylised time line consists of three periods. In period 1, banks can acquire liquidity in the primary market by participating in the auction conducted by the central bank. Afterwards liquidity shocks materialise. It is important to stress that random volumes discussed above are nothing else than these liquidity shocks, implying random prices in period 2. In that period, banks trade in the interbank market. After interbank markets close in period 3, all obligations are settled and banks have to fulfil their reserve requirements set by the central bank.[9] At this point the market in aggregate may be short (or long) of liquidity and hence some banks may have to access the marginal lending (deposit) facility. Prices for the marginal facilities are considered key policy rates and are determined by the central bank, therefore they

[9] Most countries have positive reserve requirements for banks. However, theoretically it is only necessary that there is a threshold, e.g. zero, and banks would be penalised if their balances with the central bank would drop below this level.

are already known in period 1. At the same time, these prices constitute an upper and lower bound for the interest rate in the interbank market in period 2, given that a bank with sufficient collateral can always recourse to the standing facilities at period 3 to settle any liquidity imbalances. In case of the euro area, banks pay 100bp on top of (below) the policy rate to access the marginal lending (deposit) facility.

At this point it is important to distinguish interbank markets with and without frictions as this will impact on interest rates in period 2, which in turn impact on the bids submitted by banks in the central bank auction – our variable of interest.

4.1 Bidding with frictionless interbank markets

Most theoretical models looking at bidding behaviour at open market operations conducted as price discriminating auctions are based on stylised set ups and rely on the assumption that interbank markets are frictionless and that central banks make no policy mistakes and always accurately provide the necessary (expected) amount of central bank money. For example, Välimäki (2002) and Ayuso and Repullo (2003) show that the optimal strategy for banks in such an environment is to only bid at the minimum bid rate. No bank is, therefore, willing to pay a premium above the minimum bid rate, in other words the spread is zero.

This result is intuitive. First consider the case where the central bank provides the correct amount of aggregate liquidity and banks are only subject to idiosyncratic liquidity shocks so that in period 2 there is no liquidity surplus or deficit. Given frictionless interbank markets, banks can always obtain sufficient funding in the secondary market, independent of the liquidity shocks they face. Hence, the interest rate in the interbank market equals the policy rate, which is also the minimum bid rate. This in turn implies that in period 1 bidding at the minimum bid rate is the only rational strategy and, the spread, which is our measure for funding liquidity risk, is therefore zero. And this is what it should be theoretically: funding liquidity risk in a frictionless interbank market without aggregate shocks is zero, as the bank is always able to settle all obligations with immediacy as it can obtain all necessary funds at a known and fixed interest rates from the interbank market.[10]

Aggregate liquidity shocks impact, however, on liquidity risk (see e.g. Allen and Gale, 2004a,b or Diamond and Rajan, 2005). Even with frictionless interbank markets, trading cannot eliminate the risk that the market in aggregate may be long or

[10] This is fully in line with the theoretical literature, which has shown that with fully connected interbank markets idiosyncratic liquidity shocks can be eliminated and liquidity risk vanishes (see Allen and Gale, 2000).

short of central bank money in period 3 following some aggregate shocks.[11] As prices for accessing the marginal facilities are fixed, the interest rates in period 2 purely reflect the expectations of the amount and likelihood of accessing either facility in period 3. However, the central bank is assumed to provide the right expected amount of aggregate liquidity so that the expected interest rate in the interbank market (at time 1) equals the policy rate. Given risk neutrality, all banks therefore bid at the minimum bid rate and spread above the policy rate would also be zero in such a set-up.

However, the assumption of risk neutral banks and frictionless interbank markets is unrealistic, particularly during times of stress. In the next section we show that if we relax these assumptions banks with higher liquidity risk bid more aggressively.

4.2 Bidding with interbank market frictions

It has been theoretically shown that asymmetric information (e.g. Flannery, 1996), co-ordination failures (e.g. Rochet and Vives, 2002), uncertainly about future liquidity needs (e.g. Holmstrom and Tirole, 2001) or incomplete markets (e.g. Allen and Gale, 2000) are all frictions which lead to funding liquidity risk. Such frictions imply that a bank which has to raise liquidity in the interbank market has to pay a higher price to obtain it. In the extreme, prices may even be infinite if a bank is credit rationed (see Stiglitz and Weiss, 1981). Banks, who expect to be short, will anticipate this and bid more aggressively during the OMO to avoid paying higher interest rates in the secondary market or being rationed completely.

Nyborg and Strebulaev (2004) show formally that, given frictions in the interbank market “short” banks (i.e. banks which do need to raise cash from the central bank or the interbank market to settle all obligations) will bid more aggressively than “long” banks (i.e. banks which have excess funds) as short banks want to avoid paying higher interest rates in the interbank market.[12] In particular, Nyborg and Strebulaev analyse the case where long banks have some market power during trading in the secondary market, so that they can “squeeze” short banks and demand higher interest rates. Acharya, Gromb and Yorulmazer (2008) document several banking crises where this

[11] An aggregate shock should be thought of as a state of nature, where bank specific shocks do not add up to zero.

[12] Formally, the results from Nyborg and Strebulaev will only carry over to a setting with a different interbank market frictions, if the friction implies that long players can charge a higher interest rate if short banks are sufficiently illiquid. If the interbank market is closed and only banks can trade in the interbank market this is the case. Nyborg and Strebulaev also assume that agents have full information on short and long positions prior to the OMO. However, imperfections in the interbank market are often associated with imperfect information. Nyborg and Strebulaev and conjecture that with private information about positions, long players will aim to exploit their informational advantage. But in equilibrium short banks would still bid on average at higher rates to prevent the squeeze.

effect seems to have played an important role.[13] Short banks clearly anticipate this when submitting their bid. They know they can avoid being squeezed if they obtain sufficient funds from the central bank during the OMO. It is therefore intuitive that banks bid very aggressively for the amount of funds necessary to avoid the squeeze. Nyborg and Strebulaev show that in equilibrium the threat of a squeeze induces short banks to submit bids above the minimum bid rate with a higher expected mean rate than the bids submitted by banks which are long. They also show that this price distortion is larger the larger the short position. Putting it in the language of our equation above, the higher the expected *NLD,* the higher p^{IB}, the higher the funding liquidity risk, and the more aggressively a bank will bid. Therefore a higher the spread reveals higher funding liquidity risk.

Fecht et al. (2008) find empirical support for this theory when analysing OMOs for German banks. Even though they cannot observe *NLD*, they know a bank's liquidity position with the central bank prior to the auction, relative to the reserve requirement set by the central bank. Using this as a proxy, they document that short banks bid more aggressively especially in times when the liquidity imbalance across banks is large. However, in contrast to our paper they do not link this to funding liquidity risk.

Banks may also not be risk neutral, as is generally assumed, which implies that banks with high liquidity risk will bid more aggressively. During normal times the difference between bidding of risk neutral and risk averse agents may not be material, as interbank markets work nearly frictionless and banks can obtain any required amount of funding in the secondary market. The only face the risk of small price changes in LIBOR due to small aggregate shocks.[14] However, in stressed conditions, such as the recent crisis, where a banks' inability to obtain liquidity in the secondary market can lead to failure, risk aversion can have significant consequences. Välimäki (2006) explores a model with risk averse banks, where deviations from a target level of central bank balances prior to trading in the interbank market are costly. Such a target level could for example be the result of frictions, where banks know that the desire to obtain large amount of funds would be penalised by rates above the market rate or it may even be impossible to raise the necessary amount of funds because of rationing. In line with Nyborg and Strebulaev, Välimäki shows that banks with a higher target level, or equivalently with a higher *NLD* in our set-up, bid more

[13] In the model of Archarya et al (2008) long banks take advantage of their market power to strategically underprovided liquidity to short banks. They profit from their failure by buying up assets at fire sales prices if short banks turn out to be illiquid.

[14] As long as all banks lend freely in the interbank market, aggregate liquidity shocks in the market for central bank money are technically only driven by changes in autonomous factors. Autonomous factors constitute nearly completely of banknotes, government deposits and net foreign assets. All these factors can and do change between frequently OMOs even though these fluctuations are generally not large.

aggressively during the central bank auction and a higher spread will reveal higher funding liquidity risk.

The arguments so far establish that higher bids reveal higher funding liquidity risk if there are frictions in the interbank market and/or banks are risk averse. Therefore a higher spread will measure higher funding liquidity risk. However this measure of funding liquidity risk can only be a proxy. This can happen because bidding behaviour may also be influenced by other factors. Ewerhart et al. for example consider a model with frictionless interbank markets where values for collateral used for OMOs and the secondary market differ. This in turn induces banks to submit bids which are higher than the marginal rate during the OMO. It is also shown that at year-ends, banks engage in window-dressing, to establish favourable end of year balances (see Bindseil et al 2003). This should also hold for other reporting times. Clearly, these seasonality effects are unrelated to liquidity risk as they are driven by bank managers' desire to signal a specific balance sheet to the market rather than by a reaction to funding pressures.

On a more theoretical level, given a secondary market, bidding behaviour may also be influenced by the well-known "winner's curse" problem: In single unit auction where bidders do not adjust their bid schedules, the bidder who is most optimistic about the value wins the auction and is therefore likely to overpay relative to the common value of the good (e.g. see Milgrom and Weber, 1982).[15] In anticipation of this, participants in the auction scale down their bid resulting in underbidding.

Therefore, our measure could suffer from the "winner's curse" problem. For this problem, however, to be material it is necessary that market participants have asymmetric information about the value of the good in the secondary market. Bindseil et al. (2008) test for this and find that there is no evidence that market participants in OMOs in the euro area have private information about (post auction) interest rates in the interbank market. Hence, the winner's curse problem does not seem to be material for our set-up and should therefore not impact on our measure.

4.3 Bidding with all sources of liquidity

No model in the literature on bidding behaviour in OMOs takes into account all sources of funding liquidity shown in equation 2. In this section we briefly discuss the more general set-up using the stylised time line from above. In period 2 banks can therefore not only trade in the interbank market but also obtain liquidity from depositors or from selling assets. Both sources are considered in turn.

[15] In a multi-unit set-up the winner's curse problem is also referred to as champion's plague (Ausubel, 2004)

In practice, a bank cannot expect to rely on new customer deposits to weather liquidity shocks in period 2. On the one hand, the literature has shown that deposits can act as a natural hedge against liquidity risk stemming from issuing loan commitments and lines of credit (e.g. see Kashyap et al 2002, or Gatev and Strahan, 2006).[16] On the other hand, banks cannot rely on this, as they have a limited ability to actively attract new customer deposits in the short run (for example by raising rates) because of sluggish depositors' behaviour (see Gondat-Larralde and Nier, 2004). Overall, both in- and outflows of customer deposits can therefore be seen as a random component from the banks' risk management perspective. Essentially, they can be considered a liquidity shock within the discussed model framework, especially as we only measure liquidity risk over a one week horizon.

Asset sales are an alternative source of liquidity in the short run. In line with our analysis for interbank lending, the availability of this source depends to a large extent on the existence of frictions in the markets. In a frictionless world, where the central bank distributes the correct amount of liquidity so that on aggregate no expected liquidity surpluses or deficits exist, any bank which does not have access to the primary market of liquidity can acquire the necessary liquidity in the secondary market (interbank market) or in asset markets. The costs of obtaining liquidity from either source are equal as all price differentials are arbitraged away in a frictionless world. Hence, in such an environment the results from Section 4.1 apply, and banks only bid at the policy rate as liquidity risk would be minimal.

But frictions in asset as well as interbank markets are central in theories of liquidity risk For example, several models have shown that if asset markets are characterised by cash-in-the market pricing and there is an aggregate shortfall in liquidity, interbank market rates will be higher and asset prices will deviate from fundamentals, i.e. markets will be illiquid leading to distressed pricing (for an overview see Allen and Gale, 2007). Distressed pricing can also be a result of further frictions in trading, borne by margin requirements (Brunnemeier and Pedersen, 2007), limits to arbitrage (Schleifer and Vischny, 1997) and predatory trading (Carlin, Lobo and Viswanathan, 2007). Furthermore, frictions can lead to downward spirals between market and funding liquidity (see Gromb and Vayanos, 2002, or Brunnermeier and Pedersen, 2007). Within our hypothetical time line, the latter models essentially consider an extended period 2 where falling asset prices interact with funding liquidity needs.

[16] The rational for this is a flight to quality as banks have access to emergency liquidity from the central bank and depositors are sheltered from bank failures by the deposit insurance scheme. Pennachi (2006) shows that the negative correlation between deposit inflows and draw down of committed credit lines cannot be observed prior to the introduction of deposit insurance

The inverse relationship between funding and market liquidity risk can be characterised as follows: A downward liquidity spiral can start with a bank (or brokers in the Brunnermeier and Pedersen model) which is short of liquidity and cannot obtain it from the interbank market. Therefore it has to sell assets. If asset markets are characterised by frictions, (large) asset sales induce a fall in asset prices. These in turn imply that the bank has to post higher margins, i.e. liquidity outflows increase. To remain liquid banks have to sell more assets, which depresses market prices even further (because of a lack of market liquidity), leading to further margin calls and so forth. The downward spiral can also start with falling asset prices.

Overall, whatever the friction, a bank which expects to be short in period 2 and knows that the markets are characterised by frictions will anticipate that it has to pay higher prices to obtain the necessary liquidity from any available source. Hence, our results of Section 4.2 generalise, i.e. banks with higher liquidity risk will bid more aggressively in the open market operations. Therefore the spread can be used as a measure of funding liquidity risk.

5. Measuring funding liquidity risk

In Section 4 we have shown that a higher bid reveals higher funding liquidity risk. To measure funding liquidity risk empirically we normalise individual bank bids (consisting of the price and quantity submitted). We name these normalised bids "adjusted bids". We define the adjusted bid (*AB*) of bank *i* at auction *t* as a normalised variable of the bid price times the bid volume for successful bids, that is

$$AB_{b,i,t} = \frac{(bid\_rate - policy\_rate)_{b,i,t} * volume_{b,i,t}}{total\_allotment_t} \tag{4}$$

where, $bid\_rate_{b,i,t}$ is the price for liquidity, $policy\_rate_{b,i,t}$ is the rate set at the Governing Council meeting the first Thursday of each month and equals the minimum bid rate and the (allotted) $volume_{b,i,t}$ the bid volume of bank *i*, submitting from bid *b* *(from 1 to B)* at time (auction) *t*. We only consider successful bids, i.e. the prices for which the demanded volume was granted by the central bank, albeit rationed. The bids are normalised by the total allotment supplied by the central bank during auction *t*. The normalization of bids is necessary to remove changes in the monetary policy stance and ensure consistency across auctions which can differ in size. This will also ensure that our measure is unaffected by "frontloading" practices after August 2007 as discussed in Section 3.

Based on the individual normalised bids we can construct an aggregate proxy of funding liquidity risk by summing across the adjusted bids of all banks. Following that reasoning, our first liquidity risk proxy (*LRP*) is simply the sum of all individual adjusted bids across banks for each auction.

$$LRP_t = \sum_{i=1}^{N} \sum_{b=1}^{B} AB_{b,i,t} \ , \tag{5}$$

where b (from *b=1 to B)* are the bids of each bank *i* (from *i=1 to N*) for each time (auction) *t*.

This proxy contains two categories of bidders: The ones who bid at the marginal rate and the ones who bid above the marginal. As discussed above without frictions and risk neutrality all banks should bid at the marginal rate. It is therefore not certain to what extent the first group of bidders paying a premium to acquire liquidity. Therefore we look at a second proxy for funding liquidity risk only capturing bids above the marginal rate.

Along the lines of equations 4 and 5 we replace the policy rate with the marginal rate. The adjusted bid over the marginal rate (*AB_M)* is

$$AB\_M_{b,i,t} = \frac{(bid\_rate_{b,i,t} - marginal\_rate) * volume_{b,i,t}}{total\_allotment_t} \tag{6}$$

and the measure *LRP_M* measuring funding liquidity risk based on the bids over and above the marginal rate,

$$LRP\_M_t = \sum_i \left(AB\_M_{b,i,t} \right) \tag{7}$$

Chart A3.1 in Annex 3 provides a graphical representation of our two measures using one auction as an example. The two axes present the bid price (vertical) and the bid volumes (horizontal). *LRP* is nothing else than the normalised area under this demand curve (equal to area A plus area B divided by the total allotment). The figure also shows that *LRP* nests *LRP_M* (area A divided by the total allotment). Given our normalisation by the total allotment, it can be easily shown that the difference between the *LRP* and *LRP_M* equals the spread between the marginal rate (in the example 2.3%) and the policy rate which is also the minimum bid rate (in the example 2.25%).

Our two aggregate measures have an important practical advantage. Both can essentially be constructed using publicly available data as they collapse to the weighted average bid rate minus the policy rate (for *LRP*) or the marginal rate (for

LRP_M).[17] The weighted average bid rate, the policy rate and the marginal rate are series reported by the ECB after each auction. Historical time series are also available from the ECB website.[18] In that sense, these measures are particularly useful for policymakers and market observers, who would want a quick and easy proxy to monitor funding liquidity risk conditions in the economy in real time. In Annex 2, we present the main results of this paper (aggregate measures only) using publicly available data, as will be discussed in Section 7.3.

Of course, having data on individual bid rates can be more interesting from a policy maker's point of view. For example, it is possible to look at individual data in order to monitor bidding behavior of individual banks and hence their funding liquidity risk. Equally indeces for particular groups or even countries can be constructed.

6. Data

Our analysis profits from a unique data set of 135 MROs conducted by the ECB from June 2005 to December 2007. ECB data for MRO auctions allow us to follow the bidding behaviour of each of the 877 banks that took part at least once over these years. Information includes an anonymous but unique code for each bidder, the submitted bid schedule (bid rate and bid volume) of each bank and the allotted volume. These data are not publicly available. However, data on the policy rate (minimum bid rate), the marginal rate, the weighted average rate and the maintenance periods and the settlement dates of the auctions are publicly available and taken from the ECB's internet site.

Annex 3 provides an overview over the distribution of the individual bid rates, the spreads over the policy as well as the marginal rate and volumes. More specifically, Chart A3.2 displays the individual bid rates, as well as the policy and marginal rate, whereas Charts A3.3 and A3.4 present a more detailed graph of the two components (spreads and volumes) of the adjusted bids, as described in eq. 4 and 6. Each data point corresponds to a single dot in the graph. Therefore it is easy to have a first impression of the variability of the individual rates in each auction and the levels they tended to concentrate on. For example, it becomes clear that the turmoil period is associated with a larger variability in bid rates and more aggressive bidding, as

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17 The weighted average bid rate (WABR) is calculated as the sum of the bid rate times the volume, normalised by the percentage allotted and the total allotment for all successful bids.

$$WABR = \frac{\sum_{i=1}^{N}\sum_{b=1}^{B} bid\_rate_{b,i,t} * volume_{b,i,t} * percentage\_allotted}{total\_allotment_t}$$ In our case, we use the allotted volumes, which is effectively equal to the *volume*percentage_alloted*.

18 http://www.ecb.eu/mopo/implement/omo/html/index.en.html

suggested by the amount and extent of bids above the marginal rate (see Charts A3.2 and A3.3). However, only a slight increase in the adjusted allotted volumes (i.e. the volumes allotted individually adjusted for the size of each auction) is noted over the whole period, with a single exception of a significant increase on the last MRO of 2007.[19]

Annex 2 presents the results of the main analysis for an extended sample until 7 October 2008. The evidence presented there is based entirely on publicly available data on the weighted average bid rate, the policy rate and the marginal rate, in order to indicate, as already suggested, that the construction of our aggregate measures can rely on publicly available data only. Nevertheless, it does not reach further than October 2008. This was the date of the last MRO before temporary changes to the auction design of the ECB were implemented. These changes involved switching from variable rate tender to fixed rate – full allotment tenders. They also included a symmetric narrowing of the ECB corridor from 100bps to 50 bps. Under the new framework only the volumes of liquidity demand are revealed but not the price, therefore one of the fundamental drivers of funding liquidity risk is shaded. As a result, our measure does not apply on the new auction design after October 2007.

7. Results

7.1 Funding liquidity risk: Individual adjusted bids

Chart 1 presents the adjusted bids (*AB* and *AB_M*) of each bank for every auction. In essence, the chart combines information in Charts A3.3 and A3.4 (in Annex 3), which present the two individual components of the adjusted bids, following equations 4 and 6. Both panels in Chart 1 are scaled in the same way, in order to give a better impression of the relative size of each measure.

In particular when looking at *AB_M,* it is obvious from Chart 1 that the last operation of the year is of particular intensity, the more so during the turmoil period, at the end of December 2007. End of year effects are well known by practitioners and in the literature. For example, Bindseil et al. (2003) argue that banks engage in window-dressing to establish favourable end of year balances. As already mentioned in

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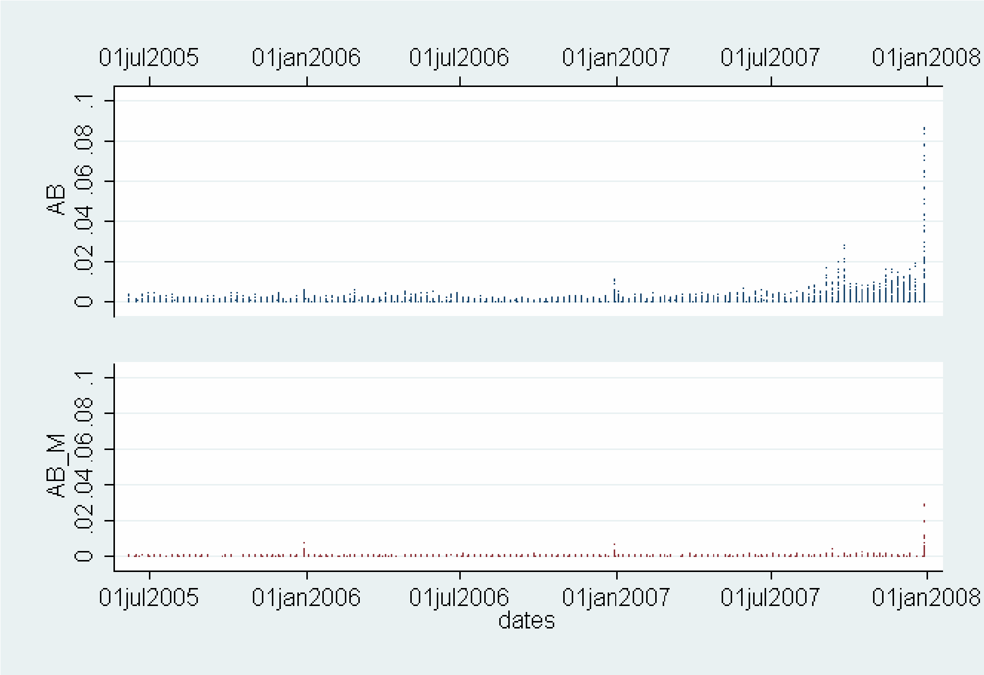
[19] On that particular date (28/12/2007) the number of bidders is significantly lower (only 118 compared to an average of 340 during the year, as other banks had already fulfilled their reserve requirements. The volumes of liquidity demanded by banks were broadly balanced with respect to the smaller size of the operation, but one particular banks demanded extraordinary high volumes for the standards of the specific operation resulting to almost one third of the total allotment. For the interested reader, the rates at which these volumes were requested were higher than the marginal rate.

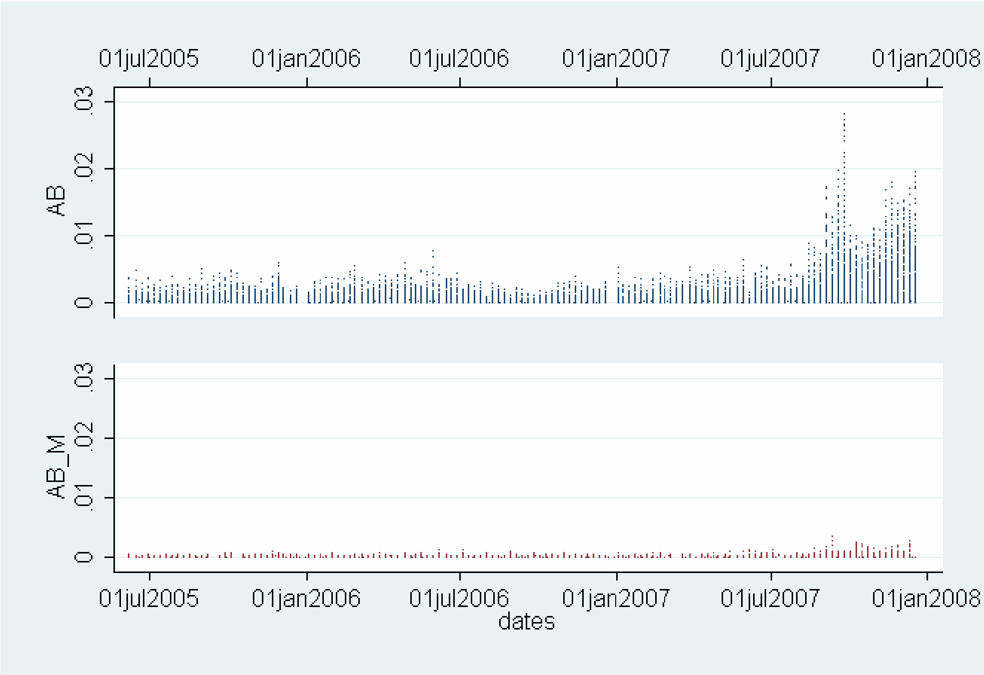
Section 4, these seasonality effects are unrelated to liquidity risk. Therefore, we exclude auctions conducted at year ends in Chart 2.

Chart 1: Distribution of adjusted bids (including year-ends)



Note: The Chart presents adjusted bids including the last operation of each year. The upper chart, denoted AB, depicts individual adjusted bids where the spread is equal to the bid rate minus the policy rate. Equivalently, the lower chart denoted AB_M depicts individual adjusted bids where the spread is equal to the bid rate minus the marginal rate.

Chart 2: Distribution of adjusted bids (excluding year-ends)



Note: The Chart presents adjusted bids excluding the last operation of each year. The upper chart, denoted LRP, depicts individual adjusted bids where the spread is equal to the bid rate minus the policy rate. Equivalently, the lower chart denoted LRP_M depicts individual adjusted bids where the spread is equal to the bid rate minus the marginal rate.

When we exclude end-of-year operations, an increased pressure during the turmoil period becomes apparent. This is especially the case for the adjusted bids over the policy rate (upper chart in Chart 2), where the dispersion of the adjusted bids increases significantly after August 2007. To a lesser extent the increase in the dispersion is also evident in *AB_M* (lower chart in Chart 2).

However the reader should keep in mind that the graphs do not clear reveal funding liquidity pressures in the same way as the Charts of the aggregate data do. Even though individual bids are presented as a dot in the graph, these merge into a line in particular for low values of *AB* and *AB_M* given a lack of granularity. The same charts but with different scales are presented also in Annex 3 (Charts A3.5). There it becomes clearer that both measures display similar increases during the turmoil period. This means that it is aggressive bidding over the marginal rate which mostly drives the results of that period. Nevertheless, it is more informative to look at the aggregate measures.

7.2 Aggregate funding liquidity risk measures

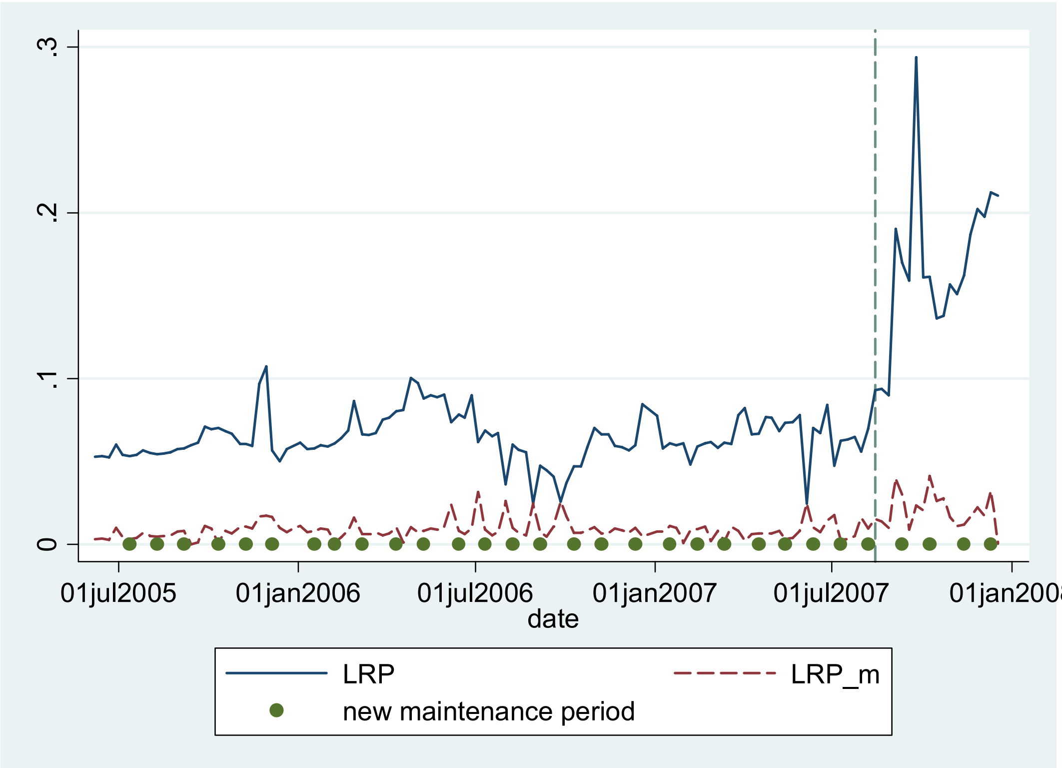
Our aggregate measure of funding liquidity risk is presented in Chart 3 summarising the information of Chart 1 and 2 into one measure according to equations 5 and 7. Given the previous discussion, we exclude end-of year effects[20], which are however included in Chart A3.6 in the Annex. Chart 3 clearly suggests that funding liquidity risk is time varying and persistent, but subject to occasional spikes. These properties bode well with measures for market liquidity (Amihud, 2002; Chordia et al., 2000, 2002; Pastor and Staumbaugh, 2003; Brunnemeier and Pedersen, 2007).

The time series of our liquidity risk measures *LRP* and *LRP_M* reveal that liquidity risk climbs to higher levels towards the end of the sample. Most practitioners would certainly agree that these months have witnessed the most pronounced events in terms of funding liquidity in our sample. For the *LRP* measure this change in level coincides perfectly with the beginning of the turmoil in August 2007. Since then, the measure increased significantly as we observe the reaction of the banking system to the credit market turmoil. After the initial reaction in August, a peak was reached in September, when Northern Rock had to be rescued by the UK government. After a short lived fall, *LRP* rose again as tensions continued in interbank markets up to the end of 2007.

[20] This is essentially equivalent to running a regression of the measure *LRP* on three dummy variables for each year end.

Table 1 provides the summary statistics for this data. It is apparent that both *LRP* and *LRP_M* increase during the turmoil following 9 August 2007. In fact, both measures more than double on average. The increase in volatility is also enormous, especially for *LRP* which increases more than ten-fold.

Chart 3 LPR and LRP_M (excluding year ends)



Note: The chart presents the LRP and LRP_M measures excluding the last operation of each year. The light blue horizontal line indicates the beginning of the turmoil (here 14 August when the first MRO was undertaken after the turmoil started). Green dots indicate starting dates of new maintenance periods.

Table 1: Statistics (excluding year-ends)

	LRP			LRP_1		
	Turmoil	Normal	Ratio	Turmoil	Normal	Ratio
mean	0.167	0.064	2.59	0.021	0.009	2.34
variance	0.00234	0.00021	11.07	0.00012	0.00003	3.65
min	0.090	0.025	3.63	0.001	0.0001	3.79
max	0.294	0.107	2.74	0.041	0.032	1.30

Note: *Normal* indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007. *Ratio* equals *Turmoil/Normal.*

With the beginning of the turmoil a wedge between *LRP* and *LRP_M* appears (consistent with the evidence on Chart 1 and 2). This suggests that banks on average faced significant funding pressures which lead to a higher dispersion in their bid rates (see Chart A3.2 in Annex 3) and a rise in the marginal rate. Therefore, the spread between the marginal rate and the policy rate also increased (see Chart A3.2 and A3.8 in Annex 3).

Nevertheless, at the end of the sample period, both measures rise significantly. This was combined with a steep rise of the marginal rate (see Chart A3.8, in Annex 3). The means that in the second half of September and early October funding liquidity risk was perceived so high, that there were banks submitting bids at extremely high prices, although all banks were bidding more aggressively, (therefore raising the marginal rate), In fact some banks just a bid only marginally lower than the marginal lending facility rate.

Another issue worth of attention is the several peaks prior to the turmoil in *LRP_M*, which are nearly as high as during the early stages of the turmoil period. This can partly be explained. Most of these spikes occur at dates when the marginal rate was equal or very close to the policy rate and all bidding banks were more or less satisfied. As a result, the area captured by the two measures was approximately the same, which is why we observe a drop in *LRP* for the same dates.

Overall, looking at both *LRP* measures it is possible to get complementary information on the bidding behaviour that drives the final results. Overall *LRP* captures increased aggressiveness in bidding. *LRP_M*, which is included in *LRP*, mirrors the effect of certain extraordinary high bids. In essence *LRP_M* can be seen as the peek of *LRP*, over and above the marginal rate. Consequently, comparing the difference between the two, it is possible to get an idea about how far the marginal rate lies from the minimum bid rate. It becomes clear that during the turmoil period, there was an overall increase in funding liquidity risk, which manifested itself in increased bidding aggressiveness, creating the apparent wedge between the *LRP* and the *LRP_M* measure. Therefore, *LRP_M* is a complementary indicator of aggregate funding liquidity risk in the market.

Finally, a closer inspection of Chart 3 also reveals that spikes in *LRP_M* prior to the turmoil are generally associated with the end of maintenance periods (green dots indicate the start of a new maintenance period). This is normal given that at the last operation of the maintenance period the bidding is more aggressive because the need to fulfil the reserve requirements becomes binding.

It is worth noting that the same analysis has been undertaken with an extended data set using only publicly available information. Annex 2 presents Table A2.1 and Chart A2.1, which are effectively updated versions of Table 1 and Chart 3. There it is possible to see the development of our aggregate measures during 2008 before the allocation mechanism for MROs was temporarily chagned in October. The analysis shows that liquidity conditons for banks were even worse in 2008 than in 2007, in particular after the Lehmann Brothers collapse in September 2008, where funding liquidity risk reached unforeseen levels.

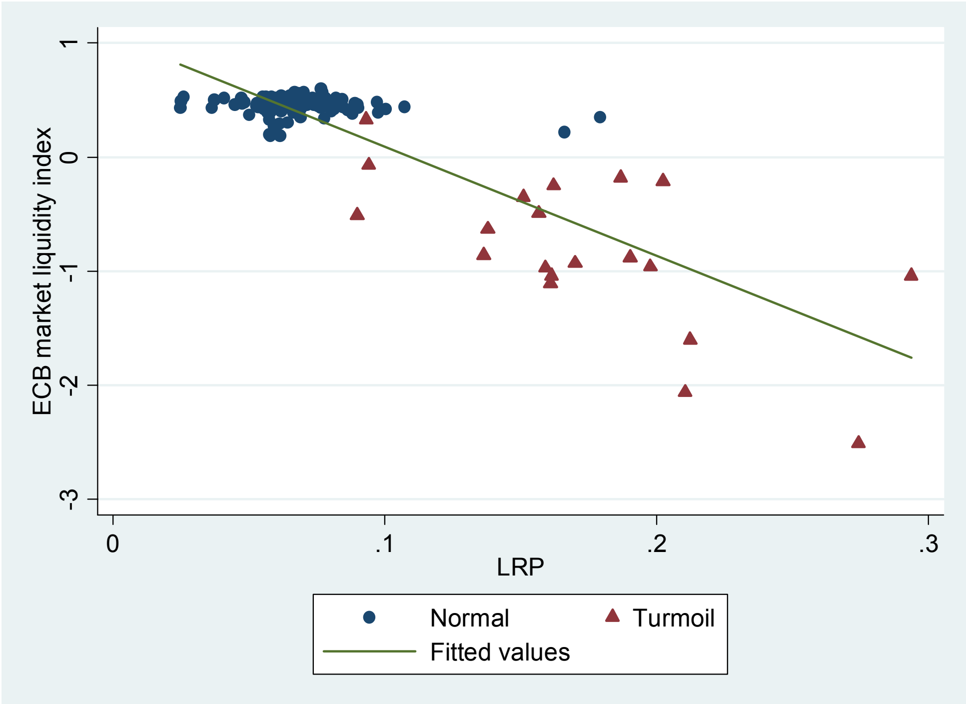
7.3 Funding liquidity risk and market liquidity

In section 4.3 we have discussed that market and funding liquidity are strongly interrelated. Once there are frictions and banks are constrained, downward spirals of falling asset prices and higher funding liquidity risk can emerge. Whilst the theoretical expositions are clear and many observers attribute the recent turmoil to these interactions, it has not been shown empirically due to a lack of measures for funding liquidity risk. Using our measure we are able to empirically support these interactions by looking at the interrelationships between our measure *LRP* and an index of market liquidity used by the ECB Financial Stability Review in June 2008 (see ECB, 2008) (see Chart A3.9 Annex 3 for a time series). This index is a weighted average of different market liquidity measures such as bid-ask spreads in FX, equity, bond and money markets.

Chart 4 shows a scatter plot of *LRP* and the ECB market liquidity index. A clear negative relationship can be seen, i.e. when market liquidity is drying up (i.e. is low), funding liquidity risk is high (which would be equivalent to saying that high funding liquidity risk is associated with high market liquidity risk). The red line shows the predicted values based on a simple regression of the index on *LRP*. These results are shown in Table 2. The scatter plot already suggests that the negative relationship is primarily driven by the turmoil. The econometric analysis supports this as there is no significant relationship between our measure of funding liquidity risk and market liquidity prior to the turmoil.[21] However, once the turmoil unfolds a significant negative relationship emerges. This is exactly what the theory predicts as these interactions should only emerge once banks become funding constraint. Therefore this analysis strongly supports the current theoretical insights.

[21] Similar results emerge when undertaking the same analysis with *LRP_M* and the spread between the marginal and policy rate. Interestingly, the R-squared is highest for *LRP* (.76) and lowest for *LRP_M* (.26) whilst the regression with the spread between the marginal and policy rate has an explanatory power of .66 (R-squared is given for the regression using the full sample).

Chart 4: Interactions between funding liquidity risk and market liquidity



Note: *Normal* indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007. *Fitted values* are based on the regression using the whole sample.

Table 2: Regression results of market liquidity index on LRP

	Coefficient	***Standard Error***	***P-value***	***R-squared***
Full sample				
LRP	-9.47	0.51	0.00	0.73
constant	1.03	0.05	0.00	
Normal				
LRP	-0.08	0.50	0.87	0.00
constant	0.46	0.03	0.00	
Turmoil				
LRP	-6.30	2.36	0.02	0.30
constant	0.32	0.41	0.44	

Normal indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007.

Annex 2 presents an updated version of these results until October 2008, using publicly available information. The results are presented in Chart A2.2 and Table A2.2. This extended time series analysis strengthens our results on the interaction between market and funding liquidity risk.

8 Conclusion

In this paper we propose definitions of funding liquidity and funding liquidity risk and present a simple, yet intuitive measure of funding liquidity risk, based on information from the liquidity providing operations of the central bank. We define *funding liquidity* as *the ability to settle obligations with immediacy.* Accordingly, *funding liquidity risk is driven by the possibility that over a specific horizon the bank will become unable to settle obligations with immediacy*. We show that funding liquidity risk has two components: future (random) in- and outflows of money and future (random) prices of obtaining funding liquidity from different sources. Given banks anticipate prices for liquidity in interbank and asset markets, we can show that higher funding liquidity risk in turn leads to higher bids during open market operations conducted by the central bank.

Using information from a data set of 135 main refinancing operations conducted by the ECB from June 2005 to December 2007, we construct two measures of funding liquidity risk, which aim to take into account the (normalised) information of both the price and the quantity of the liquidity demanded. Unsurprisingly, we find that the resulting measures record spikes after August 2007, indicating the presence of increased funding liquidity risk as would have been expected. We also find that our measures bear resemblances with market liquidity and have properties such as low levels, persistence and occasional spikes, which the literature has already identified. Finally we are able to find evidence that there is indeed an inverse relationship between funding liquidity risk and market liquidity risk.

Our two aggregate measures have an important practical advantage. Both can essentially be constructed using publicly available data as they, on aggregate, collapse to the weighted average bid rate minus the policy rate (for *LRP*) or the marginal rate (for *LRP_M*). And the weighted average bid rate, the policy rate and the marginal rate are series reported by the ECB after each auction. In that sense, these measures are particularly interesting to policymakers and market observers, who would want a quick and easy proxy to monitor funding liquidity risk conditions in the economy in real time.

Our analysis is only a starting point in using bidding data to assess funding liquidity risk. It would certainly be interesting to implement our measure for different jurisdictions, such as the United States. There the provision of central bank money is significantly different. Daily OMOs are only conducted with a narrow set of broker dealers, who rely on settlement banks to settle all their transactions (hence they generally settle in commercial bank money). More in line with the auctions described above which should are the newly introduced Term Auction Facility.[22] Here banks can bid directly for central bank money with the maturity of one month. Even though the auction is conducted as a single-price auction format it should be possible to use bids as a measure for funding liquidity risk based on our approach.

Overall, this paper introduces the idea that a proxy for funding liquidity risk can be constructed from bidding data in the central bank auctions. An empirical proxy for funding liquidity risk was missing up to now in the literature. So far, it was thought that such a measure would require a large data set using private information from banks. However, given equilibrium relationships banks' bids during open market operations will reflect funding liquidity risk. Our idea therefore simplifies matters considerably and allows us to construct for the first time a proxy for funding liquidity risk. We are therefore able to provide, for the first time, empirical evidence that funding liquidity risk has similar properties as market liquidity and that funding liquidity co-moves with market liquidity, as suggested by the relevant literature. In that sense our paper provides a useful contribution to the liquidity literature not only because it opens up ways of further empirical research on liquidity, an area of research hindered by the unavailability of proxies, but also because it can be used as a very efficient tool for policy analysis and monitoring.

[22] For further details see http://www.federalreserve.gov/monetarypolicy/taf.htm.

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Annex 1: Funding liquidity and the role of central bank money

In this Annex we provide a more granular view of the key components of the funding liquidity constraint and explain the role of central bank in greater depth. In section 2 we argued that a funding liquidity constraint can be represented by

$$\text{Outflows}_t \leq \text{Inflows}_t + \text{Stock of Money}_t \quad (1)$$

Table A1.1: Components and sources of in- and outflows of money

	Outflow	Inflow
Depositors	$\left(L^{D}_{new} + A^{D}_{due} + AI^{D}_{due}\right)$	$\left(L^{D}_{due} + LI^{D}_{due} + A^{D}_{new}\right)$
Interbank	$\left(L^{IB}_{new} + A^{IB}_{due} + AI^{IB}_{due}\right)$	$\left(L^{IB}_{due} + LI^{IB}_{due} + A^{IB}_{new}\right)$
Asset market	A_{sold}	A_{bought}
Off-balance sheet items	OB_{out}	OB_{in}
Central Bank	$\left(CB^{MRO}_{due} + CBI^{MRO}_{due} + CB^{other}_{out}\right)$	$\left(CB^{MRO}_{new} + CB^{other}_{in}\right)$

Where:

- *L/A* are liabilities and assets of the bank;[23]
- *LI/AI/CBI* are interest payments paid or received by the bank;
- *IB/D* stands for interbank and other depositors (or borrowers);
- *due* stands for assets and liabilities which are contractually due in the period;
- *new* stands for assets and liabilities newly issued; *new* can also include liabilities or assets which are rolled over;
- *OB* are off-balance sheet items which can contribute to *out*- or *in*flows;
- Assets can also be *sold/bought* on the secondary market;
- CB^{MRO} are central bank balances obtained from the weekly main refinancing operations;
- CB^{other} are *in*- and *out*flows of central bank balances obtained directly from the central bank but not in the weekly refinancing operations, for example by accessing the marginal lending or deposit facility or participating in fine tuning operations.[24]

Note: Liquidity will also be determined by other cash flows which can be inflows such as fees and commissions or new equity capital, or outflows such as costs or dividend payments.

Table A1.1 provides an overview of key components of in- and outflows and attributes them to the five main funding sources. Note that in order to keep sub-indices to a minimum, t was dropped in Table A1.1. The reader should keep in mind that time plays an important role for funding liquidity. For liquidity risk management purposes, banks also have to distinguish between different currencies the bank is

[23] These include assets and liabilities in both the banking and trading book.

[24] In the Eurosystem reserves are also remunerated which constitute are part of CB^{other}_{in}.

active in. The stock flow constraint has to hold in each currency but as long as foreign exchange markets are functioning, (funding) liquidity can be transferred. We therefore ignore currency differences in our analysis. The analysis of the stock flow constraint and its components gets also more complicated if the banking system is tiered and some small banks use corresponded banks to participate in the settle and payment system or the central bank auctions. Even though tiering is not uncommon in banking systems, we do not take account of this in our discussion below, but instead focus on the main systemically important banks which also participate in the auctions.

The first source of inflows and outflows is driven by behaviour of depositors. A bank receives an inflow of money if borrowers pay back their loan and/or interest (A_{due}+AI_{due}) or by receiving new deposits (L_{new}). Similarly, outflows can be a result of depositors withdrawing money (L_{due}), the bank paying interest (LI_{due}) or the bank issuing new loans (A_{ne}w). Note that not all withdrawals of depositors have to necessarily lead to a change in central bank balances. A large bank can settle a lot of transactions on its own book. If for example consumer A pays company Y and both have an account at the same bank this transaction gets settled in the bank's own money. If however company Y has an account with another bank, the transfer between the banks is ultimately settled in central bank money. Even though it may be the case that, depending on the settlement system, only net transfers between both banks at the end of the day are settled in central bank money (CPSS, 2003)

The second source is different from the first one only insofar as we distinguish between interbank markets and other depositors/borrowers. Distinguishing is important because the behaviour of interbank markets and other depositors is significantly different. The latter are generally very sluggish to react and do not monitor banks very well (see Gondat- Larralde and Nier, 2004). A further important difference between depositors and the interbank market is that all transfers between large banks are settled in central bank money. In the euro area these transfers take place in TARGET2[25] which is a real time gross settlement system (RTGS), i.e. payments are settled continuously and in gross rather than net amounts.

Whether in- and outflows are secured or not does not matter for the flow analysis. Therefore, repo transactions are also contained in the interbank flows. However, depending on the legal structure, repos can also be asset sales/purchases with a binding agreement to reverse the trade in the future. Asset sales/purchases are the third component in the stock flow constraint. For the conceptual analysis it is not important to distinguish asset sales/purchases from the trading book from those of the banking book. However, practically they differ as equity and bonds held in the trading

[25] TARGET2 became operational in November 2007 and replaced the previous TARGET system.

book can often be traded on organised exchanges in relatively liquid markets (in the sense of market liquidity).[26] Whilst assets held in the banking book are sold and purchased for example via securitisation programmes "over the counter". This requires more time and effort and markets tend to be less liquid, especially during times of stress as could be observed recently (ECB, 2007). Practically, asset sales from the trading and banking book also differ how they are settled. Whilst many over the counter transactions are settled in the payment system and hence involve central money, the interaction of central bank money and securities settlement systems is more complex. A survey by the ECB (2004) highlights the range of practices in the euro area. Settlement can be effectively real time as in Crest in the UK or there can be settlement cycles such as the overnight cycle use by Monte Titoli (Italy) where central bank money is only involved to settle net amounts. Nonetheless, central bank money to achieve finality in the settlement of at least net-transfers always plays an important role.

The fourth source is cash in- and outflows from off-balance sheet activities. An important part of liquidity demands from off balance sheet items (OB_{out}) are committed credit lines to companies or off-balance sheet vehicles such as conduits (see IIF, 2007, BIS, 2006). Essentially, are drawn credit line is a new obligation for the bank. In that sense they could be included in L_{new}. However, for expositional purposes we present them in a separate group as they proved to be a key transmission channel from liquidity problems in the structured credit to the interbank market during the recent turmoil (see ECB, 2007). In addition, margin calls, which are also part of OB_{out}, can have a significant impact on cash flows. However, as part of their contingency preparation, banks themselves generally have contingent liquidity lines with other banks (OB_{in}).

The last source of the stock flow constraint is for our empirical analysis the most important one as banks can obtain new central bank money from the central bank directly. These are also important from a system perspective as all transactions discussed so far do not change the amount of central bank money but represent a transfer from bank A to bank B. Only direct interactions can change the aggregate amount of central bank money in the economy.

Given our empirical measure we distinguish MROs and other interactions with the central bank. MROs are based on repo-arrangements and have a maturity of one week. Hence, new borrowing (CB_{in}^{MRO}) can only be obtained against collateral but the transaction is reversed at the end of the maturity. At this point the bank faces an

[26] Depending on the settlement system, securities settlement generally involves central bank money, especially in the euro area (see ECB, 2004) again indicating the crucial role for central bank money in the economy.

outflow of central bank money, which also includes interest payments ($CB_{due}^{MRO} + CBI_{due}^{MRO}$). In- and outflows of central bank money (CB_{in}^{other} or CB_{out}^{other}) are also generated when banks access the marginal lending or deposit facility (also referred to as the discount window) or if banks participate in fine tuning operations or long term refinancing operations. In the Eurosystem reserves are also remunerated which constitutes another type of inflows of central bank money. In an extreme case, the central bank may also act as a lender of last resort. This is also captured by CB_{in}^{other}.[27]

Annex 2: Update Charts and Tables

This annex presents Charts 2 and 3 and Tables 1 and 2 with updated information up until October 2008. The data presented in this section are based entirely on publicly available information as suggested in Section 4 (see also footnote 19) and the conclusion. Of course, only aggregated data are presented, as data for the individual adjusted bids, the bid rates and the volumes are not available. Two main issues can be extracted from the updated data:

First, the intensification of funding liquidity risk during 2008 continued and assumed dramatic levels after the Lehman Brothers collapse in September 2008.

Second, the negative relationship between funding and market liquidity risk appears even stronger. The results are even more robust, given the extended data sample.

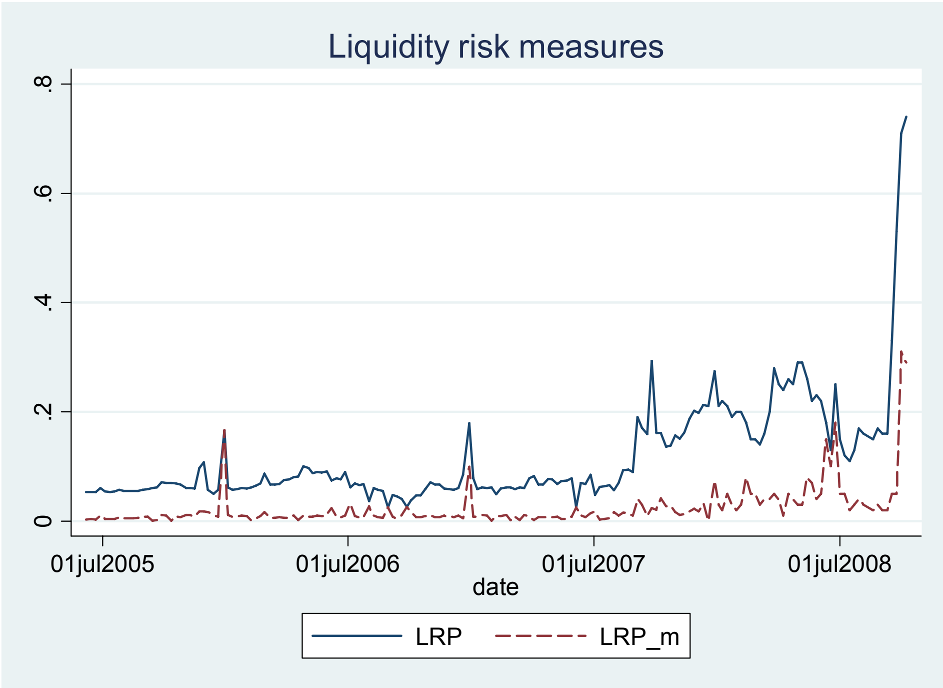
Table A2.1: Statistics (excluding year ends)

	LRP			LRP1LRP_M		
	Normal	**Turmoil**	**Ratio**	**Normal**	**Turmoil**	**Ratio**
Mean	0.066	0.213	3.216	0.011	0.048	4.365
Variance	0.020	0.118	5.815	0.018	0.056	3.156
min	0.025	0.090	3.625	0.000	0.001	3.795
max	0.179	0.740	4.124	0.166	0.310	1.866
Obs	114	60	0.526	114	60	0.526

Note: *Normal* indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007. *Fitted values* are based on the regression using the whole sample

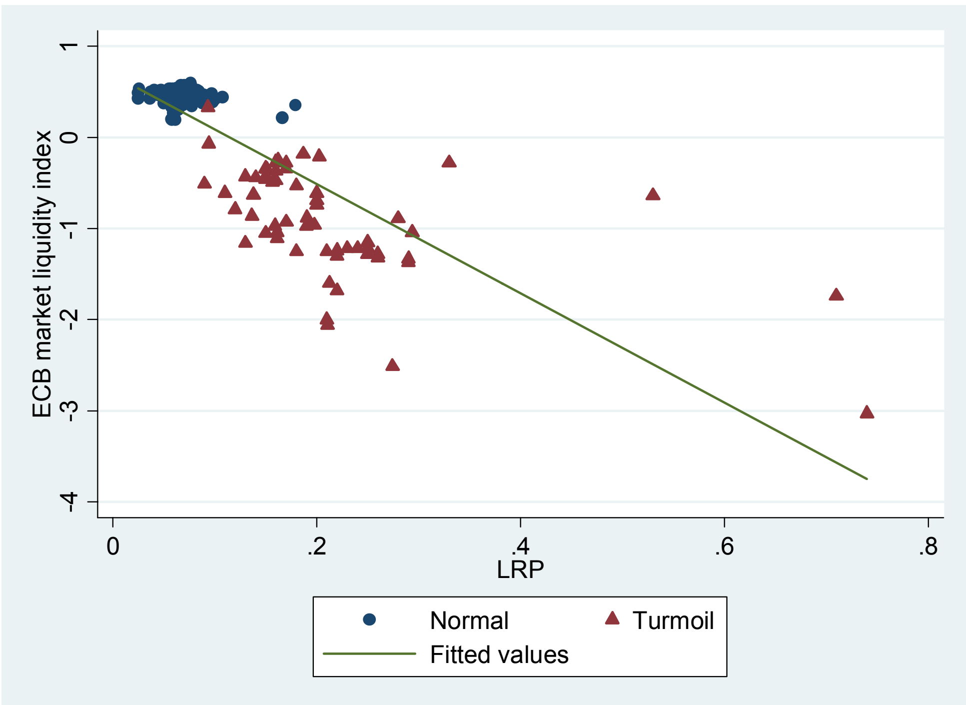
[27] Banks' direct access to central bank money differs significantly across jurisdictions as has been shown in the short discussion in Section 7 about differences in the US and Europe. Collateral accepted is also different for different countries. In many countries such as the US accessing the marginal facilities is also associated with a stigma and may have reputational repercussions for the bank. Stigma is the euro area is less pronounced.

Chart A2.1. LRP and LRP_M (excluding year-ends)



Note: The Chart presents the LRP and LRP_M measures including the last operation of each year.

Chart A2.2: Interactions between funding liquidity risk and market liquidity



Note: *Normal* indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007. *Fitted values* are based on the regression using the whole sample.

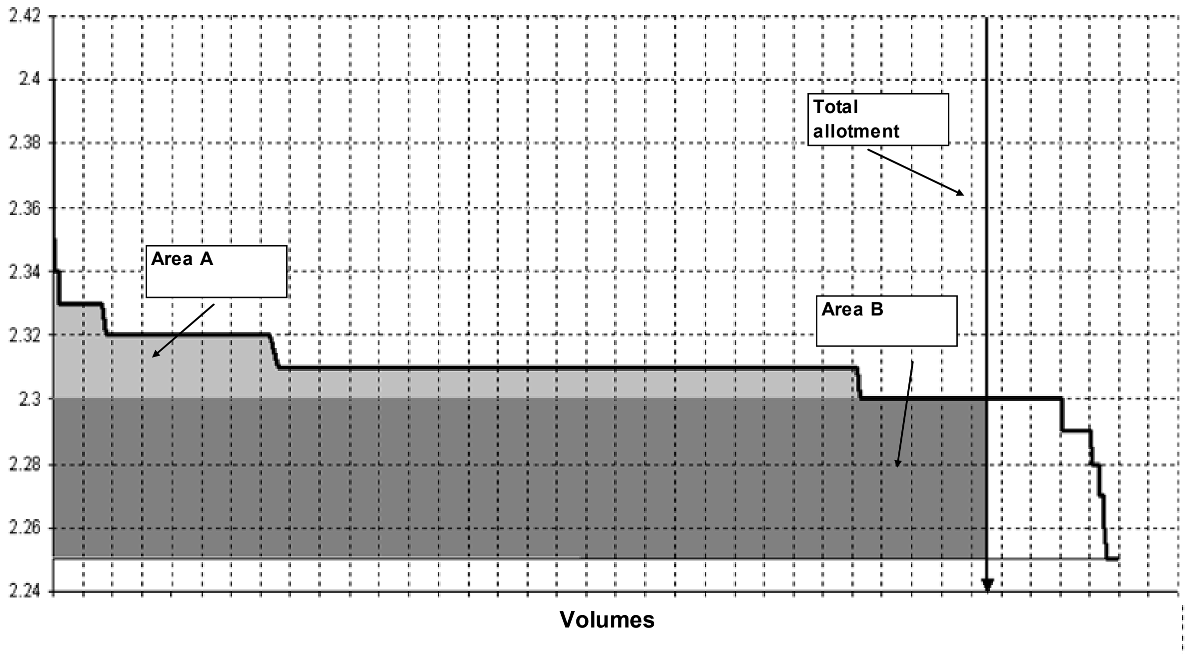
Table A2.2: Regression results of market liquidity index on LRP

	Coefficient	Standard Error	p-value	R-squared
Full sample				
Market liquidity	-0.112	0.006	-18.140	0.727
constant	0.115	0.004	25.820	
Normal				
Market liquidity	-0.003	0.018	-0.170	0.003
constant	0.066	0.008	7.780	
Turmoil				
Market liquidity	-0.121	0.022	-5.440	0.295
constant	0.106	0.023	4.540	

Normal indicates the period from June 2005 until 7 August 2007. *Turmoil* is the remaining period until December 2007.

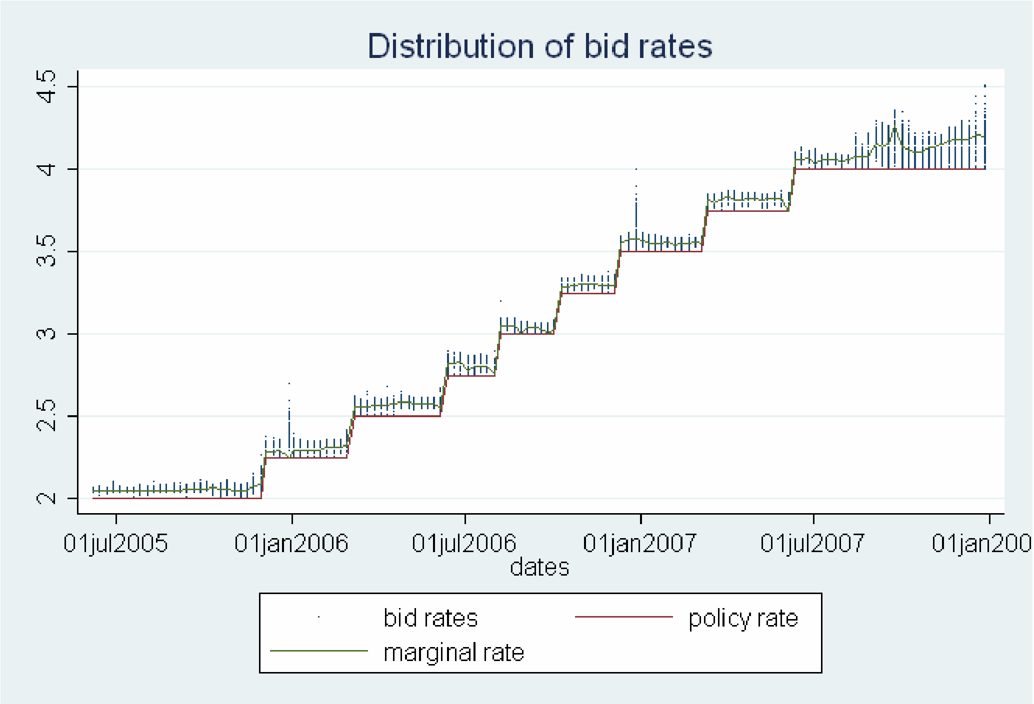
Annex 3: Additional Charts

Chart A3.1: A central bank auction and the funding liquidity risk measures.



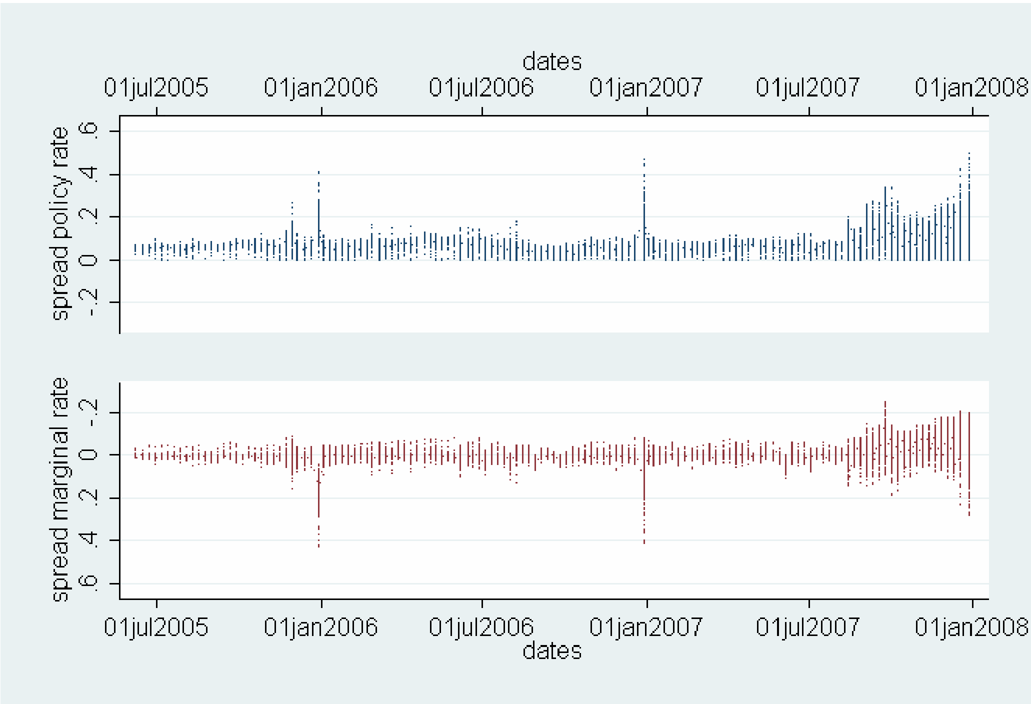
Note: Thick black line is the aggregate demand curve. LRP=[(Area A + Area B)/ total allotment], LRP_1=[Area A / total allotment]

Chart A3.2: Bid rates in ECB MRO auctions



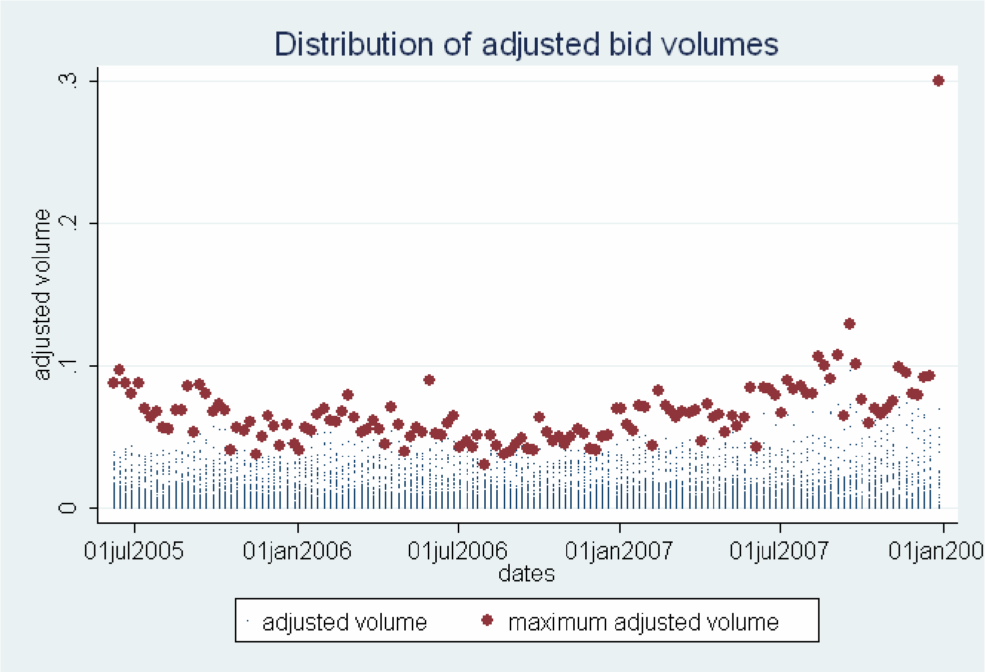
Note: The chart presents the individual bid rates of all banks participating in the ECB MROs from June 2005 until December 2007. It also presents the unique policy rate and marginal rate for each auction.

Chart A3.3: Bid spreads in ECB MRO auctions



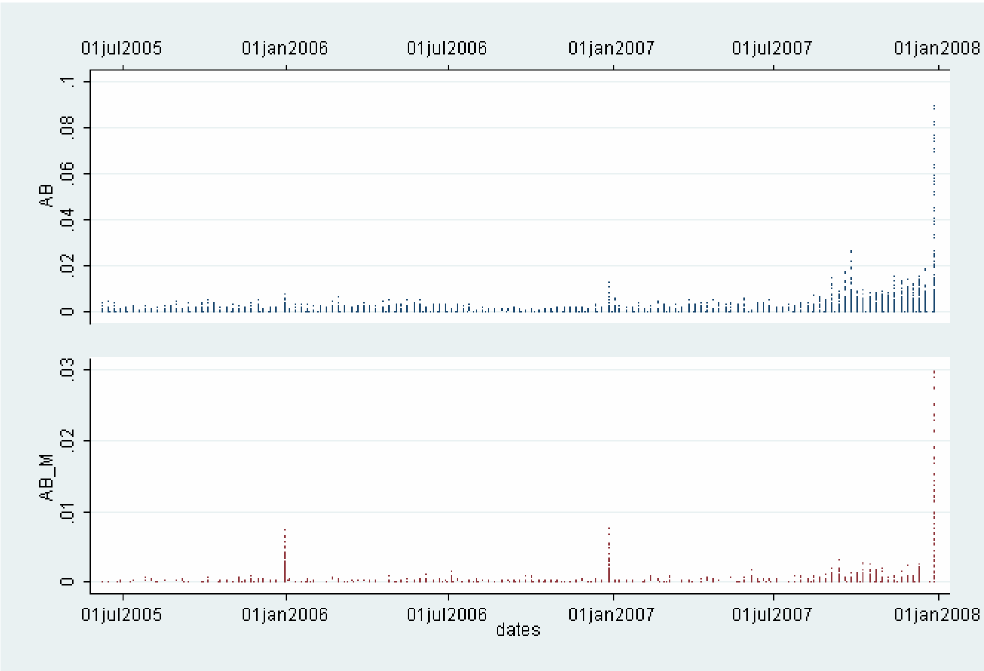
Note: The chart presents the individual bid spread of all banks participating in the ECB MROs from June 2005 until December 2007. The spread from the policy (marginal) rate is measures by the difference between the bid rate and the policy (marginal) rate.

Chart A3.4: Adjusted volumes in ECB MRO auctions



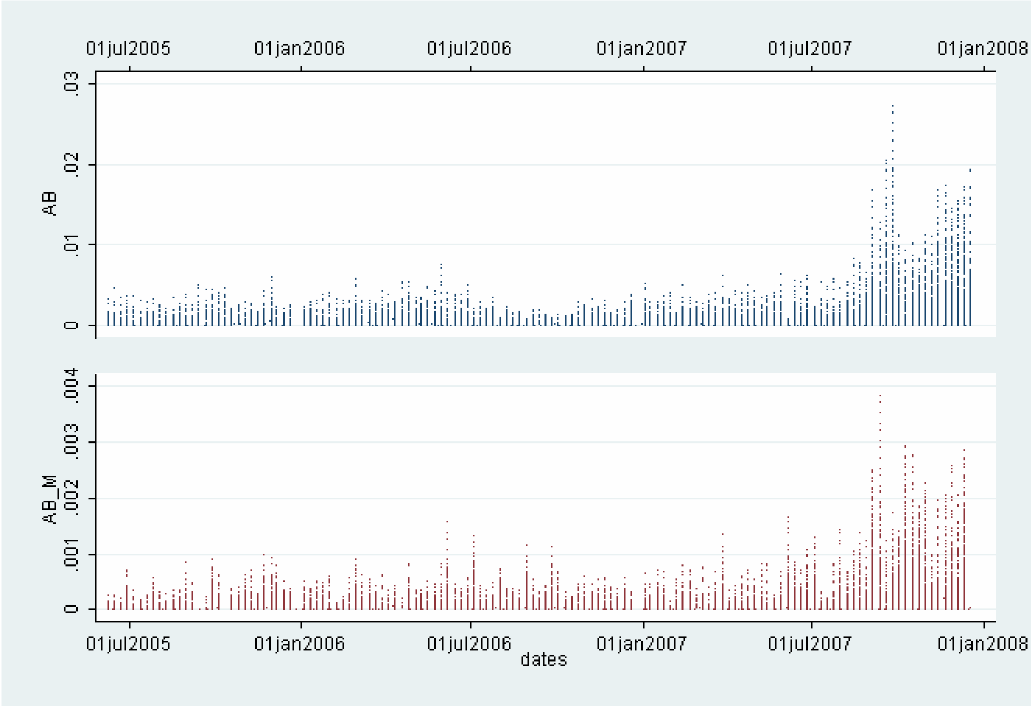
Note: The Chart presents the adjusted bid volumes of all banks participating in the ECB MROs from June 2005 until December 2007. The adjusted volume is measured as the individual allotted volume divided by the sum allotted volumes in the respective auction. For each auction it also present the maximum value for the adjusted volume measure.

Chart A3.5: Distribution of adjusted bids (including year-ends)



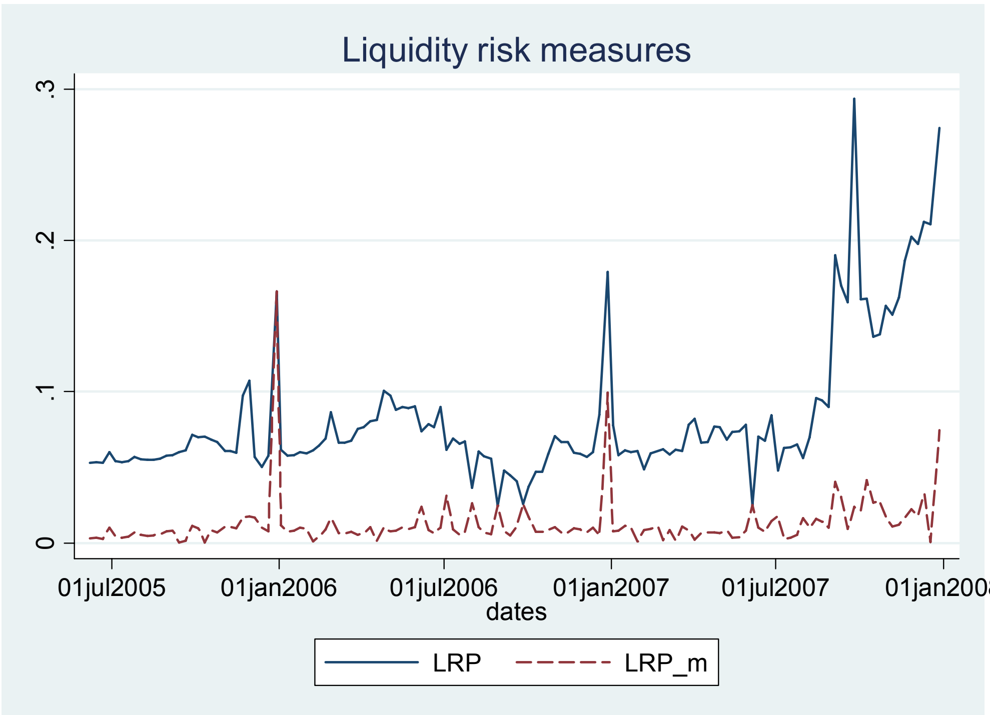
Note: The Chart presents adjusted bids including the last operation of each year. The upper chart, denoted *AB*, depicts individual adjusted bids where the spread is equal to the bid rate minus the policy rate. Equivalently, the lower chart denoted *AB_M* depicts individual adjusted bids where the spread is equal to the bid rate minus the marginal rate.

Chart A3.6: Distribution of adjusted bids (excluding year-ends)



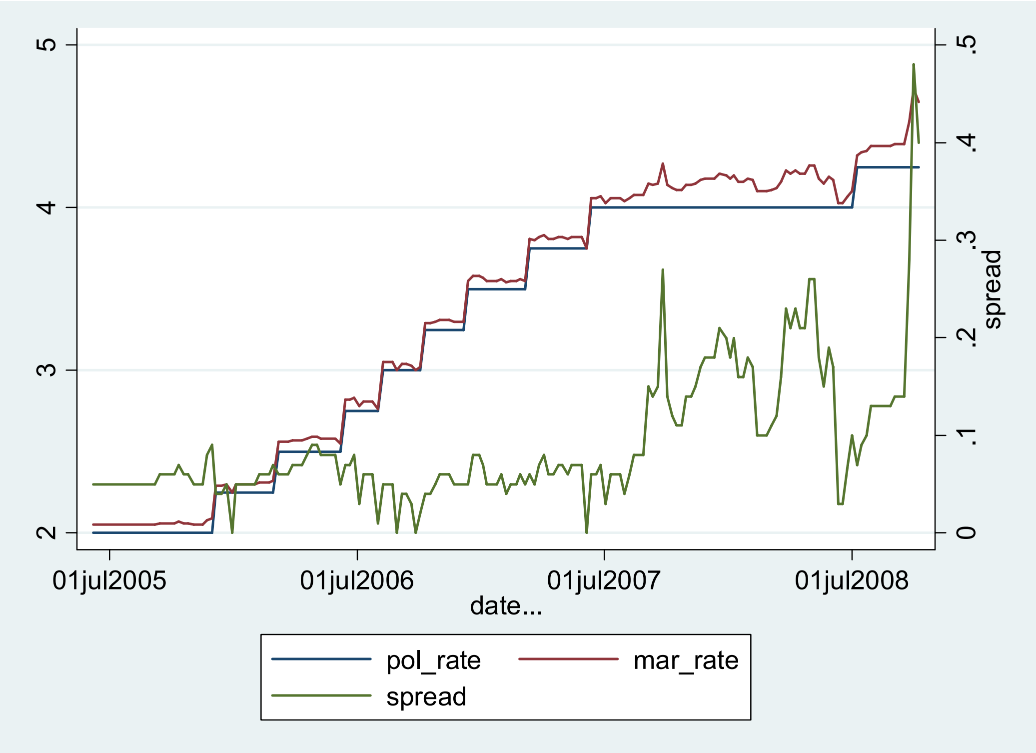
Note: The Chart presents adjusted bids excluding the last operation of each year. The upper chart, denoted *AB*, depicts individual adjusted bids where the spread is equal to the bid rate minus the policy rate. Equivalently, the lower chart denoted AB_*M* depicts individual adjusted bids where the spread is equal to the bid rate minus the marginal rate.

Chart A3.7. LRP and LRP_M (including year-ends)



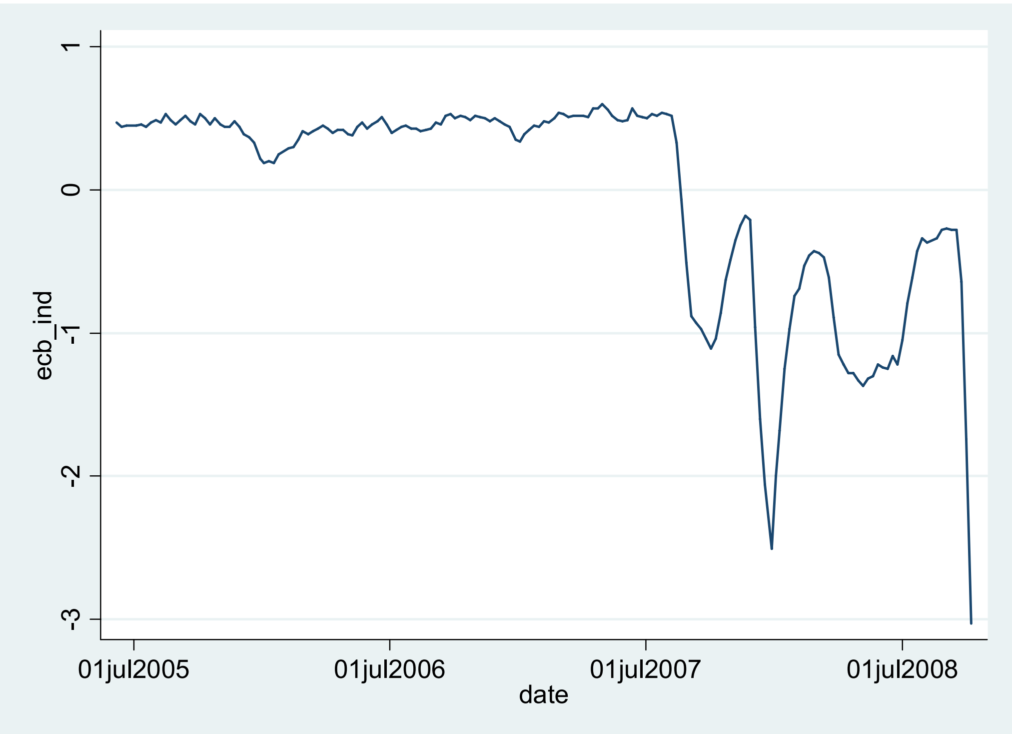
Note: The Chart presents the LRP and LRP_M measures including the last operation of each year.

Chart A3.8: Interest rates in the euro area



Note: The Chart presents the policy rate and marginal on left hand axis (in %). The spread is the difference between the marginal rate and the policy rate (right hand axis, in %)

Chart A3.9: ECB financial market liquidity indicator



Note: For further information see Chart 3.1 ECB (2008)