DISCUSSION PAPER

No 134

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March 2014

HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF

d|u|p düsseldorf university press

IMPRINT

DISCUSSION PAPER

Published by

düsseldorf university press (dup) on behalf of
Heinrich-Heine-Universität Düsseldorf, Faculty of Economics,
Düsseldorf Institute for Competition Economics (DICE), Universitätsstraße 1,
40225 Düsseldorf, Germany
www.dice.hhu.de

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ISSN 2190-9938 (online) – ISBN 978-3-86304-133-5

Frictions in the Interbank Market and Uncertain Liquidity Needs: Implications for Monetary Policy Implementation

Monika Bucher* Achim Hauck† Ulrike Neyer‡

March 2014

Abstract

This paper shows that depending on the distribution of banks' uncertain liquidity needs and on how monetary policy is implemented, frictions in the interbank market may reinforce the effectiveness of monetary policy. The frictions imply that with its lending and deposit facilities the central bank has an additional effective instrument at its disposal to impose an impact on bank loan supply. Lowering the rate on the deposit facility has, taken for itself, a contractionary effect. This result has interesting implications for monetary policy implementation at the zero lower bound.

JEL classification: E52, E58, G21

Keywords: interbank market, monetary policy, monetary policy implementation, zero lower bound, loan supply

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1 Introduction

The interbank market for overnight loans is important for monetary policy implementation. By steering the interest rate in this market, the central bank wants to influence short-term nominal interest rates, and thereby, through various channels, the price level and maybe aggregate output. In the euro area, the interest rate channel is still regarded as a main transmission mechanism of monetary policy (Čihák, Harjes, and Stavrev, 2009; Angeloni, Kashyap, Mojon, and Terlizzese, 2003). This channel rests on the central bank's ability to influence the banks' refinancing costs, and thereby, to control bank loan supply.

During the recent financial crisis, euro area interbank markets seized up. This led to concerns about the Eurosystem's ability, or the lack thereof, to actually control bank loan supply in times of malfunctioning interbank markets, and it triggered a heated debate whether the interest rate channel might be broken. Our paper contributes to this debate. We develop a theoretical model that has two central features. First, it captures main elements of the Eurosystem's[1] operational framework. Second, it accounts for interbank market frictions. This allows us to study in how far frictions in the interbank market influence the impact of monetary policy on bank loan supply and to discuss implications for monetary policy implementation.

The model captures the Eurosystem's main refinancing operations and its two standing facilities. The former are credit operations with a maturity of one week. The Eurosystem uses them to provide reserves to the euro area banking sector. The two standing facilities, a deposit facility and a lending facility, allow banks to balance their overnight liquidity needs. The interest rates on the facilities form a corridor around the rate on the main refinancing operations with the rate on the deposit facility to be lower and the rate on the lending facility to be higher than the main policy rate.[2] In our model, frictions in the interbank market emerge in the form of transaction costs. We broadly interpret these transaction costs as search costs. Banks must find suitable transaction partners first, with matching liquidity needs and second, with a willingness to conclude mutual agreements for trade. The former may be costly as, for example, banks have to split large transactions into small ones to work around credit lines (Bartolini, Bertola, and Prati, 2001). The latter may be costly because lenders in the overnight interbank market are typically unwilling to

[1]The term "Eurosystem" stands for the institution which is responsible for monetary policy in the euro area, namely the ECB and the national central banks in the euro area. For the sake of simplicity, the terms "ECB" and "Eurosystem" are used interchangeably throughout this paper.

[2]For a detailed description of the Eurosystem's operational framework see European Central Bank (2012).

expose themselves to any counterparty credit risk (Hauck and Neyer, 2013). Consequently, they engage in costly checks of the creditworthiness of potential borrowers who in turn must provide costly signals of their creditworthiness.[3]

In our model, banks grant loans to the non-banking sector by crediting the respective amount on their customers' demand deposit accounts. The banks have to decide on the loan amount as well as on their borrowing from the central bank's main refinancing operations before they learn their subsequent liquidity needs. They need liquidity for two reasons. First, the bank customers make cash withdrawals so that the banking sector as a whole faces a structural liquidity deficit. This deficit can only be covered by the central bank. Second, bank customers make deposit transfers within the banking sector. The magnitude and direction of these transfers are uncertain. Accordingly, each individual bank may finally face a liquidity surplus or deficit after the cash withdrawals and the deposit transfers of their customers. The bank then has to decide on whether to balance these liquidity needs via the interbank market or by using the central bank's facilities. The costs of the banks' transactions with the central bank (refinancing operations and facilities) and in the interbank market determine their expected refinancing costs of granting loans and, therefore, also their loan supply.

The results of our model replicate several stylized facts observed before and during the recent financial crisis. If there are no interbank market frictions, the interbank market rate will equal the policy rate, the reserves provided by the central bank to the banking sector through its main refinancing operations will correspond to the benchmark allotment, and the standing facilities will not be used. This is exactly what could be observed in the euro area before the outbreak of the financial crisis in 2007. Introducing interbank market frictions in our model leads to results which are broadly consistent with the stylized facts observed during the financial crisis. The interbank market rate falls below the main policy rate. However, as long as frictions remain below a first threshold, reserves provided through the main refinancing operations still correspond to the benchmark allotment, which captures the banking sector's liquidity needs resulting from autonomous factors

[3]One of the first papers dealing explicitly with interbank market transaction costs is the one by Bartolini, Bertola, and Prati (2001). They argue that interbank market transaction costs are responsible for the relatively high federal funds rate usually observed at the end of a reserve maintenance period. Transaction costs also play a crucial role in Hauck and Neyer (2013). They argue that transaction costs, or participation costs, can explain several stylized facts observed in the euro area interbank market during the financial crisis. Models explicitly considering a costly search process in the interbank market can be found for example in Furfine (2004) and Ashcraft and Duffie (2007). Furfine analyses the effectiveness of standing facilities offered by a central bank at reducing the volatility of the overnight interbank rate. Ashcraft and Duffie show how the search process in the decentralized organized interbank market influences intraday allocation and the pricing of federal funds.

and reserve requirements, and none of the facilities will be used. Frictions are absorbed by a lower interbank rate. If the first threshold is exceeded, the interbank market rate will reach a level close to the rate on the deposit facility, reserves provided by the central bank will exceed the benchmark allotment and the deposit facility will be used. If frictions in the interbank market increase further and pass a second threshold, the interbank market will break down. In this case, the amount of reserves which is provided by central bank via its main refinancing operations will deviate even more from the benchmark allotment and both facilities will be used.

The results of our model lead to the following implications for monetary policy implementation.

- Irrespectively of interbank market frictions, the central bank can steer the banks' expected refinancing costs of granting loans. This will enable the central bank to control bank loan supply even if the frictions imply a total interbank market freeze.
- If interbank market frictions are sufficiently high, they will reinforce the effect of a monetary policy impulse in the form of a sole change of the main policy rate. The reinforcing effect increases in the extent of the uncertainty about a bank's actual liquidity needs.
- The reinforcing effect will be avoided if the central bank changes all its interest rates (rate on its main refinancing operations and on its standing facilities) to the same extent. Obviously, this will not be possible if the rate on the deposit facility is fixed at the zero lower bound.
- If the interbank market frictions are sufficiently high, the standing facilities present an additional effective monetary policy instrument. Generally, a decrease of (increase in) the rate on the deposit facility and an increase in (decrease of) the rate on the lending facility correspond to a contractionary (expansionary) monetary policy. Therefore, the central bank can use the rates on the facilities as an effective monetary policy instrument by changing the width or the asymmetry of the interest rate corridor. Obviously, the possibility of conducting a contractionary monetary policy by decreasing the rate on the deposit facility will not be possible if the zero lower bound becomes binding.

To illustrate the main idea behind the implications of our model results for monetary policy implementation, let us assume that the central bank conducts an expansionary monetary policy by lowering solely the rate on its main refinancing operations. Then, borrowing reserves from the main refinancing operations becomes cheaper which implies that also the price for reserves in the interbank market, the interbank rate, decreases. The banks' expected marginal refinancing costs of granting loans decline which has a positive impact on their loan supply. However, frictions in the form of transactions costs in the interbank market imply that the interbank rate deviates from the central bank's main policy rate. If these costs are that high, that the interbank rate will be already at its lower bound, the above described price mechanism will not work anymore. Therefore, borrowing reserves from the central bank's refinancing operations remains to be relatively cheaper as compared to an interbank market loan. As a consequence, banks increase their borrowing from the refinancing operations. The price effect (lower interbank rate) is replaced by a quantity effect (increased borrowing from the refinancing operations). This quantity effect implies that the expansionary effect of the initial monetary policy impulse is reinforced as the decrease of expected marginal refinancing costs is stronger. The central bank can steer the extent of the reinforcing effect by changing the rate on its deposit facility. If it cuts this rate, the lower bound of the interbank rate will decline, the price mechanism will work again, at least partially, depending on the cut of the rate on the deposit facility. A similar story can be told if there is a complete break down of the interbank market due to respectively high interbank market frictions.

With respect to our model framework two aspects are worth mentioning. First, although our model focusses on the Eurosystem's operational framework by capturing its main elements, our results apply to other operational frameworks as well, as long as they allow commercial banks to balance uncertain liquidity needs by using a deposit facility and a lending facility offered by the central bank. Second, our model abstracts from two main elements of the Eurosystem's operational framework: the collateralization of central bank credits and the minimum reserve system. However, introducing these would not change the qualitative results of our model. If we considered the collateralization of central bank credits, banks would face opportunity costs of holding these collateral. This would imply higher expected refinancing costs of granting loans as refinancing at the central bank as well as in the interbank market becomes more expensive.[4] Consequently, opportunity costs of holding adequate collateral have a negative influence on bank loan supply but they do not change the qualitative results of our model. Considering reserve requirements in our

[4]Borrowing from the interbank market becomes more expensive as considering opportunity costs of holding collateral implies an increase in the interbank market rate. For an respective analysis see, for example, Neyer and Wiemers (2004); Berentsen and Monnet (2008).

analysis would not change our qualitative results either. First, reserve requirements imply a structural liquidity deficit of the banking sector. In our model, a structural liquidity deficit is already captured by considering cash withdrawals. Second, a main feature of the Eurosystem's minimum reserve system is that banks can make use of averaging provision of required reserves during a reserve maintenance period. This allows banks to smooth out liquidity fluctuations. In our model, this would imply that costs resulting from uncertain liquidity fluctuations, and therefore, also the banks' expected costs of refinancing loans decrease. This would have a positive impact on bank loan supply. However, again, the qualitative results of our model would not change.

This rest of this paper is organized as follows. Section 2 presents related literature. Sections 3 describes the framework of the model. Sections 4 and 5 derive the optimal behavior of commercial banks. Section 6 discusses the equilibrium of the model. Taking a closer look at this equilibrium in Section 7, we analyze the impact of interbank market transaction costs on the impact of monetary policy on bank loan supply and discuss the consequences for monetary policy implementation. Section 8 briefly summarizes the paper.

2 Related Literature

Our paper contributes to three strands of literature. The first strand deals with the influence of monetary policy on bank loan supply. Neglecting the interbank market, a huge part of this literature focuses on asymmetric information in credit markets and argues that these frictions amplify the effects of monetary policy. For an overview of this so called credit channel of monetary policy see, for example, Kashyap and Stein (1994), Bernanke and Gertler (1995) and Brunnermeier, Eisenbach, and Sannikov (2013). Jiménez, Ongena, Peydró, and Saurina (2012) confirm a high relevance of the credit channel in an empirical analysis referring to the Spanish credit market.

The second strand of literature deals with frictions in the interbank market. Until the outbreak of the financial crisis in 2007, the interbank market was typically regarded as frictionless, also in the theoretical literature. As a consequence, the interbank rate was assumed to be identical with the monetary policy rate or the interbank market was entirely neglected. However, the financial crisis inspired a growing literature dealing with interbank market imperfections, primarily focussing on asymmetric information about credit risks. Freixas and Jorge (2008) consider the impact of frictions in the interbank market for the transmission of monetary policy. They show that private information in the interbank market with respect to credit risks may induce rationing of firms in credit markets. With respect to the transmission mechanism of monetary policy this implies that asymmetric information in the interbank market may be responsible a) for a magnitude effect, i.e. the aggregate impact of monetary policy may be large given the small interest elasticity of investment, and b) for a liquidity effect, i.e. that the impact of monetary policy is stronger for banks with less liquid balance sheets. Heider, Hoerova, and Holthausen (2009) argue that banks' informational disadvantage with respect to counterparty credit risks induces them to hold more liquidity. Depending on the risk dispersion, this may result in either adverse selection or a market dry-up. Banks may learn about counterparty credit risks by repeatedly trading with each other. In an empirical analysis of the German unsecured overnight money market, Bräuning and Fecht (2012) determine the impact of such relationship lending for banks' ability to access liquidity. The causes of a possible dry-up of the interbank market are also analyzed by Allen, Carletti, and Gale (2009). They show that banks will also start to hoard liquidity if they are unable to hedge idiosyncratic liquidity shocks.

The third strand of literature is the most closely related strand to our paper. It looks at monetary policy implementation, bank behavior, and consequences for the conditions in the overnight interbank market. This literature can be divided into three groups. The first group focusses on U.S. before the outbreak of financial crisis in 2007. Considering major institutional characteristics of the federal funds market, Ho and Saunders (1985) as well as Clouse and Dow (2002) analyze the banks' reserve management and draw conclusions for the conditions in the interbank market for reserves. However, the largest part of the literature dealing explicitly with the federal funds market focuses on why the federal funds rate fails to follow a martingale within the reserve maintenance period.[5] The second group of the literature refers to the euro area in the pre-crisis period. A bulk of this literature deals with the under- and overbidding behaviour in the Eurosystem's main refinancing operations which could be observed in the first years of the European Monetary Union.[6] Apart from this, there are papers analyzing the consequences of alternative monetary policy implementations. Nautz (1998) shows that the central bank can influence the interbank market rate by being more or less vague about its future monetary policy.

[5]See Hamilton (1996), Clouse and Dow (1999), Furfine (2000), and Bartolini, Bertola, and Prati (2001, 2002).

[6]Under- and overbidding behavior refers to a bidding behavior in which total bids significantly exceed or remain under the Eurosystem's benchmark allotment. Analyses with respect to this under- and overbidding behavior can be found in Ayuso and Repullo (2001, 2003), Ewerhart (2002), Nautz and Oechssler (2003, 2006), and Bindseil (2005).

Välimäki (2001) analyzes the effects of alternative tender procedures with respect to the Eurosystem's refinancing operations. Neyer and Wiemers (2004) refer to the collateral framework. They show that differences in the banks' opportunity costs of holding collateral form a rationale for the existence of an interbank market for reserves. Neyer (2009) demonstrates that renumerating required reserves in a specific way increases the flexibility of monetary policy. Pérez-Quirós and Rodríguez-Mendizábal (2006) show that the two standing facilities offered by the Eurosystem in combination with its minimum reserve system are an effective instrument to stabilize the interbank market rate. Whitesell (2006), not explicitly referring to the euro area, looks at a minimum reserve system and standing facilities as two alternative regimes for controlling overnight interest rates. Also focussing on the standing facilities, Berentsen and Monnet (2008) develop a general equilibrium framework and show that changing the rates on these facilities may be used actively as a monetary policy instrument. Also Goodhart (2013) points out that by changing the rates on the standing facilities the central bank has an additional instrument at hand. Beaupain and Durré (2008) examine the interday and intraday dynamics of the euro area overnight interbank market and argue that specific features of the Eurosystem's operational framework, as its minimum reserve system, can explain observed regular patterns. The third group of this third strand of literature comprises papers regarding changes in monetary policy implementation in response to the financial crisis. Eisenschmidt, Hirsch, and Linzert (2009) analyze the relatively aggressive bidding behavior of euro area banks in the Eurosystem's main refinancing operations at the beginning of the financial turmoil. Cassola and Huetl (2010), also referring to the first part of the financial crisis until 2008, assess the effectiveness of monetary policy implementation during this time. Borio and Disyatat (2009) describe main characteristics of unconventional monetary policies adopted during the financial crisis. They point out that an important feature of these policies is that the central bank also uses its balance sheet to influence prices and conditions in the interbank market. Cheun, von Köppen-Mertes, and Weller (2009) analyze the changes to the collateral frameworks of the Eurosystem, the Federal Reserve System and the Bank of England. Lenza, Pill, and Reichlin (2010) describe the way in which these three central banks generally conducted monetary policy during the financial crises and point to the importance of their influence on money market spreads. Hauck and Neyer (2013) develop a theoretical model considering main institutional features of the Eurosystem's operational framework which has been in place since September 2008 to explain several stylized facts observed during the financial crisis.

Our paper adds to this literature by analyzing the consequences of frictions in the overnight interbank market, in the form of broadly defined transaction costs, for the impact of monetary policy on bank loan supply. With respect to monetary policy implementation, we point out the crucial role the central bank's standing facilities play for the effectiveness of monetary policy in the presence of interbank market frictions and uncertain liquidity needs.

3 Framework

We consider a model economy consisting of a continuum of measure one of price-taking commercial banks and a large number of bank customers. Furthermore, in our economy, a central bank is in charge of the monetary policy. All agents are assumed to be risk neutral. The commercial banks grant loans and credit the respective amount to the customers' demand deposit accounts. Bank customers use the newly created money to make payments.

Customers make their payments either by using cash or by transferring deposits. If the customers want to use cash to make payments, they have to withdraw the respective amount of their newly created deposits as cash. These cash withdrawals imply that the banking sector as a whole has to borrow liquidity from the central bank which is the monopoly producer of currency. For a single bank the net deposit transfers of its customers are uncertain. It may be that the bank faces a net deposit outflow or a net deposit inflow. Banks can use an interbank market to balance their individual liquidity needs. Different net deposit transfers among banks provides the rationale for an interbank market to exist.

Generally, a single bank can balance its liquidity needs by borrowing and lending from the central bank and by using the interbank market. The costs of these activities determine a bank's liquidity costs which again determine its costs of granting loans. Considering the different costs and revenues of its activities, a bank has to decide on its optimal lending to the non-banking sector, its optimal transactions with the central bank and its optimal transactions in the interbank market. In the following, we comment on single aspects of this model framework in more detail.

Commercial Banks

A commercial bank i grants loans to its customers at the interest rate i^L. The respective loan volume L_i is credited to customers' demand deposit accounts. Customers prefer to hold currency and demand deposits in a fixed proportion. This proportion is expressed by the currency ratio c which is defined as the ratio of currency to total money holdings. Consequently, a bank's individual cash withdrawals read

$$C_i = cL_i. \tag{1}$$

From the remaining demand deposits $(1-c)L_i$ a share t_i is transferred to customers of other banks. There are banks which face a net deposit inflow and those facing a net deposit outflow. For a single bank the net deposit outflow is uncertain. We denote this random variable by T and its realization by t_i. Among all banks, t_i is distributed in the interval $[t^{min}, t^{max}]$ according to the density function $g(t_i) = G'(t_i)$. Note that for those banks being a net receiver of deposits $t_i < 0$, and that

$$E[T] = \int_{t^{min}}^{t^{max}} t_i g(t_i)\, dt_i = 0. \tag{2}$$

In order to measure the extent of uncertainty, we allow for a transformation of T which captures second-order stochastic dominance. Focusing on transformations characterized by a mean preserving spread we only analyze changes to the dispersion of the distribution. In detail, we consider a simple linear transformation χt_i with $\chi \in [1, \frac{1}{t^{max}}]$.[7] If χ increases, the transformed distribution will exhibit a higher dispersion than the original distribution. Accordingly, uncertainty with respect to net deposit transfers increases.[8]

Considering both, cash withdrawals and deposit transfers, a bank's individual remaining deposits are given by

$$D_i = L_i - cL_i - (1-c)\chi t_i L_i = (1-c)(1-\chi t_i)L_i. \tag{3}$$

Banking technology is represented by a cost function which describes the costs of managing specific volumes of loans, and which satisfies the usual assumptions of convexity and regularity. This captures the idea that loans differ in their complexity so that the

[7]Restricting χ to values larger than one ensures that an increase in χ always corresponds to an increase in uncertainty. Moreover, χ has to be lower than $\frac{1}{t^{max}}$, as the share of net deposit transfers cannot exceed one.

[8]Note that usually the transformed distribution is characterised by a lower dispersion so that this distribution stochastically dominates the original distribution, see Ormiston (1992); Nautz (1998); Wolfstetter (1999).

bank adds the least complex loans to its portfolio first. For the sake of simplicity we assume these costs to be quadratic:

$$\frac{1}{2}\lambda L_i^2. \tag{4}$$

Central Bank

We consider a central bank which provides liquidity in form of reserves to commercial banks. Reserves consist of the deposits commercial banks hold on their accounts with the central bank and of currency. Deposits held at the central bank can be immediately transformed into currency. There are no reserve requirements but commercial banks need reserves to satisfy the cash withdrawals by their customers. To obtain reserves from the central bank, a commercial bank i has to borrow from the central bank. It can participate in refinancing operations and borrow the amount $RO_i \geq 0$ at the rate i^{RO}. Moreover, it can use a lending facility to borrow $LF_i \geq 0$ at the rate i^{LF}.[9] However, a commercial bank can also place an amount $DF_i \geq 0$ of liquidity in the deposit facility at the rate i^{DF}. The rates on the facilities form a corridor around the rate on the refinancing operations. We thus have $i^{LF} > i^{RO} > i^{DF}$.

Interbank Market

A commercial bank can also borrow and lend liquidity in the interbank market. A bank's position in this market is B_i. If $B_i > 0$, the bank will borrow the amount B_i at the rate i^{IBM}. Conversely, $B_i < 0$ indicates that the bank will lend the amount $|B_i|$ at this rate. Independently of whether a bank borrows or lends in the interbank market, transaction costs γ per amount $|B_i|$ accrue, with $\gamma \geq 0$. Therefore, costs in the interbank market account for

$$i^{IBM} B_i + \gamma \left| B_i \right|. \tag{5}$$

[9] Generally, credit operations with the central bank require adequate collateral. In our setting a bank's loan volume L_i serves as collateral, and therefore, limits its central bank borrowing. The central bank may impose a haircut on these loans when accepting them as collateral, like in Bindseil and König (2011). In this setting, however, we assume that such a hair cut is not binding and neglect the collateralization of central bank loans. See in this context also our remarks to this aspect made in the introduction.

A Commercial Bank's Optimization Problem

Commercial bank i aims to maximize its profit Π_i given by

$$\Pi_i = i^L L_i - \frac{1}{2}\lambda L_i^2 - i^{RO} RO_i - i^{LF} LF_i + i^{DF} DF_i - i^{IBM} B_i - \gamma |B_i| \quad (6)$$

$$\text{s.t.} \qquad L_i + DF_i = RO_i + LF_i + D_i + B_i. \quad (7)$$

Equation (6) reveals that a commercial bank's profit is determined by the interest revenues from its lending to the non-banking sector, its management costs, the interest costs due to its central bank borrowing (refinancing operations, lending facility), the interest revenues from placing liquidity in the central bank's deposit facility and the interest costs/revenues as well as the transaction costs of its interbank market activities. The bank chooses its optimal credit supply L_i, its optimal transactions with the central bank DF_i, LF_i, RO_i, and its optimal transactions in the interbank market B_i. When maximizing its profit the bank has to consider the balance sheet constraint (7). The assets of a commercial bank consist of its loans L_i and its deposits DF_i held at the central bank. Its liabilities comprise its central bank borrowing (RO_i+LF_i) and its customers' deposits D_i. The bank's position in the interbank market B_i might constitute an item on the asset or liability side of the balance sheet, depending on whether the bank borrows from or lends in the interbank market.

For solving this optimization problem, the sequence of moves is important. First, each bank decides on its lending to the non-banking sector and credits the respective amounts to the demand deposit accounts. Afterwards, but still before customers make their deposit transfers and cash withdrawals, banks have to decide on their borrowing from the central bank's refinancing operations. Consequently, banks have to make this decision under uncertainty regarding their actual liquidity needs. After customers have made their transfers and cash withdrawals uncertainty is resolved. Each commercial bank then has to decide on its transaction in the interbank market and on its use of the central bank's facilities.

This implies that the optimization problem can be split up into two stages. Solving this optimization problem by backward induction, we first investigate the second stage of the model. At this stage, uncertainty is resolved as banks' customers have made their transfers and have withdrawn cash. We identify the optimal behavior of an individual bank, which takes the interbank rate as given, and discuss the properties of the interbank market equilibrium. Then, we analyze a bank's optimal behavior at the first stage with respect to its lending to the non-banking sector L_i and its borrowing from the central bank in the refinancing operations RO_i. This allows us to finally determine the equilibrium variables at the aggregate level. Because of uncertain deposit transfers banks face uncertainty with respect to their individual liquidity needs at this first stage. Hence, their decision is based on expectations regarding these transfers. On the aggregate level, however, banks face no uncertainty. This implies that banks' expectations regarding the interbank rate are certain.

4 Optimal Behavior at the Second Stage

4.1 A Bank's Optimization Problem

When entering the second stage of the model, each bank learns its respective share of transferred deposits t_i and, therefore, its actual liquidity needs. Accordingly, banks face no uncertainty at this stage. Using (3) we define a bank's actual individual liquidity needs as

$$N_i := L_i - RO_i - D_i = L_i \left(c + (1-c)\chi t_i\right) - RO_i. \tag{8}$$

Considering N_i in the bank's balance sheet constraint (7) and taking the interbank rate as given, the optimization problem at the second stage reads

$$\begin{aligned} \max_{B_i, DF_i, LF_i} \Pi_{i,2} &= -i^{LF} LF_i + i^{DF} DF_i - i^{IBM} B_i - \gamma \left| B_i \right| \\ \text{s.t.} \quad B_i &= N_i + DF_i - LF_i. \end{aligned} \tag{9}$$

Bank i aims at maximizing its second-stage profit subject to the balance sheet constraint. The second-stage profit depends on the costs and revenues of using the central bank's facilities and those resulting from the commercial bank's transactions in the interbank market.

4.2 A Bank's Optimal Behavior

Solving the individual optimization problem, we can restrict our attention to $i^{IBM} \in \left[i^{DF}, i^{LF}\right]$, as no bank is willing to lend in or borrow from the interbank market at less profitable rates than those offered by the central bank. Denoting the optimal values of variables by the superscript *opt*, we obtain

Lemma 1: *Suppose that* $i^{IBM} \in \left[i^{DF}, i^{LF}\right]$. *At the second stage, bank i facing liquidity needs* N_i *will behave as follows:*

- *Given that* $N_i \geq 0$, *i.e. bank i inherits a liquidity deficit from the first stage, then,*

$$\begin{array}{llll} B_i^{opt} = 0, & LF_i^{opt} = N_i, & DF_i^{opt} = 0, & if \;\; i^{IBM} + \gamma > i^{LF}, \\ B_i^{opt} \in [0, N_i], & LF_i^{opt} = N_i - B_i^{opt}, & DF_i^{opt} = 0, & if \;\; i^{IBM} + \gamma = i^{LF}, \\ B_i^{opt} = N_i, & LF_i^{opt} = 0, & DF_i^{opt} = 0, & if \;\; i^{IBM} + \gamma < i^{LF}. \end{array} \tag{10}$$

- *Given that* $N_i < 0$, *i.e. bank i inherits excess liquidity from the first stage, then,*

$$\begin{array}{llll} B_i^{opt} = N_i, & LF_i^{opt} = 0, & DF_i^{opt} = 0, & if \;\; i^{IBM} - \gamma > i^{DF}, \\ B_i^{opt} \in [N_i, 0], & LF_i^{opt} = 0, & DF_i^{opt} = B_i^{opt} - N_i, & if \;\; i^{IBM} - \gamma = i^{DF}, \\ B_i^{opt} = 0, & LF_i^{opt} = 0, & DF_i^{opt} = -N_i, & if \;\; i^{IBM} - \gamma < i^{DF}. \end{array} \tag{11}$$

Proof: Omitted.

Lemma 1 states that a bank compares marginal costs/revenues of transactions in the interbank market with those of using the central bank's facilities. If the bank inherits a liquidity deficit, it will compare marginal costs of borrowing from the interbank market given by $i^{IBM} + \gamma$ with those of using the lending facility which are simply i^{LF}. Lemma 1 shows that due to constant marginal costs, corner solutions occur. If $i^{IBM} + \gamma > i^{LF}$ the bank will cover its total liquidity deficit by borrowing from the lending facility. If $i^{IBM} + \gamma < i^{LF}$ it will borrow from the interbank market only. In case both marginal costs are identical, the bank is essentially indifferent between interbank borrowing and the usage of the lending facility. In case of a liquidity surplus, the bank decides analogously. If the marginal revenues in the interbank market $i^{IBM} - \gamma$ are higher (lower) than the marginal revenues of the central bank's deposit facility i^{DF}, it will place its total surplus in the interbank market (in the central bank's deposit facility). In case marginal revenues are identical, the bank will again be indifferent.

4.3 Equilibrium Interbank Rate

After having clarified the behavior of an individual bank at the second stage, we can now determine the equilibrium interbank rate. Banks will only trade liquidity in the interbank market if this is more beneficial than using the central bank's facilities. Consequently, the interbank rate in equilibrium will be $i^{IBM*} \in [i^{DF} + \gamma, i^{LF} - \gamma]$. The transaction costs γ determine whether banks prefer the interbank market or the central bank's facilities.

If these transaction costs are that high, that for each bank it will be more beneficial to use the central bank's facilities instead of trading in the interbank market, the interbank market will break down. This will be the case if $i^{IBM*} - \gamma < i^{DF}$ and $i^{IBM*} + \gamma > i^{LF}$, i.e. if

$$\gamma > \frac{i^{LF} - i^{DF}}{2} =: \bar{\bar{\gamma}}. \tag{12}$$

In conjunction with Lemma 1, we thus obtain

Proposition 1: *If $\gamma \leq \bar{\bar{\gamma}}$, the interbank market will be active and we will have to distinguish between three cases regarding the interbank rate:*

$$\begin{aligned} i^{IBM*} &= i^{LF} - \gamma && \text{if } RO < cL, \\ i^{IBM*} &\in \left[i^{DF} + \gamma, i^{LF} - \gamma\right] && \text{if } RO = cL, \\ i^{IBM*} &= i^{DF} + \gamma && \text{if } RO > cL. \end{aligned} \tag{13}$$

If $\gamma > \bar{\bar{\gamma}}$, the interbank market will be inactive.

Proof: Omitted.

The proposition states that the interbank rate depends crucially on the aggregate liquidity position of the banking sector. We therefore have to distinguish three cases. Denoting aggregate borrowing from the refinancing operations by RO and aggregate lending to the non-banking sector by L, an aggregate liquidity deficit will arise if banks' cash withdrawals cL are larger than the aggregate amount obtained in the refinancing operations RO. In this case, competition for scarce liquidity brings the interbank rate to its upper limit $i^{LF} - \gamma$. A higher interest rate would not be accepted by the liquidity deficit banks, since then they would prefer to borrow from the central bank's lending facility instead. If an aggregate liquidity surplus occurs, as cash withdrawals are lower than the aggregate amount of liquidity obtained in the refinancing operations, competition for limited lending possibilities in the interbank market brings the interbank rate to its lower limit $i^{DF} + \gamma$. If there is neither an aggregate liquidity deficit nor surplus, neither market side possesses market power. In consequence, any rate within the lower and the upper limit depicts a possible equilibrium.

5 Optimal Behavior at the First Stage

5.1 A Bank's Optimization Problem

At the first stage of the model, commercial bank i must decide on its loan volume L_i and on its borrowing from the refinancing operations offered by the central bank RO_i. This decision is made without knowing the actual liquidity needs resulting from uncertain deposit transfers. However, also these liquidity needs determine banks' refinancing costs. The bank expects refinancing costs to occur as due to certain cash withdrawals and uncertain deposit transfers there may be a net loss of non-interest bearing deposits. This net loss has to be costly balanced by borrowing liquidity from the central bank and/or from the interbank market. Consequently, bank i forms expectations about the deposit transfers of its customers, and therefore, about its liquidity needs when deciding on L_i and RO_i. Formally, the decision problem of bank i which aims at maximizing its expected profit $E[\pi_i]$ at the first stage reads

$$\begin{aligned}\max_{L_i, RO_i} E\left[\pi_i\right] = i^L L_i - \tfrac{1}{2}\lambda L_i^2 - i^{RO} RO_i - \max\left\{i^{IBM} - \gamma, i^{DF}\right\} \int_{t^{min}}^{\bar{t}_i} N_i g(t_i)\, dt_i \\ - \min\left\{i^{IBM} + \gamma, i^{LF}\right\} \int_{\bar{t}_i}^{t^{max}} N_i g(t_i)\, dt_i.\end{aligned} \tag{14}$$

The first term on the right hand side of (14) reflects the interest revenues of granting loans while the second term expresses the management costs associated with these loans. Covering liquidity needs via the refinancing operations generates borrowing costs for the bank (third term). Moreover, the bank faces either a liquidity surplus or deficit N_i as defined in (8). The fourth term depicts the expected return in case the bank faces a liquidity surplus at the beginning of the second stage ($N_i < 0$) while the last term shows the expected costs in case the bank faces a liquidity deficit ($N_i > 0$). In the following, we elaborate on these last two terms in more detail.

Liquidity needs at the beginning of the second stage are given by (8). The currency ratio c is certain and identical for all banks. In addition, the amounts L_i and RO_i are certain once they are chosen at the first stage. Therefore, deposit transfers, more precisely the share t_i, is the only source of uncertainty of an individual bank at the first stage regarding its liquidity needs N_i. From (8) we can infer that an individual bank will face neither a liquidity deficit nor a surplus at the second stage, i.e. $N_i = 0$, only if

$$t_i = \tfrac{RO_i - cL_i}{(1-c)\chi L_i} =: \bar{t}_i. \tag{15}$$

It follows directly from (15) that this critical share of deposit transfers of an individual bank $\bar{t}_i$ increases in RO_i and decreases in L_i. If a bank's individual share of deposit transfers is smaller than the critical share ($t_i < \bar{t}_i$), the net deposit transfers to other banks are that low that the bank faces a liquidity surplus at the beginning of the second stage ($N_i < 0$). In this case, the bank will lend in the interbank market or will place its excess liquidity in the deposit facility, depending on which option is more profitable. This is reflected by the fourth term of (14). If $t_i > \bar{t}_i$, the bank will face a liquidity deficit $N_i > 0$ and will be forced to borrow either from the interbank market or from the central bank's lending facility. Apparently, the bank chooses the alternative which is less costly. This aspect is reflected by the last term of (14).

Note that uncertainty with respect to deposit transfers exists only at the individual level. At the aggregate level, deposit transfers are certain with $E[T] = 0$, see equation (2). This has the following implications. First, for any given loan volume L_i and any amount RO_i of liquidity obtained in the refinancing operations, each bank has the same expectations about its subsequent liquidity needs. Second, banks form the same expectations about the subsequent interbank rate that will prevail in equilibrium. The interbank rate will only depend on the aggregate liquidity position in the banking sector. Once all banks have granted their loans and borrowed from the refinancing operations, this aggregate liquidity position is certain. This implies that an individual bank takes the aggregate liquidity needs and therefore, also the interbank rate as given. Consequently, all banks face exactly the same decision problem given by (14). The optimal individual borrowing from the refinancing operations RO_i^{opt} as well as the optimal individual lending to the non-banking sector L_i^{opt} are identical for all banks and are, therefore, equal to the respective aggregate values RO and L.

5.2 A Bank's Optimal Behavior

5.2.1 Optimal Borrowing from the Refinancing Operations

Determining a bank's optimal behavior at the first stage, we can restrict our attention to the case $i^{IBM} \in \left[i^{RO} - \gamma, i^{RO} + \gamma\right]$. Suppose $i^{IBM} < i^{RO} - \gamma$. Then, no bank has an incentive to borrow from the central bank's refinancing operations at the first stage since borrowing from the interbank market at the second stage is strictly cheaper. However, due to cash withdrawals the banking sector as a whole faces a certain liquidity deficit which can only be covered by borrowing from the central bank's refinancing operations or lending facility. Refusing to borrow from the central bank's refinancing operations at the first stage would thus imply the usage of the lending facility at the second stage. As the lending facility is strictly more expensive than the refinancing operations, $i^{IBM} < i^{RO} - \gamma$ constitutes no possible equilibrium. If $i^{IBM} > i^{RO} + \gamma$ each bank would be incentivized to borrow unlimitedly from the central bank's refinancing operations to place its liquidity in the interbank market. Apparently, this cannot be an equilibrium either. Considering this and solving the optimization problem (14) we obtain

Lemma 2: *Suppose that* $i^{IBM*} \in \left[i^{RO} - \gamma, i^{RO} + \gamma\right]$ *and assume that* $\bar{t}_i^{opt} > -\frac{c}{(1-c)\chi}$. *Then at the first stage, bank* i *will borrow from the central bank's refinancing operations according to the following first order condition:*

$$i^{RO} = \max\left\{i^{IBM*} - \gamma, i^{DF}\right\} G\left(\bar{t}_i^{opt}\right) + \min\left\{i^{IBM*} + \gamma, i^{LF}\right\}\left[1 - G\left(\bar{t}_i^{opt}\right)\right] \tag{16}$$

with

$$\bar{t}_i^{opt} = \frac{RO_i^{opt} - cL_i^{opt}}{(1-c)\chi L_i^{opt}}.$$

Proof: See appendix.

Optimal borrowing from the central bank's refinancing operations requires marginal costs of this borrowing to be equal to expected marginal revenues. Marginal costs are equal to the interest rate on these operations given by the left hand side of (16). The right hand side of (16) reflects expected marginal revenues. With probability $G(\bar{t}_i^{opt})$, bank i will face a liquidity surplus at the second stage, i.e. $N_i < 0$. In this case, the bank will either lend its excess liquidity in the interbank market or place it in the deposit facility, depending on which alternative yields the higher marginal revenues. With probability $1 - G(\bar{t}_i^{opt})$, the bank will face a liquidity deficit, i.e. $N_i > 0$, so that it will borrow from the interbank market or close its liquidity gap by borrowing from the central bank's lending facility. In this case borrowing from the central bank's refinancing operations implies marginal revenues in the form of avoided illiquidity costs.

In the following, we will briefly describe the adjustment process in the case marginal costs differ from expected marginal revenues as this adjustment process plays a crucial role in our analysis. Assume that marginal costs are higher than expected marginal revenues. Then, the bank has an incentive to reduce its borrowing from the central bank's refinancing operations: If RO_i declines, the probability of facing a liquidity deficit at the second stage will increase and the probability of facing a liquidity surplus will decrease, respectively.[10] As marginal revenues in the case of a liquidity deficit given by $\min\left\{i^{IBM}+\gamma, i^{LF}\right\}$ are strictly larger than those in the case of a liquidity surplus given by $\max\left\{i^{IBM}-\gamma, i^{DF}\right\}$, expected marginal revenues will always increase if the bank reduces its borrowing from the refinancing operations. Consequently, as long as marginal costs are higher than marginal revenues, the bank wishes to reduce RO_i until expected marginal revenues equal marginal costs. Restricting $\bar{t}_i^{opt}$ to $\bar{t}_i^{opt} > -\frac{c}{(1-c)\chi}$ ensures expected marginal revenues at the second stage to be always sufficiently high so that the bank will always participate in the refinancing operations at the first stage.[11]

5.2.2 Optimal Lending to the Non-Banking Sector

Solving the optimization problem (14) with respect to the optimal lending L_i^{opt} to the non-banking sector, we obtain

Lemma 3: *Given that $\bar{t}_i^{opt} > -\frac{c}{(1-c)\chi}$, then bank i will supply loans at the first stage according to the following first order condition:*

$$i^L = \lambda L_i^{opt} + c i^{RO} + (1-c)\chi\phi, \tag{17}$$

with

$$\phi = \max\left\{i^{IBM}-\gamma, i^{DF}\right\} \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i + \min\left\{i^{IBM}+\gamma, i^{LF}\right\} \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i. \tag{18}$$

Proof: See appendix.

Optimal lending L_i^{opt} to the non-banking sector requires balancing marginal revenues with expected marginal costs of granting loans. Marginal revenues are equal to the interest

[10] Formally, a reduction in RO_i implies a decrease in $\bar{t}_i$, as equation (15) reveals. Consequently, the probability of facing a liquidity surplus $G(\bar{t}_i)$ decreases, whereas the probability of a liquidity deficit $1-G(\bar{t}_i)$ increases.

[11] This will be the case if both cash withdrawals and the degree of uncertainty are sufficiently large or if the distribution of T is not too right-skewed. We comment on the results for $\bar{t}_i^{opt} \leq -\frac{c}{(1-c)\chi}$ in the proof to Lemma 3.

rate i^L. Expected marginal costs consist of marginal management costs λL_i^{opt} and expected marginal refinancing costs $ci^{RO} + (1-c)\chi\phi$. The latter can be divided into two parts. The first part ci^{RO} refers to the certain refinancing costs due to borrowing from the central bank's refinancing operations at the first stage. The second part $(1-c)\chi\phi$ captures the uncertain refinancing costs occurring at the second stage with ϕ being specified in (18). If bank i faces a liquidity surplus at the beginning of the second stage as $t_i \leq \bar{t}_i^{opt}$, it will either lend its liquidity surplus in the interbank market at $i^{IBM} - \gamma$ or place it in the deposit facility at i^{DF}. Hence, the first term on the right hand side of (18) captures the expected (negative) marginal refinancing costs in the case of a liquidity surplus. The second term reflects the expected marginal refinancing costs in case the bank faces a liquidity deficit. A liquidity deficit will occur if $t_i > \bar{t}_i^{opt}$. In this case, bank i will borrow either from the interbank market at $i^{IBM} + \gamma$ or from the lending facility at i^{LF}.

Commercial banks' expected refinancing costs are crucial for monetary policy. The central bank can influence banks' expected refinancing costs to change their credit supply behavior. Therefore, we take a closer look at banks' expected refinancing costs in the different cases described in Proposition 1. Considering this proposition, we obtain

Lemma 4: *If $\gamma \leq \bar{\bar{\gamma}}$, a bank's expected marginal refinancing costs will read*

$$ci^{RO} + (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i 2\gamma. \tag{19}$$

If $\gamma > \bar{\bar{\gamma}}$, a bank's expected marginal refinancing costs will read

$$ci^{RO} + (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i \left(i^{LF} - i^{DF}\right). \tag{20}$$

Proof: Omitted.

The first term in equation (19) and (20) describes certain marginal refinancing costs due to borrowing from the central bank's refinancing operations at the first stage. The second term reflects expected marginal refinancing costs of transactions at the second stage. Equation (19) reveals that for $\gamma \leq \bar{\bar{\gamma}}$ expected second stage marginal refinancing costs are formally the same for all cases described in Proposition 1. For interpreting this term in more detail, it is useful to consider that, due to $E[T] = 0$, the expected second stage liquidity deficit per unit of loans equals the negative value of the expected second stage liquidity surplus per unit of loans:

$$(1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i = -(1-c)\chi \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i. \tag{21}$$

Expected second stage marginal refinancing costs as described in (19) consist of the expected share per unit of loans for which refinancing costs are expected multiplied with the relevant refinancing costs. If there is neither an aggregate liquidity surplus nor deficit as $RO = cL$, banks will balance their liquidity needs solely via the interbank market. Considering (17), expected second stage marginal refinancing costs are then

$$(1-c)\chi \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i (i^{IBM*} - \gamma) + (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i (i^{IBM*} + \gamma). \tag{22}$$

Inserting (21) yields that expression (22) is equivalent to the second term of (19). Obviously, the interbank rate constitutes negative marginal refinancing costs in the case of an individual liquidity surplus and positive marginal refinancing costs in the case of an individual liquidity deficit, while transaction costs have a positive impact on marginal refinancing costs in both cases. Expression (22) shows that the effects of the interbank rate on expected marginal refinancing costs compensate each other so that only interbank market transaction costs are relevant for a bank's expected second stage marginal refinancing costs. Considering (21), the expected share per unit of loans for which refinancing costs are expected is $2(1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i$, the relevant refinancing costs are γ.

If there is an aggregate liquidity surplus as $RO > cL$, banks will cover their individual liquidity deficit in the interbank market at marginal costs of $i^{IBM*} + \gamma = i^{DF} + 2\gamma$. In case of an individual liquidity surplus, they place their excess liquidity in the interbank market or in the deposit facility so that marginal revenues are given by i^{DF}. Consequently, expected second stage marginal refinancing costs are

$$(1-c)\chi \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i i^{DF} + (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i (i^{DF} + 2\gamma), \tag{23}$$

which is again equivalent to the second term of (19). The expected marginal refinancing costs given by (23) show that the interest rate i^{DF} has a negative impact on these costs in the case of a liquidity surplus and a positive impact in the case of a liquidity deficit. As these effects compensate each other, the expected share per unit of loans for which those refinancing costs accrue are expected is equal to the expected liquidity deficit per unit of loans given by $(1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i$, the relevant refinancing costs are 2γ. Transaction costs are relevant for two reasons. First, they will accrue if the bank borrows the liquidity in the interbank market and, second, because they imply a higher interbank rate which is $i^{DF}+\gamma$.

Analogously, if there is an aggregate liquidity deficit as $RO < cL$, the expected share per unit of loans for which refinancing costs are expected is $-(1-c)\chi \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i = (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i$, and the relevant refinancing costs are 2γ.

In case there is no interbank market as $\gamma > \bar{\bar{\gamma}}$, expected second stage marginal refinancing costs are

$$(1-c)\chi \int_{t^{min}}^{\bar{t}_i^{opt}} t_i g(t_i)\, dt_i i^{DF} + (1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i i^{LF}. \tag{24}$$

Considering (21) we obtain that expected second stage marginal refinancing costs are equal to the second term of (20). The expected share per unit of loans for which refinancing costs are expected is $(1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i$, and the relevant refinancing costs are $i^{LF} - i^{DF}$.

6 Equilibrium

After having clarified the optimal behavior of an individual bank, we are now in a position to determine the equilibrium of our model. We have a continuum of ex-ante identical banks of unit mass. Consequently, the bank-individual optimal values L_i^{opt} and RO_i^{opt} correspond to the respective equilibrium aggregate levels L^* and RO^*.

In the euro area, aggregate borrowing from the ECB's main refinancing operations has been systematically equal or higher than the ECB's benchmark allotment. As in our model, cL^* corresponds to the benchmark allotment, we focus in our analysis on equilibria in which $RO^* \geq cL^*$. These equilibria will emerge if $G(0) < 0.5$ and if $i^{LF} - i^{RO} \geq i^{RO} - i^{DF}$. The latter means that the corridor, which the rates on the central bank's facilities form around the main policy rate, is symmetric or asymmetric in the sense that the lower difference is smaller than the upper difference. These two cases have been relevant in the euro area.[12] The former means that there will be a left-skewed distribution of T. From an

[12] From April 1999 until November 2013 the rates on the Eurosystem's facilities generally formed a symmetric corridor around the rate on the main refinancing operations. However, due to the zero lower bound, the rate on the deposit facility was not decreased in November 2013 contrary to the rates on the lending facility and on the main refinancing operations. Consequently, there has been an asymmetric interest rate corridor since then.

ex-post perspective, this means that most banks will face relatively small net liquidity outflows ($t_i > 0$) while few banks will be confronted with large net liquidity inflows ($t_i < 0$). From an ex-ante perspective, this means that each individual bank expects small outflows with a high probability and large inflows with low probability. To understand this pattern, it is useful to distinguish between two types of bank customers. First, consider customers who predominantly generate liquidity outflows by making payments for, e.g., consumption purposes. These customers may experience a massive preference shock with a small probability, which significantly reduces their spending and thus contributes to large net liquidity inflows to the bank. Second, bank customers, who predominantly receive payments as suppliers of consumption goods, may benefit from spikes in demand for their goods, e.g. caused by a major innovation, with small probability. Again, this would contribute to large net liquidity inflows to the bank.

Combining the results of Proposition 1, Lemma 2 and Lemma 3, we obtain

Proposition 2: *Assume that* $G(0) < 0.5$ *and that* $i^{LF} - i^{RO} \geq i^{RO} - i^{DF}$. *Then, depending on* γ, *we have to distinguish between three equilibria*

$$\mathrm{I}: \quad RO^* = cL^*, \quad DF^* = 0, \; LF^* = 0, \quad i^{IBM*} = i^{RO} - \gamma\left[1 - 2G(0)\right] \qquad \textit{if} \;\; \gamma \leq \bar{\gamma}, \tag{25}$$

$$\mathrm{II}: \quad RO^* > cL^*, \quad DF^* > 0, \; LF^* = 0, \quad i^{IBM*} = i^{DF} + \gamma \qquad \textit{if} \;\; \gamma \in (\bar{\gamma}, \bar{\bar{\gamma}}], \tag{26}$$

$$\mathrm{III}: \quad RO^* > cL^*, \quad DF^* > LF^* > 0 \qquad \textit{if} \;\; \gamma > \bar{\bar{\gamma}}, \tag{27}$$

with

$$\bar{\gamma} := \frac{i^{RO} - i^{DF}}{2[1 - G(0)]}, \tag{28}$$

and $\bar{\bar{\gamma}}$ *being defined in* (12).

Proof: See appendix.

In Equilibrium I, interbank market transaction costs are that low that each bank borrows exactly an amount equal to its cash withdrawals from the central bank's refinancing operations and balances its liquidity needs resulting from the deposit transfers of its customers solely by using the interbank market. None of the facilities is used. Only this behavior implies that the optimality condition given by (16) is fulfilled. To see this, suppose as a starting point that $\gamma = 0$. If banks borrowed an amount larger than their cash withdrawals from the refinancing operations, there would be an aggregate surplus at the second stage bringing the interbank market to its lower bound $i^{DF} + \gamma = i^{DF}$. However, this cannot be an equilibrium, as then marginal costs of borrowing from the refinancing operations given by i^{RO} would exceed expected marginal revenues which in this case are equal to i^{DF}.[13] Consequently, banks will have an incentive to reduce their borrowing from the refinancing operations to balance marginal costs and expected marginal revenues (see the adjustment process described in subsection 5.2.1). Analogously, if banks borrowed an amount lower than their cash withdrawals, there would be an aggregate liquidity deficit bringing the interbank rate to its upper bound $i^{LF} - \gamma = i^{LF}$. This is no equilibrium either, as for this interbank rate expected marginal revenues of borrowing from the refinancing operations, which are equal to i^{LF}, exceed marginal costs given by i^{RO}, so that banks wish to increase their borrowing. Consequently, for $\gamma = 0$ an equilibrium will be reached if each bank borrows an amount equal to its cash withdrawals from the refinancing operations. This implies that the interbank market rate i^{IBM*} equals the central bank's policy rate i^{RO}.

Let us assume next that γ becomes positive. Then, expected marginal revenues of borrowing from the central bank's refinancing operations increase: If a bank faces a liquidity surplus at the second stage, its marginal revenues from placing liquidity in the interbank market will decrease but its avoided marginal illiquidity costs in case of a liquidity deficit will increase (see Lemma 2). Due to the left-skewed distribution of T, the probability of facing a liquidity deficit at the second stage will be higher than of facing a liquidity surplus as long as the bank borrows an amount equal to its cash withdrawals from the central bank's refinancing operations, i.e. as long as $RO_i = cL_i$. Consequently, a bank's expected marginal revenues of borrowing from the refinancing operations will increase if γ becomes positive in that case. To balance marginal costs and expected marginal revenues again, each bank will have an incentive to increase its borrowing from the refinancing operations above cL_i (see the adjustment process described in subsection 5.2.1). However, such an aggregate borrowing behavior will result in excess aggregate liquidity so that the interbank rate will decline. This decline will reduce expected marginal revenues of borrowing from the refinancing operations. Accordingly, the incentive to borrow more than cL_i becomes weaker. No bank will borrow more than an amount equal to its cash withdrawals from the refinancing operations if the interbank rate decreases to $i^{IBM} = i^{RO} - \gamma\,[1 - 2G\,(0)]$. Consequently, as long as the interbank rate is unrestricted, an increase in expected marginal revenues due to higher interbank market transaction costs will be offset by a decrease of the interbank rate. The price mechanism works. This mechanism ensures that banks have no incentive to borrow more than an amount equal to their cash withdrawals from the

[13] One obtains expected marginal revenues by inserting the equilibrium interbank market rate into the right hand side of (16).

central bank's refinancing operations. Equilibrium I as described by equation (25) will be realized.

However, if transaction costs exceed the critical level $\bar{\gamma}$, further decreases of the interbank market rate will not be possible to balance marginal costs and expected marginal revenues as the interbank market rate has reached its lower bound $i^{DF}+\gamma$. Consequently, a further increase in γ implies that banks actually start to increase their borrowing from the refinancing operations. This will reduce the probability of facing a liquidity deficit and, therefore, expected marginal revenues. As the price mechanism does not function, marginal costs and expected marginal revenues are balanced via a quantity effect. As this behavior implies that banks increase their borrowing from the refinancing operations above the cash withdrawals, an aggregate liquidity surplus will materialize, $RO^* > cL^*$, while the interbank rate will remain at its lower limit. The excess liquidity will then be placed in the deposit facility. Hence, for sufficiently high transaction costs, Equilibrium II given in equation (26) will be realized. In this equilibrium, all banks with a liquidity deficit still cover their liquidity needs by using the interbank market. Some surplus banks have to use the deposit facility due to the aggregate excess liquidity.

However, if transaction costs reach the critical level $\bar{\bar{\gamma}}$, the deficit banks are no longer willing to borrow their liquidity from the interbank market but prefer to use the central bank's lending facility instead. The interbank market breaks down. Both, the deficit banks as well as the surplus banks, exclusively use the facilities to balance their liquidity needs at the second stage. As there is aggregate excess liquidity, it follows that $DF^* > LF^*$. Equilibrium III as given in (27) will be realized.

In Proposition 2 we assume that $G(0) < 0.5$ and that $i^{LF} - i^{RO} \geq i^{RO} - i^{DF}$. These assumptions imply that the equilibrium is characterized by $RO^* \geq cL^*$, which is the situation observed in the euro area. However, for the sake of completeness, we will also briefly comment on the also possible equilibrium $RO^* < cL^*$. This equilibrium will emerge if the distribution of T becomes sufficiently right-skewed or if the interest rate corridor becomes sufficiently asymmetric with $i^{LF} - i^{RO} < i^{RO} - i^{DF}$. We start with the importance of the distribution of T. Let us assume that T is distributed symmetrically around $t_i = 0$ and that the interest rates on the facilities form a symmetric corridor around the main policy rate. Then, the probability of facing a net deposit outflow equals the probability of facing a net deposit inflow due to customers' deposit transfers. In this case, only $RO_i = cL_i$ implies that (16) is fulfilled. Transaction costs play no role as they increase marginal revenues of borrowing from the refinancing operations in the case of a liquidity deficit and decrease them in the case of a liquidity surplus, and for $RO_i = cL_i$ both scenarios occur with the same probability given the symmetric distribution of T.

Now let us assume that the distribution of T becomes right-skewed. For $RO_i = cL_i$, the probability of facing a liquidity surplus thus increases. In this case, transaction costs imply that expected marginal revenues of borrowing from the refinancing operations decrease. Accordingly, banks are incentivized to borrow less from the refinancing operations. Analogously to the case of a left-skewed distribution of T this results in an increase in the interbank market rate to balance marginal costs and expected marginal revenues of borrowing from the refinancing operations. However, if the interbank rate reaches its upper bound so that it cannot increase further, banks start to borrow less from the refinancing operations and $RO_i^{opt} < cL_i^{opt}$.

In order to highlight the importance of the asymmetry of the interest rate corridor let us assume that T is distributed symmetrically around zero. In case $i^{LF} - i^{RO} < \gamma < i^{RO} - i^{DF}$, $RO_i = cL_i$ does not correspond to the optimal behavior of bank i, but $RO_i^{opt} < cL_i^{opt}$: Facing these relatively high interbank market transaction costs, banks with a liquidity deficit will only accept an interbank rate below i^{RO}. Otherwise, they would prefer to use the lending facility. However, an interbank rate below i^{RO} reduces banks' expected marginal revenues of borrowing from the refinancing operations and they are incentivized to borrow less from the refinancing operations. Generally, this would lead to an increase in the interbank rate. However, such an adjustment is not possible as the deficit banks would not accept a higher interbank rate. Therefore, banks actually start to borrow less from the refinancing operations and $RO_i^{opt} < cL_i^{opt}$.

7 The Influence of Monetary Policy on Bank Loan Supply

Generally, uncertainty about net deposit transfers and interbank market frictions have a negative impact on bank loan supply.[14] An increase in uncertainty about net deposit transfers leads to an increase in both, the expected liquidity surplus and the expected liquidity deficit per unit of loans as equation (21) shows. As this surplus or deficit has to be costly balanced either in the interbank market or via the central bank's facilities, an increase in uncertainty implies increasing expected marginal refinancing costs of granting loans, as formally shown in Lemma 4. Consequently, banks start to reduce their loan supply. Obviously, a change in interbank market transaction costs will only have an impact

[14] We provide the respective formal analysis in Appendix A.4.

on banks' loan supply if these costs are still low enough to ensure an active interbank market, i.e. if $\gamma \leq \bar{\bar{\gamma}}$. In this case, it follows from Lemma 4 that an increase in marginal transaction costs γ results in an increase in expected marginal refinancing costs. Accordingly, banks will reduce their loan supply. In the following, we will analyse in detail in how far interbank market transaction costs and uncertainty about net deposit outflows influence the impact of monetary policy on bank loan supply.

7.1 Main Monetary Policy Rate

The central bank has several alternatives to impose an effect on bank loan supply. Starting with the possibility of changing its policy rate i^{RO}, we obtain

Proposition 3: *A change in the policy rate implies for Equilibrium j*

$$\frac{\partial L^{j*}}{\partial i^{RO}} = -\frac{1}{\lambda}\left[c + (1-c)\chi\bar{t}^{*}\right] < 0 \quad \forall \quad j \quad \textit{with}$$
$$\frac{\partial L^{\text{III}*}}{\partial i^{RO}} < \frac{\partial L^{\text{II}*}}{\partial i^{RO}} < \frac{\partial L^{\text{I}*}}{\partial i^{RO}} < 0.$$

Furthermore, we get

$$\frac{\partial^2 L^{\text{III}*}}{\partial i^{RO}\partial\chi} < \frac{\partial^2 L^{\text{II}*}}{\partial i^{RO}\partial\chi} < \frac{\partial^2 L^{\text{I}*}}{\partial i^{RO}\partial\chi} = 0,$$
$$\frac{\partial^2 L^{\text{III}*}}{\partial i^{RO}\partial\gamma} = 0, \quad \frac{\partial^2 L^{\text{II}*}}{\partial i^{RO}\partial\gamma} < 0, \quad \frac{\partial^2 L^{\text{I}*}}{\partial i^{RO}\partial\gamma} = 0.$$

Proof: See appendix.

This proposition reveals that, independently of potential frictions in the interbank market and the extent of uncertainty about net deposit transfers, by changing its policy rate i^{RO} the central bank affects banks' marginal refinancing costs and, therefore, their loan supply in all equilibria. However, frictions in the interbank market and uncertainty about net deposit transfers may reinforce the impact of this monetary policy impulse on bank loan supply.

Proposition 3 shows that in Equilibrium I, in which $\bar{t}^{*} = 0$, the effect of monetary policy on aggregate loan supply depends only on the management cost parameter λ and the currency ratio c. The impact of monetary policy on bank loan supply is not influenced by interbank market frictions or by uncertainty about net deposit transfers: An increase in i^{RO} implies marginal costs of borrowing from the main refinancing operations to become higher than expected marginal revenues, leading to the adjustment process described in subsection 5.2.1. The interbank rate increases which again balances marginal costs and expected marginal revenues. In this case, only the price effect prevails. A quantity effect to balance marginal costs and expected marginal revenues does not occur so that $\bar{t}^*$ remains unchanged. Therefore, we can conclude from Lemma 4 that in Equilibrium I only first stage marginal costs of granting loans will change if the monetary policy rate is changed. Frictions in the interbank market and uncertainty about net deposit transfers, which both refer to the second stage, play no role for the effectiveness of monetary policy.

In contrast, in Equilibrium II and III a change in the policy rate i^{RO} does not only have an impact on first stage marginal refinancing costs but also on expected second stage marginal refinancing costs. The reason is that in both equilibria, a change in the interbank market rate cannot balance marginal costs and expected marginal revenues of borrowing from the central bank's refinancing operations. Either the interbank market rate is at its lower bound or an interbank market does not exist due to high transaction costs.[15] Consequently, banks start to adjust their borrowing from the refinancing operations to balance marginal costs and expected marginal revenues. According to Lemma 4, this behavior implies a change in expected second stage marginal refinancing costs: Suppose the central bank decreases i^{RO}. Then, marginal costs of borrowing from the refinancing operations fall below expected marginal revenues inducing banks to increase their borrowing from the refinancing operations. This borrowing behavior implies that the expected liquidity deficit per unit of loans, which has to be covered costly by borrowing from the interbank market (Equilibrium II) or from the central bank's lending facility (Equilibrium III), decreases, whic is formally reflected by an increase in $\bar{t}_i^{opt}$. This decreased expected liquidity deficit reduces the banks' expected marginal refinancing costs, so that banks are willing to supply more loans. Consequently, contrary to Equilibrium I, in Equilibrium II and III not only first stage marginal refinancing costs decrease but in addition, there is a reduction of expected second stage marginal refinancing costs. Therefore, the impact of monetary policy on bank loan supply is stronger than in Equilibrium I.

In Equilibrium II, the reinforcing effect increases in interbank market transaction costs: Crucial with respect to the reinforcing effect is the decrease of the expected liquidity deficit due to the increased borrowing from the refinancing operations, formally reflected by an increase in $\bar{t}_i^{opt}$. As the deficit will be costly refinanced in the interbank market, the

[15] Note that in Equilibrium II, the interbank rate has reached its lower bound so that an increase in the interbank rate is generally possible. This would however imply a switch from Equilibrium II to Equilibrium I. In this section, we thus only consider changes in i^{RO} which ensure that $\gamma > \frac{i^{RO}-i^{DF}}{2[1-G(0)]}$, i.e. we stay in Equilibrium II and the interbank rate is fixed at its lower bound.

impact of the decreased expected liquidity deficit on expected marginal refinancing costs is the stronger, the larger the interbank market transaction costs are. Furthermore, in both equilibria, I and II, the reinforcing effect is the stronger the higher the extent of uncertainty about a bank's net deposit transfers χ is. The reason ist that the expected liquidity deficit per unit of loans, given by $(1-c)\chi \int_{\bar{t}_i^{opt}}^{t^{max}} t_i g(t_i)\, dt_i$, is determined by this uncertainty. Therefore, a large χ gives the decrease of the expected deficit due to the increased borrowing from the refinancing operations a higher weight.

Finally, Proposition 3 shows that the reinforcing effect is stronger in Equilibrium III than in Equilibrium II. The intuition behind this result is that covering a liquidity deficit by borrowing from the lending facility in Equilibrium III is more expensive than of using the interbank market in Equilibrium II.[16]

7.2 Main Policy Rate and the Rates on the Facilities

Alternatively, the central bank might change all its interest rates instead of solely changing its policy rate. In this case we obtain

Proposition 4: *A likewise change in all central bank's interest rates, i.e.* $di^{RO} = di^{DF} = di^{LF}$*, implies for Equilibrium j*

$$\frac{\partial L^{j*}}{\partial i^{RO}} = -\frac{c}{\lambda} < 0 \quad and \quad \frac{\partial^2 L^{j*}}{\partial i^{RO} \partial \chi} = \frac{\partial^2 L^{j*}}{\partial i^{RO} \partial \gamma} = 0 \quad \forall \quad j.$$

Proof: See appendix.

If the central bank changes all interest rates to the same extent, a reinforcing effect will be avoided. Recall from Proposition 3 that the reinforcing effect will occur if the interbank rate has already reached its lower bound so that the interbank rate cannot adjust to changes in the policy rate anymore (Equilibrium II) or if due to high transaction costs an interbank market does not exist (Equilibrium III). Changing the rates of the facilities leads to a change of the lower bound which allows the interbank rate to adjust in Equilibrium II as well. The price mechanism works again so that the quantity effect which is responsible for the reinforcing effect does not occur, i.e. $\bar{t}_i^{opt} = \bar{t}^*$ does not change. In Equilibrium III, a likewise change in the rates on the facilities as in the main policy rate implies that expected marginal revenues of borrowing from the refinancing operations

[16] Lemma 4 shows that relevant costs in Equilibrium III are given by $i^{LF} - i^{DF}$, in Equilibrium II they are 2γ. As in Equilibrium II $\gamma \leq \bar{\bar{\gamma}} = (i^{LF} - i^{DF})/2$, the relevant marginal refinancing costs in Equilibrium III are higher than in Equilibrium II.

change to the same extent as marginal costs.[17] Consequently, banks do not change their borrowing behavior so that also in this equilibrium $\bar{t}_i^{opt} = \bar{t}^*$ does not change. A quantity effect, which is responsible for the reinforcing effect, does not occur. Therefore, in all equilibria a likewise change in all central bank's interest rates will only affect first stage marginal refinancing costs (see Lemma 4). This means that in all equilibria, this central bank behavior has the same impact on bank loan supply. A reinforcing effect does not occur.

However, these results point to the problem of a zero lower bound on interest rates. In Equilibrium II and III, the reinforcement of an expansionary monetary policy cannot be avoided by a likewise change in the rates on the facilities if the rate on the deposit facility i^{DF} is already equal to zero. As a result, the zero lower bound on the deposit facility rate may imply an unavoidable reinforcement effect of an expansionary monetary policy.

The findings of this subsection point to the importance of the rates on the facilities in the presence of uncertain liquidity needs and interbank market frictions. Their high relevance will also become obvious in the next subsection.

7.3 Interest Rate Corridor

Changing the Width of the Corridor

The central bank might consider to change the width of the interest rate corridor around its policy rate. In this case we obtain

Proposition 5: *Suppose, we have a symmetric interest rate corridor, i.e.* $i^{RO} = \frac{i^{DF}+i^{LF}}{2}$*. A change in the width of the interest rate corridor, i.e.* $di^{LF} = -di^{DF}$ *and* $di^{RO} = 0$*, will imply*

$$\begin{aligned}
\frac{\partial L^{\mathrm{I}*}}{\partial(i^{LF} - i^{DF})} &= 0, \\
\frac{\partial L^{\mathrm{II}*}}{\partial(i^{LF} - i^{DF})} &= -\frac{(1-c)\chi}{\lambda}\bar{t}^* < 0, \\
\frac{\partial L^{\mathrm{III}*}}{\partial(i^{LF} - i^{DF})} &= -\frac{(1-c)\chi}{\lambda}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i < 0,
\end{aligned}$$

[17] Referring to the right hand side of (16), expected marginal revenues are given by $i^{DF}G(\bar{t}_i^{opt}) + i^{LF}[1 - G(\bar{t}_i^{opt})]$ in Equilibrium III.

with

$$\frac{\partial^2 L^{\mathrm{I}*}}{\partial(i^{LF}-i^{DF})\partial\chi}=0,\quad \frac{\partial^2 L^{\mathrm{II}*}}{\partial(i^{LF}-i^{DF})\partial\chi}<0,\quad \frac{\partial^2 L^{\mathrm{III}*}}{\partial(i^{LF}-i^{DF})\partial\chi}<0,$$
$$\frac{\partial^2 L^{\mathrm{I}*}}{\partial(i^{LF}-i^{DF})\partial\gamma}=0,\quad \frac{\partial^2 L^{\mathrm{II}*}}{\partial(i^{LF}-i^{DF})\partial\gamma}<0,\quad \frac{\partial^2 L^{\mathrm{III}*}}{\partial(i^{LF}-i^{DF})\partial\gamma}=0.$$

Proof: See appendix.

Proposition 5 shows that by changing the width of the interest rate corridor, the central bank may influence banks' loan supply without changing its policy rate i^{RO}. The central bank thus has an additional instrument at hand.

Obviously, changing the width of the corridor has no effect in Equilibrium I. In this equilibrium, banks will never use the facilities to balance their liquidity needs so that the rates on the facilities are irrelevant for banks' decisions on borrowing from the refinancing operations and on granting loans.

In Equilibrium II, an interbank market still exists, but an aggregate liquidity surplus emerges at the second stage as $RO^* > cL^*$. Accordingly, the interbank rate is at its lower bound and the central bank's deposit facility is used. The consequence of both is that the relevant central bank interest rate for expected marginal revenues of borrowing from the refinancing operations is i^{DF} as revealed by Lemma 2. Therefore, an increase in the width of the interest rate corridor implies that expected marginal revenues of borrowing from the refinancing operations become lower than marginal costs. Hence, banks start to borrow less from the refinancing operations. A decreased borrowing from the central bank's refinancing operations implies an increase in the expected liquidity deficit per unit of loans. Analogously to the situation described in section 7.1 this implies that the banks' expected marginal refinancing costs will increase which has a negative impact on their loan supply. Consequently, an increase in the width of the corridor corresponds to a contractionary monetary policy impulse. As expected marginal refinancing costs increase in γ and χ, the impact of this monetary policy impulse is the stronger the higher the frictions in the interbank market and the uncertainty about net deposit transfers are (for details see analogously section 7.1).

In Equilibrium III a change in the width of the corridor does not alter expected marginal revenues of borrowing from the refinancing operations and $\bar{t}_i^{opt}$ remains unchanged.[18] Although therefore, the expected liquidity deficit per unit of loans does not

[18]In equilibrium, marginal costs will equal expected marginal revenues of borrowing from the refinancing operations, i.e. $i^{RO} = i^{DF}G(\bar{t}_i^{opt}) + i^{LF}[1 - G(\bar{t}_i^{opt})]$. With a symmetric interest rate corridor, $G(\bar{t}_i^{opt}) =$

change, it follows from Lemma 4 that the relevant marginal refinancing costs, given by $i^{LF} - i^{DF}$, increase. Therefore, widening the interest rate corridor leads to an increase in expected marginal refinancing costs, implying a negative effect on banks' loan supply. As the expected liquidity deficit increases in the extent of uncertainty about net deposit transfers χ, the impact of this monetary policy impulse on bank loan supply increases in χ (for details see analogously again section 7.1).

Note that in the case the zero lower bound on the deposit rate becomes binding, changing the width of the corridor can not be used any longer as an instrument for conducting contractionary monetary policy. However an expansionary monetary policy is still feasible.

Changing the Asymmetrie of the Corridor

The central bank can also change the interest rate corridor in the sense that it becomes more or less asymmetric around the main policy rate. Against this background we obtain

Proposition 6: *A change in the interest rate corridor in the form of* $di^{LF} = di^{DF}$ *and* $di^{RO} = 0$, *will imply*

$$\begin{aligned}\frac{\partial L^{\mathrm{I}*}}{\partial i^{DF}} &= 0,\\ \frac{\partial L^{\mathrm{j}*}}{\partial i^{DF}} &= \frac{(1-c)\chi}{2\lambda}\bar{t}^{*} > 0 \quad \textit{for} \quad j = \mathrm{II}, \mathrm{III}\end{aligned}$$

with

$$\begin{aligned}\frac{\partial^2 L^{\mathrm{I}*}}{\partial i^{DF}\partial\chi} = 0 \quad \frac{\partial^2 L^{\mathrm{II}*}}{\partial i^{DF}\partial\chi} > 0, \quad \frac{\partial^2 L^{\mathrm{III}*}}{\partial i^{DF}\partial\chi} > 0,\\ \frac{\partial^2 L^{\mathrm{I}*}}{\partial i^{DF}\partial\gamma} = 0 \quad \frac{\partial^2 L^{\mathrm{II}*}}{\partial i^{DF}\partial\gamma} > 0, \quad \frac{\partial^2 L^{\mathrm{III}*}}{\partial i^{DF}\partial\gamma} = 0.\end{aligned}$$

Proof: See appendix.

Obviously, in Equilibrium I, in which the facilities will not be used and are not expected to be used, the change in the rates on the facilities has no effect on bank loan supply. However, in the equilibria II and III, the central bank has an additional effective instrument at its disposal. If, for example, the central bank increases both rates but leaves its main rate unchanged, its monetary policy will be expansionary: An increase in i^{DF} and i^{LF} implies in both equilibria that expected marginal revenues of borrowing from

0.5. Consequently, a change in the width of the corridor in the form of $di^{LF} = -di^{DF}, di^{RO} = 0$ does not alter expected marginal revenues.

the refinancing operations increases (see Lemma 2). Consequently, banks actually start to borrow more from the refinancing operation. This implies that the expected liquidity deficit per unit of loans decreases. This reduces the banks' expected refinancing costs (see Lemma 4), so that this monetary policy impulse has a positive impact on bank loan supply. Analogously to the situation described in section 7.1, in Equilibrium II, this monetary policy impulse is the more effective, the higher the transaction costs in the interbank market are, and in both equilibria, II and III, the impact of this monetary policy impulse on bank loan supply increases in the extent of uncertainty about net deposit transfers.

8 Summary

The interbank market is regarded to play a crucial role for the implementation of monetary policy as it serves as the starting point of the transmission mechanism. Based on a theoretical model, this paper analyzes in how far interbank market frictions in the form of transaction costs influence the effectiveness of monetary policy and which conclusions can be drawn for monetary policy implementation.

We show that independently of interbank market frictions monetary policy is effective. The central bank is able to influence banks' refinancing costs of granting loans, and therefore their loan supply, just by changing its main policy rate. However, frictions in the interbank market may reinforce this impact.

Generally, the central bank can steer this reinforcing effect by changing the rates on its facilities. This indicates that for sufficiently high interbank market transaction costs, the standing facilities present an additional effective monetary policy instrument. By changing the width or the asymmetry of the interest rate corridor the central bank can influence banks' expected marginal refinancing costs and therefore, their loan supply. It should be noted that lowering the rate on the deposit facility taken for itself, corresponds to a contractionary monetary policy. This implies that the zero lower bound of the rate on the deposit facility is not a problem in the case the central bank wants to conduct a an expansionary monetary policy.

Appendix

A.1 Proof of Lemma 2

Recall from (14) that the first stage optimization problem of a bank reads:

$$\begin{aligned}\max_{L_i,RO_i} E\left[\pi_i\right] = i^L L_i - \tfrac{1}{2}\lambda L_i^2 - i^{RO}RO_i - \max\left\{i^{IBM}-\gamma, i^{DF}\right\}\int_{t^{min}}^{\bar{t}_i} N_i g(t_i)\,dt_i \\ - \min\left\{i^{IBM}+\gamma, i^{LF}\right\}\int_{\bar{t}_i}^{t^{max}} N_i g(t_i)\,dt_i.\end{aligned} \tag{29}$$

subject to (8) and (15). By applying the Leibniz rule and making use of the fact that $N_i = 0$ for $t_i = \bar{t}_i$, we obtain:

$$\begin{aligned}\tfrac{\partial E[\pi_i]}{\partial RO_i} = -i^{RO} - \max\left\{i^{IBM}-\gamma, i^{DF}\right\}\int_{t^{min}}^{\bar{t}_i} \tfrac{\partial N_i}{\partial RO_i} g(t_i)dt_i \\ - \min\left\{i^{IBM}+\gamma, i^{LF}\right\}\int_{\bar{t}_i}^{t^{max}} \tfrac{\partial N_i}{\partial RO_i} g(t_i)dt_i.\end{aligned} \tag{30}$$

We can infer from (8) that $\frac{\partial N_i}{\partial RO_i} = -1$. Insertion of this in (30) and rewriting terms yields

$$\tfrac{\partial E[\pi_i]}{\partial RO_i} = -i^{RO} + \max\left\{i^{IBM}-\gamma, i^{DF}\right\} G\left(\bar{t}_i\right) + \min\left\{i^{IBM}+\gamma, i^{LF}\right\}\left[1 - G\left(\bar{t}_i\right)\right]. \tag{31}$$

Note that $\frac{\partial E[\pi_i]}{\partial RO_i}$ is decreasing in $G\left(\bar{t}_i\right) \in [0,1]$, which in turn is (weakly) increasing in $\bar{t}_i$. Moreover, we know

- from (15) that $\bar{t}_i$ is increasing in RO_i, so that $\frac{\partial E[\pi_i]}{\partial RO_i}$ is (weakly) decreasing in RO_i,
- from the restriction $RO_i \geq 0$ that $\bar{t}_i$ is restricted to $\bar{t}_i \geq -\frac{c}{(1-c)\chi} =: \tilde{t}$.

Denoting optima by the superscript *opt*, we can distinguish three cases:

1. If $i^{IBM} > i^{RO} + \gamma$, then $\frac{\partial E[\pi_i]}{\partial RO_i} > 0$ for all $G\left(\bar{t}_i\right)$. Therefore, we obtain $\bar{t}_i^{opt} = \infty$. In conjunction with (15) and the restriction $RO_i \geq 0$, this yields $RO_i^{opt} = \infty$.
2. If $i^{IBM} \in \left[i^{RO} - \gamma, i^{RO} + \gamma\right]$, then $\frac{\partial E[\pi_i]}{\partial RO_i} = 0$ only if $\bar{t}_i = \bar{t}_i^{opt}$, where $\bar{t}_i^{opt}$ is implicitly defined by (16). In conjunction with (15) and the restriction $RO_i \geq 0$, this yields $RO_i^{opt} = \max\left\{0, \bar{t}_i^{opt}\left(1-c\right)\chi L_i^{opt} + cL_i^{opt}\right\}$, which brings us to two subcases.
    - If $\bar{t}_i^{opt} > \tilde{t}$ and thus $G\left(\bar{t}_i^{opt}\right) > G\left(\tilde{t}\right)$, then $RO_i^{opt} = \bar{t}_i^{opt}\left(1-c\right)\chi L_i^{opt} + cL_i^{opt} > 0$.
    - If $\bar{t}_i^{opt} \leq \tilde{t}$ and thus $G\left(\bar{t}_i^{opt}\right) \leq G\left(\tilde{t}\right)$, then $RO_i^{opt} = 0$.

3. If $i^{IBM} < i^{RO} - \gamma$, then $\frac{\partial E[\pi_i]}{\partial RO_i} < 0$ for all $G\left(\bar{t}_i\right)$. Therefore, we obtain $\bar{t}_i^{opt} = -\infty$. In conjunction with (15) and the restriction $RO_i \geq 0$, this yields $RO_i^{opt} = 0$.

A.2 Proof of Lemma 3

By applying the Leibniz rule on (29) and making use of the facts that $N_i = 0$ for $t_i = \bar{t}_i$ and that optimal borrowing in the refinancing operation implies $\bar{t}_i = \max\left\{\bar{t}_i^{opt}, \tilde{t}\right\}$, we obtain:

$$\begin{aligned}\frac{\partial E[\pi_i]}{\partial L_i} &= i^L - \lambda L_i - \max\left\{i^{IBM} - \gamma, i^{DF}\right\} \int_{t^{min}}^{\max\left\{\bar{t}_i^{opt},\tilde{t}\right\}} \frac{\partial N_i}{\partial L_i} g(t_i) dt_i \\ &\quad - \min\left\{i^{IBM} + \gamma, i^{LF}\right\} \int_{\max\left\{\bar{t}_i^{opt},\tilde{t}\right\}}^{t^{max}} \frac{\partial N_i}{\partial L_i} g(t_i) dt_i + \frac{\partial E[\pi_i]}{\partial RO_i^{opt}} \frac{\partial E\left[RO_i^{opt}\right]}{\partial L_i}.\end{aligned} \tag{32}$$

We can infer from (8) and the envelope theorem that $\frac{\partial N_i}{\partial L_i} = c + (1-c)\chi t_i$ and $\frac{\partial E[\pi_i]}{\partial RO_i^{opt}} \frac{\partial E\left[RO_i^{opt}\right]}{\partial L_i} = 0$. Insertion of this in (32) and rewriting terms yields

$$\begin{aligned}\frac{\partial E[\pi_i]}{\partial L_i} &= i^L - \lambda L_i - (1-c)\chi \max\left\{i^{IBM} - \gamma, i^{DF}\right\} \int_{t^{min}}^{\max\left\{\bar{t}_i^{opt},\tilde{t}\right\}} t_i g(t_i) dt_i \\ &\quad - (1-c)\chi \min\left\{i^{IBM} + \gamma, i^{LF}\right\} \int_{\max\left\{\bar{t}_i^{opt},\tilde{t}\right\}}^{t^{max}} t_i g(t_i) dt_i \\ &\quad - c \max\left\{i^{IBM} - \gamma, i^{DF}\right\} G\left(\max\left\{\bar{t}_i^{opt}, \tilde{t}\right\}\right) \\ &\quad - c \min\left\{i^{IBM} + \gamma, i^{LF}\right\} \left[1 - G\left(\max\left\{\bar{t}_i^{opt}, \tilde{t}\right\}\right)\right].\end{aligned} \tag{33}$$

This brings us to two cases.

- If $\bar{t}_i^{opt} > \tilde{t}$ and thus $G\left(\bar{t}_i^{opt}\right) > G\left(\tilde{t}\right)$, then insertion of (16) in (33) implies that $\frac{\partial E[\pi_i]}{\partial L_i} = 0$ only if (17) is met.
- If $\bar{t}_i^{opt} \leq \tilde{t}$ and thus $G\left(\bar{t}_i^{opt}\right) \leq G\left(\tilde{t}\right)$, then $\frac{\partial E[\pi_i]}{\partial L_i} = 0$ only if (17) is met, however with

$$\phi = \max\left\{i^{IBM} - \gamma, i^{DF}\right\} \int_{t^{min}}^{\tilde{t}} t_i g(t_i)\, dt_i + \min\left\{i^{IBM} + \gamma, i^{LF}\right\} \int_{\tilde{t}}^{t^{max}} t_i g(t_i)\, dt_i. \tag{34}$$

Comment on $\bar{t}_i^{opt} \leq -\frac{c}{(1-c)\chi}$

If $\bar{t}_i^{opt} \leq -\frac{c}{(1-c)\chi}$ and thus $G\left(\bar{t}_i^{opt}\right) \leq G\left(\tilde{t}\right)$, the distribution of t_i is very right skewed so that bank i is no longer able to balance its first and second stage marginal liquidity costs. In this case, first stage marginal costs are higher than expected marginal net liquidity costs at the second stage. Bank i is thus incentivized to reduce the amount of borrowing RO_i from the central bank's refinancing operation as this would decrease its probability $G(\bar{t}_i)$ of facing a liquidity surplus at the second stage. However, this is no longer feasible as the non-negativity constraint for RO_i becomes binding. In consequence, bank i abstains from participation in the refinancing operation of the central bank and its probability of facing a liquidity surplus persists at $G\left(\tilde{t}\right)$.

With respect to optimal loan supply L_i^{opt} to the non-banking sector, bank i again balances the marginal revenues with the expected marginal costs. The only difference with respect to the case of $\bar{t}_i^{opt} > -\frac{c}{(1-c)\chi}$ is that the expected marginal refinancing costs $ci^{RO} + (1-c)\chi\phi$ changed, as (34) reflects.

A.3 Proof of Proposition 2

Following Proposition 1, we distinguish between an active and an inactive interbank market to determine the interbank market rate in equilibrium and banks' optimal borrowing and lending decision on aggregate.

Active Interbank Market

It is useful to distinguish between the three cases described in Proposition 1:

1. Suppose that an equilibrium exists with $\gamma \leq \bar{\bar{\gamma}}$ and $RO^* < cL^*$. Then, (13) implies $i^{IBM^*} = i^{LF} - \gamma$ while according to (15) $RO^* = \bar{t}^* (1-c)\chi L^* + cL^* \geq 0$ implies $\bar{t} < 0$ and thus

$$G\left(\bar{t}\right) < G\left(0\right).$$

   Insertion of i^{IBM^*} in (16) yields

$$G\left(\bar{t}\right) = \tfrac{i^{LF} - i^{RO}}{2\gamma} < G\left(0\right).$$

   However, for all $\gamma \in [0, \bar{\bar{\gamma}}]$ it follows due to $i^{LF} - i^{RO} \geq i^{RO} - i^{DF}$ that $\frac{i^{LF} - i^{RO}}{2\gamma} > 0.5$ while we assume that $G(0) < 0.5$. Accordingly, $RO^* < cL^*$ does not constitute an equilibrium.

2. Suppose that an equilibrium exists with $\gamma \leq \bar{\bar{\gamma}}$ and $RO^* = cL^*$. Then, (13) implies

$$i^{IBM^*} \in \left[i^{DF} + \gamma, i^{LF} - \gamma\right]$$

while according to (15) $RO^* = \bar{t}^* (1-c) \chi L^* + cL^* > 0$ implies $\bar{t} = 0$ and thus $G(\bar{t}) = G(0)$. Insertion of $G(\bar{t})$ in (16) yields

$$i^{IBM} = i^{RO} - \gamma + 2\gamma G(0).$$

and thus $G(0) \in \left[\frac{i^{DF}+2\gamma-i^{RO}}{2\gamma}, \frac{i^{LF}-i^{RO}}{2\gamma}\right]$. As $RO^* = cL^*$, there is no aggregate liquidity deficit at the second stage so that neither the lending nor the deposit facility is used.

3. Suppose that an equilibrium exists with $\gamma \leq \bar{\bar{\gamma}}$ and $RO^* > cL^*$. Then, (13) implies $i^{IBM^*} = i^{DF} + \gamma$ while $RO^* = \bar{t}^* (1-c) \chi L^* + cL^* > 0$ implies $\bar{t} > 0$ and thus

$$G(\bar{t}) > G(0).$$

Insertion of i^{IBM^*} in (16) yields

$$G(\bar{t}) = \frac{i^{DF}+2\gamma-i^{RO}}{2\gamma} > G(0).$$

As $RO^* > cL^*$, banks have to place the aggregate liquidity surplus of the second stage in the deposit facility so that $DF^* > 0$.

Inactive Interbank Market

It is useful to distinguish between the same three cases as for an active interbank market:

1. Suppose that an equilibrium exists with $\gamma > \bar{\bar{\gamma}}$ and $RO^* < cL^*$. Then, we have $i^{IBM^*} \in \left[i^{LF} - \gamma, i^{DF} + \gamma\right]$ while $RO^* = \bar{t}^* (1-c) \chi L^* + cL^* > 0$ implies $\bar{t} < 0$ and thus

$$G(\bar{t}) < G(0).$$

Insertion of i^{IBM^*} in (16) yields

$$G(\bar{t}) = \frac{i^{LF}-i^{RO}}{i^{LF}-i^{DF}} < G(0).$$

However, it follows due to $i^{LF} - i^{RO} \geq i^{RO} - i^{DF}$ that $\frac{i^{LF}-i^{RO}}{i^{LF}-i^{DF}} > 0.5$ while we assume that $G(0) < 0.5$. Accordingly, $RO^* < cL^*$ does not constitute an equilibrium.

2. Suppose that an equilibrium exists with $\gamma > \bar{\bar{\gamma}}$ and $RO^* = cL^*$. Then, we have $i^{IBM^*} \in \left[i^{LF} - \gamma, i^{DF} + \gamma\right]$ while $RO^* = \bar{t}^* \left(1 - c\right) \chi L^* + cL^* > 0$ implies $\bar{t} = 0$ and thus

$$G\left(\bar{t}\right) = G\left(0\right).$$

Insertion of i^{IBM^*} in (16) yields

$$G\left(\bar{t}\right) = \tfrac{i^{LF} - i^{RO}}{i^{LF} - i^{DF}} = G\left(0\right).$$

Due to $G(0) < 0.5$, $RO^* = cL^*$ does not constitute an equilibrium either.

3. Suppose that an equilibrium exists with $\gamma > \bar{\bar{\gamma}}$ and $RO^* > cL^*$. Then, we have $i^{IBM^*} \in \left[i^{LF} - \gamma, i^{DF} + \gamma\right]$ while $RO^* = \bar{t}^* \left(1 - c\right) \chi L^* + cL^* > 0$ implies $\bar{t} > 0$ and thus

$$G\left(\bar{t}\right) > G\left(0\right).$$

Insertion of i^{IBM^*} in (16) yields

$$G\left(\bar{t}\right) = \tfrac{i^{LF} - i^{RO}}{i^{LF} - i^{DF}} > G\left(0\right).$$

As $RO^* > cL^*$, banks have to place the aggregate liquidity surplus of the second stage in the deposit facility so that $DF^* > 0$.

A.4 Impact of Uncertainty and Transaction Costs on Bank Lending

In this subsection, we present the derivation of the argument presented in Section 7 that an increase in both uncertainty and frictions in the interbank market have a negative effect on bank lending.

It follows from (17) and Proposition 2 that

$$L^{j*} = \frac{1}{\lambda}\left[i^L - ci^{RO} - \left[(1-c)\chi \int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i\right] \xi\right] \tag{35}$$

with

$$\xi = \begin{cases} 2\gamma & \text{if} \quad \gamma \leq \bar{\bar{\gamma}}, \\ i^{LF} - i^{DF} & \text{if} \quad \gamma > \bar{\bar{\gamma}}. \end{cases} \tag{36}$$

Uncertainty

Applying the Leibniz rule on (35), the first derivative w.r.t. χ thus reads

$$\frac{\partial L^{j*}}{\partial \chi} = -\frac{(1-c)\xi}{\lambda}\left[\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i - \chi \frac{\partial \bar{t}^*}{\partial \chi}\bar{t}^* g(\bar{t}^*)\right]. \tag{37}$$

We derive from (16) the function

$$F := \max\left\{i^{IBM} - \gamma, i^{DF}\right\} G\left(\bar{t}^*\right) + \min\left\{i^{IBM} + \gamma, i^{LF}\right\}\left[1 - G\left(\bar{t}^*\right)\right] - i^{RO} = 0. \tag{38}$$

Applying the implicit function theorem on (38) thus yields

$$\frac{\partial \bar{t}^*}{\partial \chi} = -\frac{\frac{\partial F}{\partial \chi}}{\frac{\partial F}{\partial \bar{t}^*}} = 0 \;\; \forall \;\; \bar{t}^* \tag{39}$$

so that

$$\frac{\partial L^{j*}}{\partial \chi} = -\frac{(1-c)\xi}{\lambda}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i < 0 \;\; \forall \;\; j. \tag{40}$$

Transaction Costs

If $\gamma \leq \bar{\bar{\gamma}}$, it follows from (36) that $\xi = 2\gamma$. Applying the Leibniz rule on (35), the first derivative w.r.t. γ thus reads

$$\frac{\partial L^{j*}}{\partial \gamma} = -\frac{(1-c)2\chi}{\lambda}\left[\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i - \gamma \frac{\partial \bar{t}^*}{\partial \gamma}\bar{t}^* g(\bar{t}^*)\right]. \tag{41}$$

Applying the implicit function theorem on (38) yields

$$\frac{\partial \bar{t}^*}{\partial \gamma} = -\frac{\frac{\partial F}{\partial \gamma}}{\frac{\partial F}{\partial \bar{t}^*}} = -\frac{G(\bar{t}^*)}{\gamma g(\bar{t}^*)} \qquad \text{if} \;\; j = \text{I}, \tag{42}$$

$$\frac{\partial \bar{t}^*}{\partial \gamma} = -\frac{\frac{\partial F}{\partial \gamma}}{\frac{\partial F}{\partial \bar{t}^*}} = \frac{1 - G(\bar{t}^*)}{\gamma g(\bar{t}^*)} \qquad \text{if} \;\; j = \text{II}. \tag{43}$$

so that

$$\frac{\partial L^{\text{I}*}}{\partial \gamma} = \frac{2(1-c)\chi}{\lambda} G\left(\bar{t}^*\right)\left[E\left[t_i | t_i < \bar{t}^*\right] - \bar{t}^*\right] < 0, \tag{44}$$

$$\frac{\partial L^{\text{II}*}}{\partial \gamma} = -\frac{2(1-c)\chi}{\lambda}\left[1 - G(\bar{t}^*)\right]\left[E\left[t_i | t_i \geq \bar{t}^*\right] - \bar{t}^*\right] < 0. \tag{45}$$

If $\gamma > \bar{\bar{\gamma}}$, it follows from (36) that $\xi = i^{LF} - i^{DF}$. Applying the implicit function theorem on (38) yields

$$\frac{\partial \bar{t}^*}{\partial \gamma} = -\frac{\frac{\partial F}{\partial \gamma}}{\frac{\partial F}{\partial \bar{t}^*}} = 0 \tag{46}$$

so that $\frac{\partial L^{\mathrm{III}*}}{\partial \gamma} = 0$.

Moreover, it follows from (39) that the mixed partial derivative with respect to χ reads

$$\frac{\partial^2 L^{\mathrm{I}*}}{\partial \gamma \partial \chi} = \frac{2(1-c)}{\lambda} G\left(\bar{t}^*\right)\left[E\left[t_i | t_i < \bar{t}^*\right] - \bar{t}^*\right] < 0, \tag{47}$$

$$\frac{\partial^2 L^{\mathrm{II}*}}{\partial \gamma \partial \chi} = -\frac{2(1-c)}{\lambda}\left[1 - G(\bar{t}^*)\right]\left[E\left[t_i | t_i \geq \bar{t}^*\right] - \bar{t}^*\right] < 0. \tag{48}$$

A.5 Proof of Proposition 3

We proof this proposition in two steps. First, we determine the derivative with respect to i^{RO} for each feasible equilibrium. Afterwards, we derive the respective mixed partial derivative with respect to χ and γ.

1. Applying the Leibniz rule on (35), the first derivative w.r.t. i^{RO} reads

$$\frac{\partial L^{j*}}{\partial i^{RO}} = -\frac{1}{\lambda}\left[c - (1-c)\chi \frac{\partial \bar{t}^*}{\partial i^{RO}} \bar{t}^* g(\bar{t}^*)\xi\right] \quad \forall \;\; j. \tag{49}$$

   Applying the implicit function theorem on (38) yields

$$\begin{aligned} \frac{\partial \bar{t}^*}{\partial i^{RO}} &= -\frac{\frac{\partial F}{\partial i^{RO}}}{\frac{\partial F}{\partial \bar{t}^*}} = 0 && \text{if } \; j = \mathrm{I}, \\ \frac{\partial \bar{t}^*}{\partial i^{RO}} &= -\frac{\frac{\partial F}{\partial i^{RO}}}{\frac{\partial F}{\partial \bar{t}^*}} = -\frac{1}{\xi g(\bar{t}^*)} && \text{if } \; j = \{\mathrm{II}, \mathrm{III}\}. \end{aligned}$$

   As $\bar{t}^* = 0$ for $j = \mathrm{I}$, it follows for all j

$$\frac{\partial L^{j*}}{\partial i^{RO}} = -\frac{1}{\lambda}\left[c + (1-c)\chi \bar{t}^*\right].$$

   If $\gamma \leq \bar{\bar{\gamma}}$, it follows that $2\gamma < i^{LF} - i^{DF}$. In Equilibrium II expected marginal revenues of borrowing from the refinancing operations are given by

$$i^{DF} + 2\gamma\left[1 - G\left(\bar{t}_i^{opt}\right)\right] \tag{50}$$

while in Equilibrium III they read

$$i^{DF}G\left(\bar{t}_i^{opt}\right)+i^{LF}\left[1-G\left(\bar{t}_i^{opt}\right)\right] \tag{51}$$

Comparing (50) and (51) shows that $G(\bar{t}_i^{opt})^{\mathrm{II}} < G(\bar{t}_i^{opt})^{\mathrm{III}}$ so that $\bar{t}_i^{opt\mathrm{II}} < \bar{t}_i^{opt\mathrm{III}}$. Due to $L_i^{opt} = L^*$ and $RO_i^{opt} = RO^*$, it follows that $\bar{t}^{*\mathrm{II}} < \bar{t}^{*\mathrm{III}}$ and thus $\frac{\partial L^{\mathrm{III}*}}{\partial i^{RO}} \leq \frac{\partial L^{\mathrm{II}*}}{\partial i^{RO}} < \frac{\partial L^{\mathrm{I}*}}{\partial i^{RO}} < 0$.

2. (a) In order to determine the mixed partial derivative with respect to χ, we make use of the result obtained in (39). It thus follows that

$$\frac{\partial^2 L^{j*}}{\partial i^{RO}\partial\chi} = -\frac{1-c}{\lambda}\bar{t}^* \tag{52}$$

so that $\frac{\partial^2 L^{\mathrm{III}*}}{\partial i^{RO}\partial\chi} < \frac{\partial^2 L^{\mathrm{II}*}}{\partial i^{RO}\partial\chi} < 0$ and $\frac{\partial^2 L^{\mathrm{I}*}}{\partial i^{RO}\partial\chi} = 0$.

(b) In order to determine the mixed partial derivative with respect to γ, we make use of the results obtained in (42), (43) and (46). It thus follows that

$$\frac{\partial^2 L^{\mathrm{I}*}}{\partial i^{RO}\partial\gamma} = 0, \tag{53}$$

$$\frac{\partial^2 L^{\mathrm{II}*}}{\partial i^{RO}\partial\gamma} = -\frac{(1-c)\,\chi}{\lambda}\frac{\partial\bar{t}^*}{\partial\gamma} = -\frac{(1-c)\,\chi\left[1-G(\bar{t}^*)\right]}{\lambda\gamma g(\bar{t}^*)} < 0, \tag{54}$$

$$\frac{\partial^2 L^{\mathrm{III}*}}{\partial i^{RO}\partial\gamma} = 0. \tag{55}$$

A.6 Proof of Proposition 4

We proof this proposition in two steps. First, we apply the total derivative to determine the impact of a change in the overall interest rate level. Afterwards, we derive the respective mixed partial derivative with respect to χ and γ.

1. Given $di^{LF} = di^{RO} = di^{DF}$, applying the total derivative on (35) yields

$$dL^{j*} = \frac{1}{\lambda}\left[-cdi^{RO} - \left[(1-c)\chi d\bar{t}^*\frac{\partial}{\partial\bar{t}^*}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i)dt_i\right]\xi\right]. \tag{56}$$

Moreover, applying the total derivative on (38) yields

$$\begin{aligned}\frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*}d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{I},\\ di^{DF} - 2\gamma \frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*}d\bar{t}^* - di^{RO} &= 0 \quad \text{if} \quad j = \text{II},\\ di^{LF} - \left(i^{DF} - i^{LF}\right)\frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*}d\bar{t}^* + (di^{DF} - di^{LF})G\left(\bar{t}^*\right) - di^{RO} &= 0 \quad \text{if} \quad j = \text{III}.\end{aligned}$$

Due to $di^{RO} = di^{DF} = di^{LF}$ it follows for all j that $d\bar{t}^* = 0$ so that

$$\frac{dL^{j*}}{di^{RO}} = -\frac{c}{\lambda}. \tag{57}$$

2. It follows directly from (57) that $\frac{\partial^2 L^{j*}}{\partial i^{RO}\partial\chi} = \frac{\partial^2 L^{j*}}{\partial i^{RO}\partial\gamma} = 0$ for all j.

A.7 Proof of Proposition 5

We proof this proposition analogously to the proof of Proposition 4 in two steps. First, we apply the total derivative to determine the impact of a change in the rates of the facilities. Afterwards, we derive the respective mixed partial derivative with respect to χ and γ.

1. Given $di^{LF} = di^{DF}$ and $di^{RO} = 0$, applying the total derivative on (35) yields

$$\begin{aligned}dL^{j*} &= -\frac{2\gamma(1-c)}{\lambda}\chi d\bar{t}^* \frac{\partial}{\partial \bar{t}^*}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i & \text{if} \quad j = \{\text{I}, \text{II}\},\\ dL^{j*} &= -\frac{1-c}{\lambda}\chi\left[(i^{LF} - i^{DF})d\bar{t}^* + 2di^{LF}\right]\frac{\partial}{\partial \bar{t}^*}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i) dt_i & \text{if} \quad j = \text{III}.\end{aligned}$$

Moreover, applying the total derivative on (38) yields

$$\begin{aligned}\frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*}d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{I},\\ di^{DF} - 2\gamma\frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*}d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{II}.\end{aligned}$$

As long as the interest rate corridor is symmetric, it follows for $\gamma > \bar{\gamma}$ that $G\left(\bar{t}^*\right) = 0.5$ so that

$$d\bar{t}^* = 0 \quad \text{if} \quad j = \text{III}.$$

Considering $\frac{\partial i^{LF}}{\partial(i^{LF}-i^{DF})} = 0.5$ and $\frac{\partial i^{DF}}{\partial(i^{LF}-i^{DF})} = -0.5$ it follows

$$\frac{\partial L^{\mathrm{I}*}}{\partial(i^{LF}-i^{DF})} = \frac{dL^{\mathrm{I}*}}{di^{LF}} \frac{\partial i^{LF}}{\partial(i^{LF}-i^{DF})} = 0, \tag{58}$$

$$\frac{\partial L^{\mathrm{II}*}}{\partial(i^{LF}-i^{DF})} = \frac{dL^{\mathrm{II}*}}{di^{DF}} \frac{\partial i^{DF}}{\partial(i^{LF}-i^{DF})} = -\frac{(1-c)\chi}{\lambda}\bar{t}^* < 0, \tag{59}$$

$$\frac{\partial L^{\mathrm{III}*}}{\partial(i^{LF}-i^{DF})} = \frac{dL^{\mathrm{III}*}}{di^{LF}} \frac{\partial i^{LF}}{\partial(i^{LF}-i^{DF})} = -\frac{(1-c)\chi}{\lambda}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i)dt_i < 0. \tag{60}$$

2. Making use of the result obtained in (39), it follows directly from (58) to (60) that

$$\frac{\partial^2 L^{\mathrm{I}*}}{\partial(i^{LF}-i^{DF})\partial\chi} = 0, \tag{61}$$

$$\frac{\partial^2 L^{\mathrm{II}*}}{\partial(i^{LF}-i^{DF})\partial\chi} = -\frac{(1-c)}{\lambda}\bar{t}^* < 0, \tag{62}$$

$$\frac{\partial^2 L^{\mathrm{III}*}}{\partial(i^{LF}-i^{DF})\partial\chi} = -\frac{(1-c)}{\lambda}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i)dt_i < 0. \tag{63}$$

Making use of the result obtained in (43) and (46), it follows that

$$\frac{\partial^2 L^{\mathrm{j}*}}{\partial(i^{LF}-i^{DF})\partial\gamma} = 0 \quad \text{for} \quad j = \mathrm{II},\, \mathrm{III}, \tag{64}$$

$$\frac{\partial^2 L^{\mathrm{II}*}}{\partial(i^{LF}-i^{DF})\partial\gamma} = -\frac{(1-c)}{\lambda}\frac{1-G(\bar{t}^*)}{\gamma g(\bar{t}^*)} < 0. \tag{65}$$

A.8 Proof of Proposition 6

Again, we proof this proposition in two steps. First, we apply the total derivative to determine the impact of a change in the rates of the facilities. Afterwards, we derive the respective mixed partial derivative with respect to χ and γ.

1. Given $di^{LF} = -di^{DF}$ and $di^{RO} = 0$, applying the total derivative on (35) yields

$$dL^{j*} = -\frac{2\gamma(1-c)}{\lambda}\chi d\bar{t}^* \frac{\partial}{\partial\bar{t}^*}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i)dt_i \qquad \text{if} \quad j = \{\mathrm{I},\mathrm{II}\},$$

$$dL^{j*} = -\frac{1-c}{\lambda}\chi(i^{LF}-i^{DF})d\bar{t}^* \frac{\partial}{\partial\bar{t}^*}\int_{\bar{t}^*}^{t^{max}} t_i g(t_i)dt_i \qquad \text{if} \quad j = \mathrm{III}.$$

Moreover, applying the total derivative on (38) yields

$$\begin{aligned}
\frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*} d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{I}, \\
di^{DF} - 2\gamma \frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*} d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{II}, \\
di^{LF} - (i^{LF} - i^{DF}) \frac{\partial G\left(\bar{t}^*\right)}{\partial \bar{t}^*} d\bar{t}^* &= 0 \quad \text{if} \quad j = \text{III}.
\end{aligned}$$

so that

$$\frac{\partial L^{\text{I}*}}{\partial i^{DF}} = 0, \tag{66}$$

$$\frac{\partial L^{\text{j}*}}{\partial i^{DF}} = \frac{(1-c)\chi}{\lambda} \bar{t}^* > 0 \quad \text{for} \quad j = \text{II, III}. \tag{67}$$

2. Making use of the result obtained in (39), it follows directly from (66) to (67) that

$$\frac{\partial^2 L^{\text{I}*}}{\partial i^{DF} \partial \chi} = 0, \tag{68}$$

$$\frac{\partial^2 L^{\text{j}*}}{\partial i^{DF} \partial \chi} = \frac{(1-c)}{\lambda} \bar{t}^* > 0 \quad \text{for} \quad j = \text{II, III}. \tag{69}$$

Making use of the result obtained in (43) and (46), it follows that

$$\frac{\partial^2 L^{\text{j}*}}{\partial i^{DF} \partial \gamma} = 0 \quad \text{for} \quad j = \text{I, III}, \tag{70}$$

$$\frac{\partial^2 L^{\text{II}*}}{\partial i^{DF} \partial \gamma} = \frac{(1-c)}{\lambda} \frac{1 - G(\bar{t}^*)}{\gamma g(\bar{t}^*)} > 0. \tag{71}$$

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ISSN 2190-9938 (online)
ISBN 978-3-86304-133-5