

Endogenous maturity mismatch, maturity of open market operations and liquidity regulation

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Abstract

This paper provides a theoretical model for a bank's choice of the maturity structure of its assets and liabilities in a setting where banks can be of different risk types. We derive implications for banks' demand for long-term liquidity at central bank open market operations, and discuss the impact of the newly proposed liquidity regulation under the Basel III framework. In the empirical analysis, a positive and significant relationship between a bank's maturity mismatch and its (traded) credit risk is found. Further, using data from Eurosystem refinancing operations, we find that stressed banks are more likely to participate in central bank refinancing operations in general and at those with longer maturities in particular.

JEL CLASSIFICATION: G01, G21, D82

KEYWORDS: Financial crisis; Interbank market; Liquidity; Central bank interventions, Liquidity regulation

1 Introduction

One of banks' core functions is maturity transformation. By channelling short term funds (like retail deposits or corporate cash balances) into long term investments (like mortgage loans), banks can create value and allow profitable investments to be undertaken. However, the financial crisis demonstrated clearly that maturity transformation creates or amplifies financial fragility: If markets for obtaining short-term liquidity dry up, all those financial institutions that relied on obtaining short term financing face problems. Given the potentially systemic nature of this, and the risk to fuel the spiral of further fire sales and asset devaluations, central banks in many countries offered (in most cases additional) liquidity to the banking sector, for instance in the form of repurchase agreements (repos).¹ In particular, the overall amount of such liquidity provision has increased in many countries, as has the average maturity of those repos, because (some) banks have shown a strong appetite for central bank intermediation, especially at longer maturities during the crisis. This is documented in this paper for the case of the Eurosystem.

These support measures helped in particular those institutions in need for funding, and contributed to stabilizing the financial system. However, public intervention (umbrellas) usually create moral hazard. In particular, it is not clear whether central bank liquidity provision is a factor that helps sustaining a degree of maturity mismatch that (some) banks would otherwise not be able to engage in. For instance,

¹A prominent example here is the TAF introduced in December 2007 by the Fed, which effectively increased the part of the liquidity deficit that is provided through repos. In the case of the Eurosystem, large repos operations have always played an important role. The initial response of the ECB was thus concentrated in lengthening the maturity of its menu of repos.

it is likely that especially those banks with the least ability to obtain funds in the money market will have turned to the central bank and may remain dependent on central bank refinancing for some time.

This paper investigates these issues from a theoretical and empirical perspective. In addition, the paper addresses from a theoretical viewpoint the liquidity regulation that has been proposed by the Basle Committee for Banking Supervision as a part of the Basel III package and its impact on banks' choice of maturity mismatch and the demand for liquidity at central banks' operations.

A theoretical model in which banks' optimally engage in maturity transformation depending on their inherent ability to generate profits from such an activity is used to derive these banks' demand for central bank refinancing in times of crisis. In the empirical analysis, first the relationship between the risk of a bank (its CDS spread) and the maturity structure of its assets and liabilities is analysed. To this end, we collected data for a subset of large European banks (the Euribor panel) and employ a panel econometric approach. Secondly, banks' participation in the Eurosystem's open market operations is measured and analysed according to whether or not a participating bank was subject to stress and differentiating between the pre-crisis period and the period after August 2007.

Several recent research papers have addressed the issue of maturity mismatch. Brunnermeier and Oehmke (2010) analyse the *lenders'* choice of loan maturities and argue that those have incentives for shorter maturities in order to be the first in line to retrieve funds - similar to a bank run argument. In contrast, our paper studies the *borrower's* choice of funding maturity structure. Other recent papers study the

impact of liquidity regulation: Huberman and Repullo (2010) criticize the regulations by stressing the beneficial role of short-term funding as a disciplinary device that can alleviate moral hazard. Perotti and Suarez (2010) investigate whether liquidity regulation should be in the form of a tax or in the form of quantity restrictions. Our paper tries to give a new perspective by studying the role of the central bank in this context.

The paper is structured as follows: in section 2, a theoretical model of banks' choice of their maturity structure is modelled. The role of the central bank is studied as well as the impact of liquidity requirements. Section 3 provides an empirical analysis of the main testable implications of the model. Section 4 concludes.

2 A theoretical model

We want to model the interaction with bank's choice of maturity mismatch, the liquidity provision by the central bank, and the impact of liquidity regulation. Several ingredients are necessary to capture some stylized facts observed during the recent crisis:

First, for the modelling of the maturity mismatch, *liquidity risk* is an important factor: for banks with a high degree of maturity mismatch, loans need to be rolled over frequently, and the risk implied by this should form part of the model. Second, for the modelling of central bank intervention, we would like to account for the empirical fact that predominantly troubled banks bid for central bank liquidity during crisis times. This is most likely a result of *credit risk* (and asymmetric information),

which makes market refinancing for those banks difficult or expensive.

The model does not aim at providing a judgement on whether the maturity mismatch taken on by banks was excessive prior to the crisis. Instead, the focus is on the interaction between the choice of maturity mismatch, central bank liquidity provision, and liquidity regulation.

2.1 Investment banks

We consider a model of an investment bank that has invested one unit in a long-term asset. The asset is risky and pay off a return R , with $R > 1$, after a time period of length a , with some positive probability p (and 0 otherwise). If liquidated before maturity, the assets yields zero.

Banks can only invest in this single asset, they cannot diversify. It is assumed that the bank can obtain funds in the wholesale market. It has no own capital, and does not issue demand deposit contracts, as in Diamond and Dybvig type of models, and thus does not face the probability of runs, or uncertainty about withdrawals at any point in time.

The bank can decide how to finance this investment by choosing the average length of its liabilities, l , where $l \leq a$. We would like to model the choice of maturity mismatch. In order to be able to differentiate banks, we assume that banks can be of different types, characterised by a parameter θ , where $0 \leq \theta \leq 1$. This parameter determines the bank's ability to generate profits from engaging in maturity mismatch, but at the same time, determines its credit risk. That is, there will be banks with

a high ability to generate profits (θ high), but a low probability of success of the asset, $p(\theta)$, with $p'(\theta) < 0$. Conversely, there will also be banks with a lower ability to generate profits, but a higher probability of success. θ can also be interpreted as the result of the bank's choice between risk and return.

In particular, we assume that the bank's return from a higher maturity mismatch is

$$\theta\left(1 - \frac{l}{a}\right)$$

where $\left(1 - \frac{l}{a}\right)$ characterizes the maturity mismatch. If the bank chooses a perfect match of assets' and liabilities' maturity, $l = a$, and it creates no profit from maturity mismatch. For any $l < a$, an additional return will be generated.

In later versions of the model, banks will be able to choose from a menu of different maturities in their refinancing. In the baseline model studied here, a bank only has the choice between two options: it can choose either long-term financing (with maturity a) or short term financing, with maturity $\frac{a}{2}$. The latter would need to be rolled-over once. Thus, in the baseline model we distinguish three points in time: at time 0, the investment is made and financing is secured. At time 1, the bank that has chosen short-term liabilities needs to refinance. At time 2, the asset matures and the loan providers can be repaid.

There is no asymmetric information in the model; that is, the types θ are known. The uncertainty on whether the risky asset yields a positive return is resolved only at time 2.

Finally, we assume that banks need to hold reserve requirements, which they

obtain in open market operations from the central bank, at an interest rate $1 + r^{CB}$.

2.2 Aggregate uncertainty

We assume that there is aggregate uncertainty in that there is a certain (exogenous) probability of a financial crisis.² We are particularly interested in the case that a crisis occurs at the interim state, where banks with short term liabilities need to refinance. Thus, we assume that at time 0, the probability of a financial crisis, γ , is known, and at time 1 it is revealed whether the crisis materializes or not.

If a crisis occurs at time 1, then markets for loans are assumed to dry up - banks wanting to refinance a loan will not be able to do so, no matter at which interest rate. This could be the case because lenders hoard liquidity, or because their own need for liquidity has increased.³ We take this behaviour of the market as given, and take it as a stylized fact that was observed at the peaks of the recent financial crisis.

Notice that if a crisis occurred already at time 0, there would trivially be no lending.

2.3 Interbank market

We assume that all private lending takes place in the unsecured wholesale market. The interbank market is not modelled fully.⁴ Instead, we simply assume that there are lenders in the economy who are willing to provide credit to investment banks,

²NOTE: interesting would be if the probability γ depended on the maturity mismatch of the economy. This is for later.

³See, for instance, Eisenschmidt and Tapking (2008) or Heider, Hoerova and Holthausen (2009)

⁴[A fully fledged interbank market with lender's decision problems in a financial crisis is under construction by the authors]

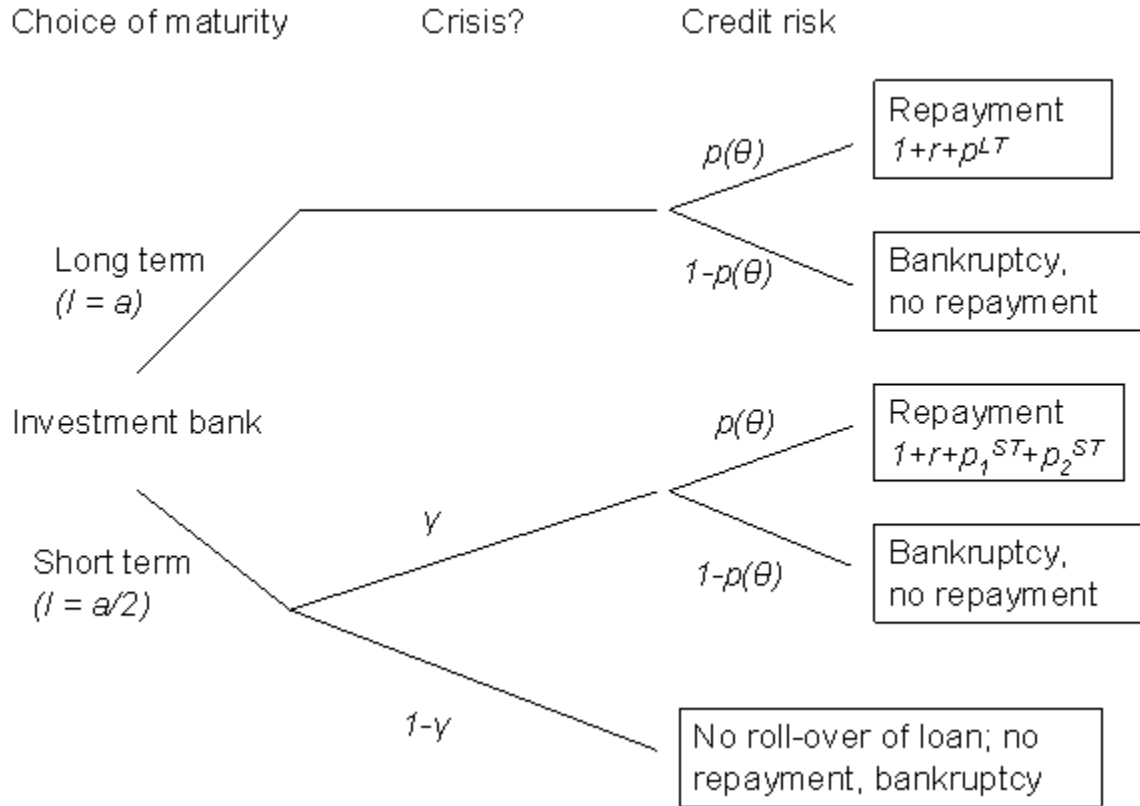


Figure 1: Event tree

as long as appropriate interest rates are paid. In particular, we assume that lenders should be indifferent between lending either short- or long term to banks and obtaining at a risk-free rate $1 + r$ elsewhere in the market. This risk-free rate is assumed to remain constant over time. This implies that lenders have to be compensated for credit and liquidity risk by charging appropriate premia.

In particular, interest rates to banks with long-term refinancing will reflect the asset's credit risk. Lenders will demand a credit risk premium p^{LT} so that they are indifferent between obtaining the risk free rate $1 + r$ for sure, or to obtain in addition

a premium, but with some risk, that is $1 + r \stackrel{!}{=} p(\theta)[1 + r + p^{LT}]$. This implies

$$p^{LT}(\theta) = \frac{1 - p(\theta)}{p(\theta)}(1 + r).$$

Similarly, the last bracket of short-term refinancing carries credit risk, such that a premium $p_2^{ST} = p^{LT}$ will apply. The first bracket of short-term lending, on the other hand, is not influenced by credit risk, but instead by liquidity risk considerations. Lenders know that banks will only be able to repay the short-term loan at time 1 if there is no crisis, i.e. with probability $1 - \gamma$. Thus, they demand a premium p_{ST}^1 so that $1 + r \stackrel{!}{=} (1 - \gamma)[1 + r + p_{ST}^1]$ or

$$p_1^{ST}(\gamma) = \frac{\gamma}{(1 - \gamma)}(1 + r).$$

2.4 Choice of maturity mismatch

The bank's only choice variable is the extent of maturity mismatch. In this baseline model, banks can choose between $l = a$ (long term) and $l = a/2$ (short term). The expected profit of a bank of type θ at time 0 for either case are

$$\Pi_{\theta}^{LT} = p(\theta) [R - (1 + r) - p^{LT}]$$

for a long-term funding strategy and

$$\Pi_{\theta}^{ST} = p(\theta)(1 - \gamma) \left[R + \frac{\theta}{2} - (1 + r) - p_1^{ST}(\gamma) - p_2^{ST} \right]$$

in case of short-term funding.

Notice that in the case of long-term financing, the bank's asset yields a positive return with probability $p(\theta)$. If the bank has chosen short-term financing, however, it faces the additional risk of a crisis in the interim stage, which would imply liquidation of the asset. Thus, it will generate positive profits only with probability $p(\theta)(1 - \gamma)$.

In order to generate interesting results, we make one additional assumption: if a bank is of a very high risk type, then the credit premium charged to it is too high to be able to be borne by the bank if it chooses long term funding. That is, we assume the following:

Assumption 1 *There is a $\bar{\theta}$, $0 < \bar{\theta} < 1$ for which $p(\bar{\theta}) = \frac{1+r}{R}$.*

This assumption says that for some intermediate type $\bar{\theta}$, the profits from a long-term funding strategy will be just zero, in case the long term asset is successful. This implies that banks with $\theta \geq \bar{\theta}$ will never be able to obtain a long term loan, because they could never repay the loan in full. In contrast, it does not preclude them from obtaining short term loans, not even in the second period, in which credit risk plays a role, because of the additional profits from maturity mismatch.

Given $p_2^{ST} = p^{LT}$, the direct comparison between the two profit functions yields

Lemma *A bank of type θ chooses long term refinancing if and only if $\theta \leq \hat{\theta}$ where*

$$\hat{\theta} = \frac{2\gamma}{1-\gamma} [R - (1+r) - p^{LT}] + \frac{2}{1-\gamma} p_1^{ST}.$$

Thus, as to be expected, only banks with a relatively low ability to profit from maturity mismatch would choose long-term refinancing.

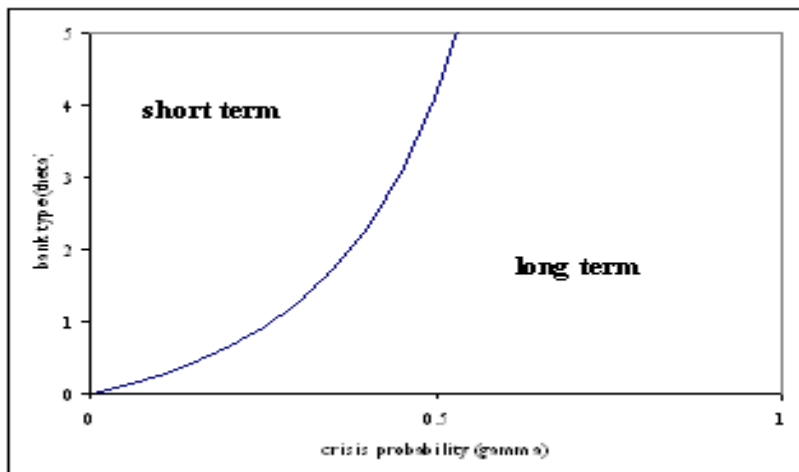


Figure 2: Bank's choice of liability structure

The choice between the two funding possibilities is essentially a trade-off between a higher return from a higher maturity mismatch and the expected costs from a financial crisis. The latter depends on two terms: the first term in the expression for $\hat{\theta}$ captures the fact that in the event of a crisis, the expected profits from investment in the asset will not be realized only if a short-term funding strategy is chosen, because a crisis impedes re-financing. The second term captures the liquidity risk premium that needs to be paid to ensure lenders against losses this event.

Moreover, the possibility of a financial crisis influences bank's behaviour: it is easy to see that $\frac{\partial \hat{\theta}}{\partial \gamma} > 0$, implying that a higher the probability of a financial crisis (γ) leads to a lower $\hat{\theta}$. In other words, more banks choose a long-term funding strategy if the crisis is more likely. This is because a high crisis probability increases the liquidity risk at time 1 and thus makes short-term funding more expensive (see figure 2)

2.5 First best

Let us first consider the case of a bank that has chosen long-term financing. Comparing investment and return from the asset, it is trivially the case that

Proposition 1 $p(\theta) \geq \frac{1}{R}$ is a sufficient condition for the investment in the asset to be efficient.

For a high success probability, that is, for a low bank type θ , investment into the asset is efficient. Note that this implies that there will be banks for which it would be efficient to invest in the asset, but who would not get long-term financing. These are all banks for which $\frac{1}{R} < p(\theta) < \frac{1+r}{R}$. The reason is banks' limited liability which gives rise to a positive risk premium which needs to be paid only in case of success.

It is less obvious under which conditions investment with short-term funding is efficient. This results from the fact that we have not specified where the additional returns from the investment in maturity mismatch stem from. If those result purely from arbitrage possibilities, then the move from a long-term to a short-term funding strategy implies only redistribution of returns, but not their creation. We leave this question open and focus on the efficiency with a long-term funding strategy.

2.6 The central bank

We now introduce a central bank. In our model, the central bank can play two distinct roles: first, it wants to influence the market interest rate and conducts open market operations with this purpose. For simplicity, assume that the central bank auctions off each period a certain amount of liquidity α at interest rate $1 + r^{CB}$,

which is equally distributed across banks. In normal times (to be specified below), banks are assumed to bid only for this quantity α . The intervention of central banks has played a big role in the resolution of the financial crisis of 2007/2010. The second function of a central bank in this model is thus one of crisis intervention.

In the present model, the rationale for central bank intervention would be the following: assume that at time 1, a financial crisis materialized. In this case, there will be banks with funding needs - essentially those who need to roll over their loans, but are unable to do so because of a market freeze. If they are not able to secure funding anywhere, then they would need to liquidate their long term asset at a penalty (recall that the liquidation value of the asset is taken to be zero, so the penalty is to forego future profits and declare bankruptcy). This is socially inefficient if projects have a positive net present value, i.e. when the probability of success is relatively high.⁵ Liquidity provision by a central bank could thus be beneficial when it provided liquidity when a crisis has materialized, because inefficient liquidation could be avoided.

Moreover, central bank liquidity provision could also have effects at time 0: consider the case that the probability of a financial crisis (γ) is very high. In this case, it might not be possible for banks to obtain short-term funding even at time 0, because lenders would demand a very high premium in order to protect them against losses in case of a financial crisis. Indeed, for the following argument, assume that γ is so high, that no bank would obtain a short term credit at time 0. If one recalls that by

⁵This would hold especially in the case that massive liquidations would have repercussion effects (downward spiral effects etc) in the economy. That is, the benefits of intervention may be larger than the benefits for the individual banks.

assumption, banks of the high type ($\theta > \bar{\theta}$) are not able to obtain long-term funding in the market because of their high credit risk, this would imply that they could not make profitable investments.

In this case, demand at the central bank's open market operations would increase compared to the normal (low probability of crisis) situation: in addition to those banks with a normal demand for liquidity, α , also those banks that would be cut off from private credit would adhere to the central bank. Moreover, those banks with no other possibility to obtain funding would be willing to pay a higher price for this source of funding than other banks. Depending on the design of the auction, this could lead to a higher auction interest rates than in normal times. In particular, this could happen in a variable rate tender in which liquidity is allocated to banks according to the level of their bid rates.

Let us consider a fixed-rate tender auction, in which the central bank supplies all the liquidity that is demanded at an interest rate $r^{CB} = r + \varepsilon$, with $\varepsilon \geq 0$. The positive ε could reflect the cost of pledging collateral in the central bank's operation, which is a usual practice among central banks in order to protect them against credit risk. Then we have the following:

Proposition 2 *Assume that the probability of a crisis, γ , is so high that no bank obtains short term funding at time 0. Then, a bank of type θ will demand funding from the central bank if and only if $p(\theta) \leq \frac{1+r}{1+r+\varepsilon}$.*

Since $p(\theta)$ is decreasing in θ , this implies that it is predominantly the high-type banks that will demand central bank funding. This result follows from the fact that

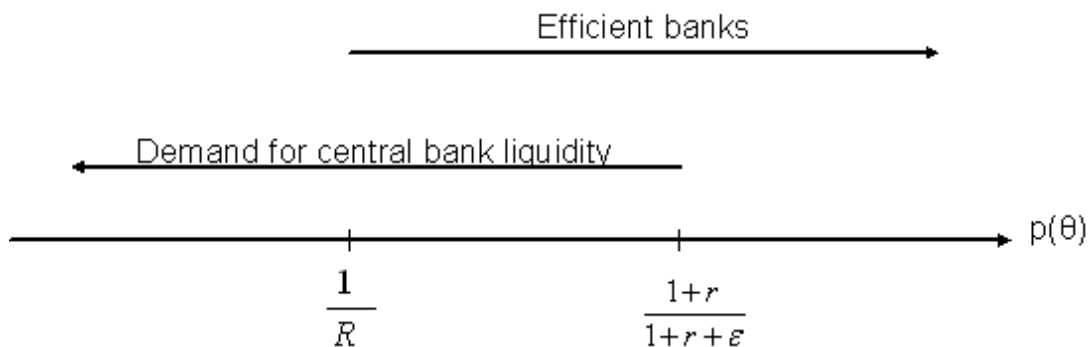


Figure 3: Demand for long-term central bank liquidity

those banks have to pay the highest credit risk premia in the market, which they would like to avoid.

With this result, is it socially optimal that the central bank supplies funding at time 0? Recall from Proposition 1 that it is not necessarily efficient that the high types invest in the asset, given their relatively high probability of failure. This is illustrated in figure 3. The central bank thus would need to weigh the benefits against the shortcomings from investment of a group of relatively high risk banks. This depends on a range of parameter values, including the distributional assumptions about θ .

2.7 The effect of liquidity regulation

Liquidity regulation, as foreseen by the Basel Committee on Banking Supervision (see BCBS 2010), will limit the amount of maturity mismatch that banks can take. In particular, it will generate incentives for banks to have more liquid assets on their balance sheets in relation to expected outflows over a short horizon.

In this model, we model the impact of liquidity regulation as limiting the difference between the average maturity chosen by a bank, $a - l$, that is, a lower bound for the ratio $\frac{l}{a}$. We assume that the regulation is binding at least for a subset of banks, i.e. those that have chosen short-term funding so that $\frac{l}{a} = 1/2$.

Assumption 2 *Assume that liquidity regulation requires $\frac{l}{a} \geq \hat{\frac{l}{a}}$ for all banks, where $0 < \hat{\frac{l}{a}} \leq 1$.*

The regulation would imply that all banks that would choose short-term funding in the absence of regulation would need to switch (at least partially) to long-term funding. However, given that for banks of high θ -types, long-term refinancing in the market is not possible, these banks would resort to the central bank to obtain long-term financing. This would boost their liquidity profile, but not force them to pay high penalty rates in the market that are related to their risk profile.

Because the most risky banks are those for whom long-term funding is most expensive, it would again be those banks that would be driven to choose long-term central bank funding. The effect discussed in the previous subsection would thus be exacerbated:

Proposition 3 *As a result of the liquidity regulation, (1) demand for longer-term operations would increase, (2) the increase would lead to an increase in the average credit risk of the banks participating in the central bank open market operations.*

3 Empirical results

In this section two empirical relationships are explored. We start with banks' liquidity risk, as measured by their maturity mismatch and their perceived riskiness as measured by CDS spreads. We then turn to evidence from Eurosystem refinancing operations and analyse banks' demand behaviour in dependence of their riskiness.

3.1 The relationship between banks' maturity mismatch and their riskiness

In this section we provide some empirical evidence on the relationship between the difference between the (average) maturity of a bank's assets and its liabilities, i.e. a bank's maturity mismatch and its perceived riskiness. To this end, we obtained data from regulatory filings (form 20-F and in some cases annual reports) of large European banks contained in the Euribor panel. The majority of these banks publish once a year a relatively detailed breakdown after maturities of the assets in their banking book (i.e. loans to customers and banks) and the liabilities used to fund these lending activities. The average maturity of banking book assets and liabilities in days is obtained for a total of 20 banks for the years 2007-2009 giving rise to an overall of 60 observations.

The average maturity of assets and liabilities in the sample is given in Table 1. The maturity of liabilities is on average roughly one-fifth of the average asset maturity. This implies that banks need to roll-over loans on their banking book on average four times.

	Mean	Max	Min
Assets	928	1,568	252
Liabilities	194	701	25

Table 1: Results of panel regression of average CDS spreads on maturity mismatch and a dummy variable reflecting severe stress

	average	2007	2008	2009
maturity mismatch	733	645	749	805

Table 2: Results of panel regression of average CDS spreads on maturity mismatch and a dummy variable reflecting severe stress

Table 2 shows the evolution over time of the average maturity mismatch. Somewhat surprisingly, the mismatch in maturities increased during the years of the financial crisis. This was probably a result of increased difficulties to obtain long-term refinancing in the market.

Given the structure of the data (small T, large N), a panel regression approach is chosen. Specifically, we estimate the standard random effects panel regression model

$$Y_{it} = \alpha + \beta X_{it} + \varepsilon_{it} \text{ where } \varepsilon_{it} = v_i + u_{it}$$

with Y_{it} being the average CDS spread of bank i in year t and X_{it} containing the maturity mismatch of bank i in year t and a control for severe stress which is either 0 (no severe stress) or 1 (bank was under severe stress in that particular year) and which can vary over time.⁶ The main reason for inclusion of this dummy variable is to control for a potentially severe heterogeneity bias, since the sample essentially contains two distinct types of banks. Furthermore, one Irish bank needed to be

⁶We use the same methodology to derive the indicator variable than used in the section on banks' participation in Eurosystem refinancing operations.

Variable	Coefficient	Standard deviation
Maturity mismatch	0.049	0.019
Severe Stress (dummy variable)	58.04	15.01

Table 3: Results of panel regression of average CDS spreads on maturity mismatch and a dummy variable reflecting severe stress

excluded from the sample, as no maturity relevant data on its (significant) mortgage lending activities could be found. The average maturity mismatch in our sample is 733 days, increasing from 645 days in 2007 to 805 days in 2009. The results of regression of the average CDS spread of the bank in the corresponding year on the banks' maturity mismatch in days and a control for severe stress are shown in table 3 below.

The standard Hausman test does not reject the random-effects specification (against the fixed-effects alternative). Overall, sign and magnitude of the coefficient appear plausible. Both coefficients are highly significant. The results suggest that, on average, an episode of severe stress was associated with a 58 basis points higher CDS spread for the bank subject to that stress. More interestingly, a day more of maturity mismatch was associated with a 0.05 basis point increase in the CDS spread of the bank.

Our approach may be overestimating the risk stemming from the banking book of the bank, as this classic lending activity is in some cases contained in the sample rather small. For instance, an investment bank (or a commercial bank with large investment banking arm) will likely have a large trading book, which can easily become bigger than the bank's banking book. We try to control for this by obtaining the share the banking book had in total assets of the bank and scaling down by this

Variable	Coefficient	Standard deviation
Maturity mismatch	0.035	0.014
Severe Stress (dummy variable)	35.94	10.98

Table 4: Results of panel regression of average CDS spreads, corrected by share of banking book in total assets of the bank, on maturity mismatch and a dummy variable reflecting severe stress

number the dependent variable in our regression (the average CDS spread). The results of the new regression are contained in table 4 above.

The results do not change qualitatively through the adjustment, although (un-surprisingly) both coefficients are now somewhat smaller and the overall explained variation decreases to 0.22 from 0.27. It can be concluded from this simple exercise that a rising maturity mismatch has been associated with higher perceived credit risk, as measured by the CDS spread of the bank. It is clear, however, that the maturity mismatch captures only one of the many risks a bank is facing. Other, excluded categories that also influence CDS spreads are, for example, the asset quality of the bank and the stability of its funding sources.

3.2 The relationship between banks' riskiness and their demand behaviour in central bank refinancing operations: the example of the Eurosystem

We start this section with two graphs, showing the evolution of the price for 3-month (secured) central bank liquidity before and after August 2007 as well as the (expected) alternative costs of funding by repeatedly borrowing overnight (the overnight index swap or OIS rate).

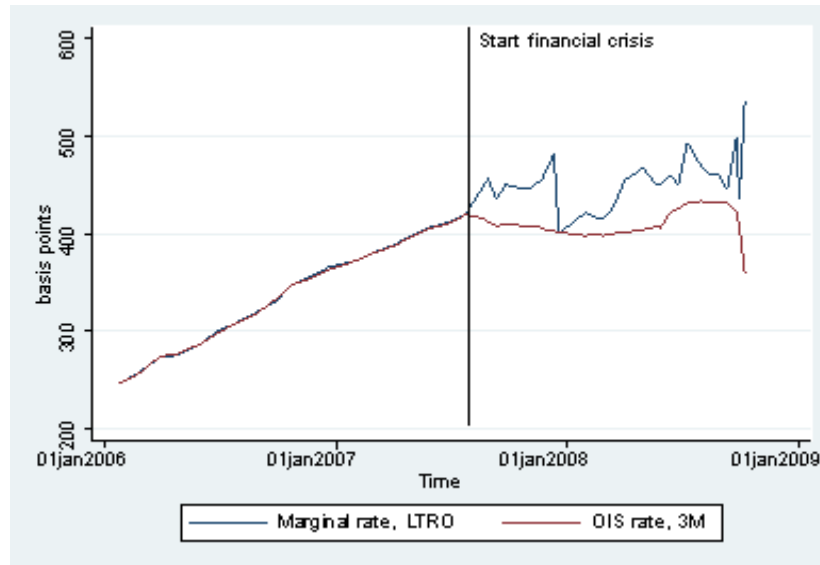


Figure 4: Marginal rates in 3-month LTROs and 3-month OIS rates at day of the auction, January 2006-September 2008

There are two important empirical facts concerning the demand for central bank reserves contained in figures 4 and 5. First of all, figure 4 suggests that before August 2007, longer-term refinancing and short-term refinancing operations were very close substitutes. In fact, the close alignment of the marginal tender rate in the standard 3-month LTROs with the comparable 3-month OIS rate suggests that banks, at the margin, were indifferent between obtaining central bank reserves for 3 months or borrowing repeatedly overnight. (The same relationship was observed for 1 week MROs, establishing the substitutability claim between LTROs and MROs.) With the start of the financial crisis in August 2007 this changed dramatically. Secured 3-month liquidity now sold at a significant premium over 3-month OIS. Given the nature of the underlying contracts, it is clear that this premium is strongly related

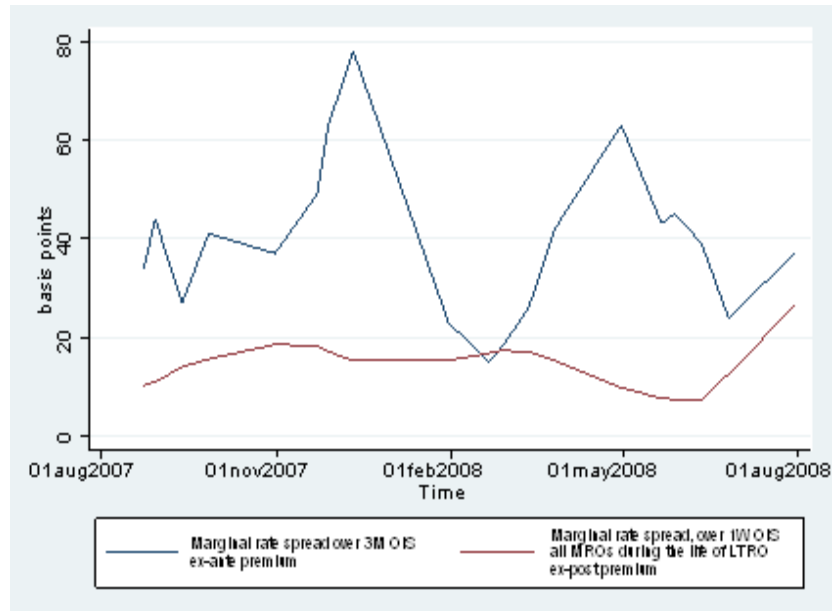


Figure 5: Spread between marginal rate and corresponding OIS rates, August 2007 - September 2008

(but not exclusively so) to liquidity risk. An even more pure liquidity risk premium, in an ex-post sense, can be obtained by comparing the premium over corresponding OIS banks were willing to pay in the LTRO to that banks would have had to pay, had they chosen to participate in the MROs that took place over the live of the operations. This premium depicted in figure 5 above and indicates that the Eurosystem had become an important provider of longer term refinancing for some banks which displayed a significant and persistent high willingness to pay for the central bank reserves.

We now turn to analyse in detail banks' demand behaviour in central bank refinancing operations during that period. To that end, we make use the bidding data of all repo auctions of the Eurosystem from January 2007 until October 2008

Operation	cat 1	cat 2	cat 3	cat 4
MRO	=0	>0	=0	>0
LTRO	=0	=0	>0	>0

Table 5: Categories of banks after their recourses to Eurosystem refinancing operations

(when the Eurosystem changed its auction procedure, fixing the auction price at the policy rate and providing as many reserves as banks would demand).⁷ Overall, 1731 banks were active (i.e. participated at least once in a refinancing operation) during that period. To keep the dataset manageable, we restrict our attention to union of the sets of the banks A_{90}^i , in descending order, that overall accounted for an outstanding volume of 90% of total refinancing operations. The data have a weekly frequency, because each an MRO takes place and changes the information contained in the dataset, giving rise to 89 weeks of observations. Therefore, formally, we are looking at $\cup_{i=1}^{89} A_{90}^i$, restricting our sample to 354 banks or 31506 observations. In addition, banks outstanding LTRO volumes are contained for each week and bank. From these data we calculate the frequency of four categories. These four categories are:

In the dataset, for each bank at each week a 1 will be assigned to the category the bank was in at that time, while all other categories receive the weight of zero. We then proceed to calculate the time averages for each category, giving rise to the relative frequencies with which each category was observed.

⁷For a detailed description of the ECB's operational framework and the changes to it after August 2007 see Eisenschmidt et al (2009).

before August 2007	cat 1	cat 2	cat 3	cat 4	observations
Frequency (in %)	51.5	20.7	11.2	16.6	10620
August 2007 - October 2008					
Frequency (in %)	43.6	12.4	27.9	24.1	20886

Table 6: Frequency of participation of banks in Eurosystem refinancing after categories before and during the financial crisis

Table 6 above summarises the results. Before the start of the crisis, the mainstay of liquidity provision was the weekly MRO, which is also reflected in its highest share (around 20%) as a sole provider of liquidity. This changed after August 2007 for two reasons. First of all, LTRO provision was increased at the expense of MRO volumes (since overall supply of central bank refinancing remained, on average, constant). Secondly, LTRO refinancing became more attractive, especially for banks that experienced more elevated stress levels, as we will show below. Overall, banks were more likely to participate in Eurosystem refinancing operations after August 2007 than before.

We now introduce a measure of credit risk into our sample of banks. Even our reduced sample contains many non-listed banks for which financial market data like CDS spreads or share prices are not available. We therefore decided to introduce a qualitative variable “stress” which is 1 if the bank during the sample period experienced one of the following events:

Overall, we obtain a total of 64 banks which experienced at least one of these events, i.e. that can be classified as having undergone some form of severe stress in the sample period. Controlling for these banks’ characteristics, we obtain

Event
default
nationalisation
forced recapitalisation or injection of government funds
forced merger
closure by national supervisory authorities

Table 7: Stress events

non-stressed banks					
before August 2007	cat 1	cat 2	cat 3	cat 4	observations
Frequency (in %)	55.1	21.4	8.3	15.2	8700
August 2007 - October 2008					
Frequency (in %)	46.7	12.7	26.2	14.4	17110

Table 8: Frequency of participation of non-stressed banks in Eurosystem refinancing after categories before and during the financial crisis

the following table of frequencies:

The most striking result contained in tables 8 and 9 is the strong reliance of stressed banks on LTRO refinancing, which started already somewhat before August 2007 but increased further after the start of the financial crisis, even though these operations became relatively expensive. At the same time, stressed banks showed a declining participation in MROs. Further, stressed banks were on average only

stressed banks					
before August 2007	cat 1	cat 2	cat 3	cat 4	observations
Frequency (in %)	35.1	18.0	24.3	22.6	1920
August 2007 - October 2008					
Frequency (in %)	30.0	10.8	35.4	23.8	3776

Table 9: Frequency of participation of stressed banks in Eurosystem refinancing after categories before and during the financial crisis

absent from any third Eurosystem operation. This figure would be even smaller, were we to correct for some of the exits that took place within the sample, i.e. we continued to count those stressed banks that had already ceased their operations. Note further that by the measure of a conventional F-test, the differences between stressed banks' behaviour and that of the non-stressed banks is significant at the 99% level of confidence.

4 Conclusion

This paper analysed the impact of banks' choice of maturity mismatch - i.e. the divergence between the average maturity of its assets and liabilities - on demand for central bank funding. Banks' maturity mismatch was an important factor in the crisis. The empirical analysis shows that it is linked to banks' perceived riskiness (CDS spreads). Moreover, it is somewhat surprising to see that the average maturity mismatch has increased between 2007 and 2009. Most likely, it was the result of increased difficulties to obtain long-term refinancing in the market. To compensate for this trend, the European Central Bank has during the crisis increased the average maturity of its open market operations, offering refinancing operations with maturities up to one year.

The theoretical model showed that central banks are indeed an alternative source of funding, especially for high-risk banks, and for those banks wanting to (or being required to) reduce the maturity mismatch. In this vein, the planned liquidity regulation, which would reduce the maturity mismatch on banks' balance sheets, might

lead to further increase in demand for central bank liquidity.

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5 Appendix

Proof of Proposition 1 Assume that a bank of type θ chooses long-term funding.

Then, the investment in asset a by this bank is profitable iff $p(\theta)R - 1 \geq 0$, i.e. whenever

$$p(\theta) \geq \frac{1}{R}.$$

Now assume that the bank chooses short-term funding. This is profitable whenever $p(\theta) \left[R + \frac{\theta}{2} \right] - 1 \geq 0$, i.e. when

$$p(\theta) \geq \frac{1}{R + \frac{\theta}{2}}.$$

Since $\frac{1}{R} \geq \frac{1}{R + \frac{\theta}{2}}$, the first condition is sufficient for optimality.