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Long-Term Implications of a Digital Euro on Liquidity and Funding Costs in the German Banking System

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Abstract

The introduction of a digital euro (D€) would allow euro area residents to exchange bank deposits for digital currency, thus offering an efficient addition to the European payment sector. It is currently being discussed how the D€ impacts liquidity outflows from banks and financial stability. To mitigate these risks, the European Commission's legislative proposal permits the ECB to impose limits on the use of the D€ as a store of value. This study contributes to the calibration of appropriate holding limits for a D€. We examine how banks adjust their liquidity buffers and funding structures in response to the D€. We explore banks' potential strategies to minimise funding costs, including raising deposit rates and expanding wholesale funding, and approximate a market equilibrium. Applying our model to the German banking system, we find that imposing a holding limit of €3,000 would reduce the return on equity by approximately 0.2 percentage points and the Liquidity Coverage Ratio by about 7 percentage points in the most adverse scenario. These findings suggest that the long-term impact remains relatively contained.

Keywords: Central Bank Digital Currency, Digital Euro, Holding Limit, Liquidity, Funding Costs, Financial Stability.

JEL codes: G21, G32, G38

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1 Introduction

After a two-year investigation phase, the Governing Council of the ECB started the first part of the preparation phase of the introduction of a digital euro (D€) on October 18, 2023. The ECB's plans for a D€ reflect the growing trend of the economy going digital. As an additional retail payment method based on central bank money, a D€ would be available to all citizens in the euro area alongside cash. It will complement cash with digital functions. During this preparation phase, the potential technical configuration of a D€ will be further specified, with the decision on its introduction to be made only after the establishment of a legal framework within the EU.

If a D€ is introduced, residents in the euro area will be able to exchange cash or bank deposits for D€. By its design the D€ would establish an efficient addition to the European payment landscape boosting autonomy, resilience and inclusion of the European payment sector. It is currently being discussed to what extent the exchange of bank deposits would lead to an outflow of liquidity from banks. In order to rule out possible negative effects on liquidity in the banking system, the European Commission's current legislative proposal on a D€ stipulates that the ECB may place limits on the use of the digital euro as a store of value.[1] At the current stage of development, the Eurosystem is focusing on impact analyses concerning holding limits for a D€. To this end, a €3,000 holding limit per person has been publicly discussed among bank regulators.[2]

The analysis presented here aims to contribute to the calibration of appropriate holding limits for a D€. Our study focuses on the long-term effects of the introduction of a D€ on banks' liquidity and funding costs. To address this research question, we simulate a new equilibrium (steady state), focussing on how banks adjust their liquidity buffers and funding structures in response to the introduction of a D€. The presence of a D€ forces banks to offer more competitive deposit rates. Although the D€ is designed to be non-interest-bearing, its impact on deposit rates is likely to be pronounced in a moderate or low interest rate environment. Under such conditions, the D€ would effectively increase the competitive pressure on banks, as depositors would have a viable outside option to traditional bank deposits given the small interest rate differential, potentially leading to an upward adjustment in offered rates to retain depositor funds. In our analysis, we do not explicitly model the role of the central bank, such as banks' access to additional liquidity through central bank funding operations to compensate for liquidity outflows into a D€. Instead, our focus is on the structural adaptability and resilience of the banking system to the introduction of a D€ through adjustments in private funding. Against this backdrop, our analysis adopts a prudential perspective.

Our analysis is deliberately partial in scope and focuses on the funding side of banks' balance sheets. We abstract from positive effects on bank profitability, such as gains through new business opportunities

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[1] Notably, the implementation of a holding limit for a D€ does not restrict its use as a means of payment. Balances of the D€ in one's e-wallet that exceed the holding limit through incoming payments will be automatically transferred to a corresponding deposit account ("waterfall approach"). Conversely, if outgoing payments exceeds the D€ balance, the remaining amount will be automatically replenished from the deposit account ("reverse waterfall approach"), see Ausschuss für Finanzstabilität (2024).

[2] See ECB (2023), Bindseil (2020), Bindseil and Panetta (2020).

associated with a D€ as discussed in Cipollone (2025). Accordingly, the estimated impact on profitability should be interpreted as conservative, as it captures the cost side of the adjustment but not offsetting benefits.

We investigate how banks navigate the nonlinear trade-off between higher funding costs for retail deposits versus alternative funding strategies to achieve cost minimisation in different interest rate environments with an unremunerated D€. On the one hand, banks could simply leave their deposit rates unchanged and compensate for the resulting deposit outflows by reducing their liquidity buffers. By avoiding higher deposit (interest) rates or alternative (costly) funding, they reduce their overall funding costs. On the other hand, a lower buffer increases the risk of becoming illiquid, which would raise credit risk costs for wholesale funding, such as bond financing, and thus increase the banks' overall funding costs. To prevent a permanent reduction to an unsustainable low buffer level, we assume a bank can employ two funding strategies. Firstly, they could reduce deposit outflows by raising deposit rates. Secondly, they could expand their wholesale funding by issuing additional bank bonds to offset deposit outflows.[3]

Our model reflects diverse market dynamics, considering the deposit market's relative risk insensitivity, due to deposit insurance schemes, in contrast to the bond market's responsiveness to risk. Furthermore, it captures the bond market's limited capacity to absorb new issuances. As the collective new issuance of bank bonds potentially leads to an increase in costs for market liquidity risk of bond financing, banks' strategic decision-making is shaped within a game-theoretic context.

We apply the theoretical model to quantify the effects on liquidity and funding costs for the German banking system in different scenarios, including alternative interest rate environments. In simulation runs with varying holding limits up to €10,000 per person and considerably adverse parameter values to model the demand for a D€, we estimate the long-term effects. Specifically, the return on equity (ROE) across banks is projected to decrease by up to 0.2 percentage points for a holding limit of €3,000, while the aggregate Liquidity Coverage Ratio (LCR) is expected to decline by up to 7 percentage points. The introduction of a D€ has heterogeneous effects across different banking groups. Commercial banks, which tend to rely only to a relatively small degree on retail deposits, experience limited impact. In contrast, savings banks and cooperative banks face significant potential deposit outflows, but possess considerable flexibility to adapt. Unlike commercial banks, which depend on unrestricted market access and are therefore constrained in reducing their liquidity buffers, savings banks and cooperatives can more extensively reduce their liquidity buffers to support profitability. They are also better positioned than other small private banks to expand market funding through their central institutions. Finally, the simulations indicate that increases in deposit rates play a relatively minor role compared to the expansion of market funding in adapting to a D€.

Related literature. In recent years, the body of literature on the impact of central bank digital currencies (CBDCs) in general and a D€ in particular has expanded significantly. One strand of literature applies macroeconomic models to analyse long-term effects. The study by Bidder, Jackson und Rottner (2024)

[3] In practice, banks have additional avenues to secure liquidity, such as the interbank market. However, the interbank market primarily facilitates short-term liquidity provision. Consistent with the assumptions made by BIS (2021), we posit that banks will (partially) offset the loss of stable deposits by issuing long-term bonds to secure alternative stable, albeit costlier, funding sources.

reveals opposing effects on financial stability and welfare. During normal times, the D€ competes with deposits, leading to 'slow' disintermediation, which reduces bank leverage and the risk of bank runs. However, without holding limits, the D€ can be held in large amounts more easily than cash, increasing the risk of bank runs and resulting in 'fast' disintermediation. The model suggests that the optimal holding limit for the D€ lies between €1,500 and €2,500, where the positive effects on financial stability and welfare outweigh the negative ones. Burlon, Montes-Galdón, Muñoz, and Smets (2022) also employ a macroeconomic model in which CBDC, cash, and deposits are imperfect substitutes for the representative household. They find that CBDC has a stabilising effect on lending and real GDP by smoothing deposit holdings in response to shocks to liquidity services. Chiu, Davoodalhosseini, Jiang, and Zhu (2023) examine the impact of CBDC issuances on bank profitability when several commercial banks compete. Their findings suggest that the introduction of a CBDC facilitates banks' competitiveness, raises deposit rates, and expands commercial banks' financial brokerage activities. Although these macroeconomic models provide valuable insight into the effects on various sectors of the economy, they exhibit certain shortcomings. Firstly, they often model banks as homogeneous entities, using a single representative bank. This approach fails to capture the heterogeneous characteristics of the German banking system, where banks vary significantly across their business models. Secondly, these type of models frequently do not take into account the important aspect of bank liquidity and the various funding options available to banks for adapting to a new environment with a D€.

Another strand of literature uses partial equilibrium models or banking models to provide a more detailed representation of the banking sector. Our research complements these studies. Meller and Soons (2023) introduce a balance sheet optimisation model to simulate the short-term response of individual institutions in the euro area banking system to an exogenous outflow of deposits following the introduction of a D€. Banks aim to maximise profitability while meeting regulatory liquidity and collateral constraints. They cover deposit outflows using excess reserves, interbank funding, and central bank funding, each affecting liquidity ratios differently. The model assumes constant lending to the real economy and keeps (interbank) funding rates unchanged. Simulations by Auer, Branzoli, Ferrero, Ilari, Palazzo and Rainone (2024) based on data from Italian banks indicate that the overall impact on bank funding could be manageable with individual holding limits and ample liquidity. However, banks with low excess reserves or those needing to issue long-term liabilities may face higher costs to maintain stable funding. Gruber, M., Siebenbrunner, C., Trachta, A. and Wipf, C. (2024) analyse long-run profitability on banks' net interest income. The authors calibrate the potential demand for a D€ based on Bidder et al. (2024). They specifically calibrate the funding cost advantage that banks lose due to deposit outflows and the subsequent need to replace these deposits with more expensive wholesale funding. This calibration is based on the period preceding the era of very low or negative interest rates. Their findings indicate a decrease in the ROE by 5 basis points (bps) in the baseline scenario and by 51 bps in the adverse scenario, both scenarios assuming a holding limit of €3,000. A report by the BIS (2021) develops a stylised model of an aggregate banking system, which explores the potential challenges posed by various CBDC adoption scenarios in a positive interest rate environment. By examining the impact of customer deposit outflows and the substitution with long-term wholesale funding (i.e. issuing bank bonds), the model estimates the effects on funding costs, effective lending rates, and bank profitability. The analysis shows that replacing deposits with more expensive long-term wholesale funding increases banks' weighted average funding costs, reduces net interest margins (NIMs) and ROE. To maintain profitability, banks may need to raise lending rates without reducing lending volumes.

Our model is inspired by the work of Meller and Soons (2023) as well as the BIS (2021). It builds on the framework proposed by Meller and Soons (2023), which employs an optimisation approach to maximise profitability subject to regulatory and financial constraints. However, our model differs in that it treats the target level of banks' liquidity buffer as an endogenous variable, determined as the outcome of banks' decision-making processes, rather than a fixed target. Additionally, instead of assuming constant interest rates for retail deposit funding and wholesale funding, our model endogenously determines these rates within the optimisation process. Whereas Meller and Soons (2023) emphasize the role of the interbank market as a mechanism for banks to secure liquidity in response to a decline in retail deposits, we argue that banks are likely to (partially) offset the reduction in stable deposits by issuing long-term bonds. This strategy, while entailing higher costs than short-term funding, provides an alternative source of stable funding and aligns with the model assumptions outlined by the BIS (2021). In contrast to the analysis presented by the BIS (2021), our model employs an optimisation model to endogenously determine banks' funding interest rates, the funding structure, and the level of banks' liquidity buffer, while focussing on the funding side and keeping lending constant.

The plan of the paper is as follows. Section 2 introduces the concept of the model and bank's optimisation problem. Section 3 provides theoretical analyses, by conducting an equilibrium analysis and examining the marginal effects of the transmission channels. Section 4 describes the data and explains how we calibrate key parameters of the model. Section 5 discusses the results, and Section 6 concludes.

2 Model

We simulate the strategic liquidity management of individual banks, which aim to adjust their funding structure. The introduction of the D€ induces pressure on banks' retail deposit funding. Offering more competitive retail deposit rates is a possible way to counteract large-scale withdrawals of deposits into a D€.[4] Alternatively, bank can increase market funding to compensate deposit outflows.

2.1 Concept

The bank's objective is to minimise its funding costs, thereby considering two primary channels: the market discipline channel and the remuneration channel. On the one hand, a decline in the liquidity buffer bolsters profitability. If retail deposit outflows are simply compensated by a reduction in the liquidity buffer, the bank can refrain from obtaining additional liquidity through alternative funding options, each of which comes with additional costs. On the other hand, drawing down the liquidity buffer to low levels (yet still above the regulatory minimum requirements) to compensate retail deposit outflows, would increase the bank's risk of becoming illiquid. This risk will, in turn, be priced in the bank's costs of wholesale funding by the bank's creditors and investors and thus have a negative impact on its profitability.[5] In this respect, wholesale funding – comprising corporate deposits and bank bonds –

[4] We posit that the limit for corporates to hold a D€ is set to zero, thereby confining the direct impact on deposit rates from the introduction of a D€ to banks' retail business, see Bindseil, Cipollone and Schaaf (2024).

[5] As part of this model, we assume that risks are adequately priced on wholesale funding markets.

strengthens market discipline through the liquidity buffer, as suggested by Hanson and Shleifer (2015).[6] Creditors and investors closely monitor the bank's liquidity position and adjust their funding terms accordingly.[7] Additionally, the remuneration for banks' liquidity, specifically the central bank's deposit facility rate, plays a crucial role. The higher the interest paid on liquidity (i.e. central bank reserves), the greater the incentive for banks to prevent or compensate deposit outflows and avoid reducing their liquidity buffer. Consequently, there is a trade-off between a low and a high liquidity buffer, and the bank aims to choose its optimal liquidity level along with the optimal composition of funding to minimise its funding costs.

The bank has two options to adjust its funding structure: (1) It can raise retail deposit rates in order to reduce the deposit outflows. (2) It can issue bank bonds on the international capital market (to primarily institutional investors) to obtain long-term funding.[8] These two options are non-exclusive and can be applied simultaneously. They improve the borrowing bank's liquidity situation. By choosing these two options the bank implicitly decides to what extent the liquidity buffer will be used to compensate for retail deposit outflows. Option 1 reduces liquidity outflows from the German banking system, whereas option 2 creates liquidity inflows to the German banking system. More specifically, option 2 most likely refers to a situation that liquidity is tapped from international institutional investors, who are not primarily domiciled in Germany. Based on this assumption, option 2 results in liquidity inflows to the German banking system from other banking systems abroad.[9]

In our model, we take into account the varying market structures. Specifically, we consider that the retail deposit market is backed by a deposit insurance scheme, which ensures that retail deposits are perceived as safe by depositors. In contrast, wholesale funding, such as corporate deposit funding and bond funding, are perceived as risky by depositors and investors. Consequently, when accepting deposits from (non-financial) corporates or issuing bonds to investors, banks must compensate for costs associated with credit risk. We also account for the bond market's constrained absorption capacity for new issuances, acknowledging the impact of market liquidity risk on bond yields as a function of the aggregate issuance volume by banks. This liquidity risk, predicated on the banks' collective issuance activity, casts their decision-making within a game-theoretic framework characterised by strategic interdependencies.

For the model we present here, it is crucial that both, wholesale funding or retail deposits, may be advantageous in terms of minimising funding costs. Increasing interest rates for retails deposits does not only apply to newly (or re-) attracted deposits, but to the entire amount of retail deposits. Whether this form of funding is cheaper than additional wholesale funding depends on the relative share of these two different forms of funding.

[6] For the market-disciplining effect of corporate deposits on risky banks see Imbierowicz, Saunders and Steffen (2024).

[7] The leverage channel plays a role, counteracting the previously mentioned channel (see Bidder, Jackson, and Rottner (2024)). A withdrawal of deposits leads to a reduction in leverage and lowers the probability of default. Our analysis assumes that in the event of a withdrawal of retail deposits and corresponding reduction in central bank reserves, the liquidity buffer channel dominates the leverage channel. Therefore, our approach reflects a prudent perspective.

[8] Therefore, we assume that corporate deposits will remain unchanged. As the holding limit for corporate deposits is expected to be set at 0, the direct impact of a D€ on corporate deposit funding is likely to be minimal.

[9] The larger the banking system under consideration, say the banking system of the euro area, the more likely the issuance of bank bonds will not result in an liquidity inflow to the banking system, but a redistribution of liquidity within the banking system, as investors are more likely to be domiciled within the member states of the euro area.

Finally, we assume banks' lending remains constant and is separable from banks' funding decisions as posited by Arping (2017); see also Klein (1971), Chiaporri et al. (1995), and Freixas and Rochet (2008, Chapter 3.

Table 1 summarises the principal characteristics of the model, while Figure 1 illustrates the decision-making processes of banks.

<table>
<tr><td>Initial shock</td><td colspan="3">Banks must either increase retail deposit rates or forgo a portion of retail deposits (D€ enhances the 'outside option' for retail depositors)</td></tr>
<tr><td>Objective of banks</td><td colspan="3">Minimisation of funding costs through optimisation of the liquidity buffer and funding structure while adhering to regulatory minimum requirements</td></tr>
<tr><td rowspan="2">Relevant funding markets</td><td colspan="2">Deposit markets</td><td rowspan="2">Bond market</td></tr>
<tr><td>Retail</td><td>(Non-financial) Corporates</td></tr>
<tr><td>Risk Sensitivity
(in normal times)</td><td>Not sensitive to default risk as deposit insurance scheme protects depositors from losses (but sensitive to deposit rates)</td><td>Sensitive to default risk</td><td>Sensitive to default risk and market risk</td></tr>
<tr><td>Bank's Funding Strategy
(bank's decision variables)</td><td>Increase in deposit rates</td><td>-</td><td>Additional bond issuance</td></tr>
</table>

Table 1: Overview of key model elements

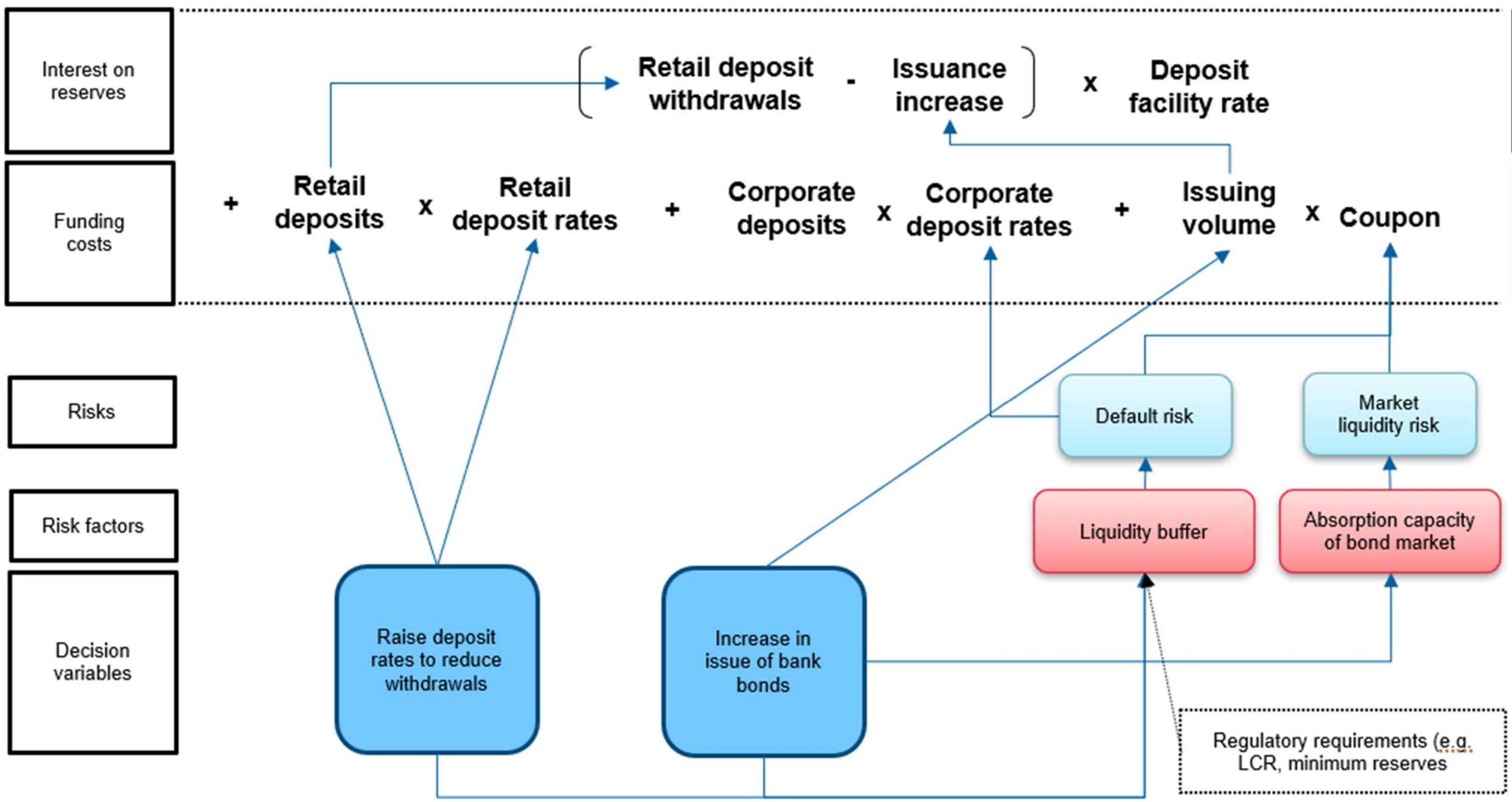

Figure 1: Conceptual overview of banks' decision-making.

2.2 Bank's decision-making

As part of its strategic liquidity management, bank i aims to minimise its net funding costs f

$$f_i = f_{D,i} + f_{K,i} + f_{B,i} - f_{C,i} \tag{1}$$

We define the objective function f_i as the sum of funding costs from retail deposits $f_{D,i}$, deposits $f_{K,i}$ from non-financial corporations and market funding through issuing bank bonds $f_{B,i}$ net of interest income on central bank reserves $f_{C,i}$.[10]

Funding costs from retail deposits

The cost component $f_{D,i}$ depends on the stock of retail deposits and the retail deposit rate. Specifically, we have

$$\begin{aligned} f_{D,i} &= r_{D,i} \cdot \left(D_i - d_i\right) \\ \text{with} \qquad r_{D,i} &= r_{0,i} + r_{1,i}. \end{aligned} \tag{2}$$

The initial deposit rate and the initial stock of retail deposits for the bank are denoted by $r_{0,i}$ and D_i respectively, while $r_{1,i}$ and d_i represent the respective changes in deposit rates and withdrawals into the D€.[11] The costs are calculated as the product of the deposit rate and the deposit volume. We assume that banks possess market power in the retail deposit market and act as quasi monopolists in their region. Consequently, banks set $r_{1,i}$ thereby also determining d_i, as a higher deposit rate increases the incentive for depositors to keep their funds in the bank. Furthermore, a holding limit for a D€ restricts the deposit outflows.

Given the skewed distribution of bank depositors' balances, the impact of holding limits varies significantly among depositors. While the holding limit would not be binding for some depositors due to their low balances, it would act as a constraint for other depositors. Consequently, depositors must be grouped according to their balances and their response behaviour to varying deposit rates is modelled specifically within their group.

We define d_i as

$$d_i = n_i \cdot \bar{w}_{hl,i}\left(r_{1,i}\right) \tag{3}$$

for $0 \leq r_{1,i} \leq r_{\max,i}$.

[10] Bank's total funding costs also include other major components of wholesale funding, such as interbank market funding costs. However, these are not relevant in our setting, since we assume that the interbank market reflects counterparty risks in marginal funding costs to a limited extent (see Martin and McAndrews (2008), Dudley (2017) and Bostic (2019)). The expanded monetary policy measures like asset purchase programs by the Eurosystem, has likely led to a certain homogenisation of interbank funding rates, making them less indicative of counterparty risks. Even with the Eurosystem's new operational framework, characterised by a 'soft floor system' with a narrow spread between the deposit facility rate and the refinancing facility rate, counterparty risks are likely to be rather modestly reflected in the rates for interbank exposures.

[11] Interest rates in the model are expressed on a net basis.

The variable n_i is the number of depositors of bank i. The variable $\overline{w}_{hl,i}$ is the average withdrawal per depositor. It depends on the increase in deposit rates $r_{1,i}$ and is specific to the limit hl for holdings of D€ by individuals imposed by the central bank. The value $r_{\max,i}$ represents the upper bound of $r_{1,i}$, at which deposit outflows would be reduced to 0. Further details on the determination of $\overline{w}_{hl,i}$ and $r_{\max,i}$ can be found in Appendix 8.1. For the choice $r_{1,i} = 0$ the quantity $d_{\max,i}$ describes the maximum outflows for the holding limit hl. This amount will be withdrawn by the depositors of bank i if the bank does not change des interest paid on deposits at all after the introduction of the D€.

The outflow function is concave and decreasing in the variable $r_{1,i}$. This curvature arises because depositors with large balances face binding holding limits, rendering them insensitive to small changes in deposit rates. Only substantial increases in deposit rates will prompt these depositors to lower their D€-holdings. At very high holding limits, the outflow function approaches a linear function (see Appendix 8.1. for further details).

We rearrange Equation (3), so that deposit outflows is defined as the bank's decision variable instead of the deposit rate. In this case, the increase in interest rates is obtained by

$$r_{1,i} = \overline{w}_{hl,i}^{-1}\left(\frac{d_i}{n_i}\right) \tag{4}$$

for $0 \leq d_i \leq d_{\max,i}$.

We assume that banks' deposits outflows are positive. Therefore, we exclude the scenario in which certain banks seek to attract deposit inflows from other banks. We do not consider interbank competition within the deposit market, but rather focus on the competition between the banks' deposit business and a D€. Furthermore, deposit outflows are capped by the upper limit $d_{\max,i}$, which corresponds to the scenario where the bank chooses not to increase the deposit rate, i.e., $r_{1,i} = 0$. Further details can be found in Appendix 8.1. The appendix also includes an explicit expression for $d_{\max,i}$.

For technical modelling purposes, it is immaterial if either $r_{1,i}$ or d_i is defined as bank's decision variable. Defining the change in interest rate as bank's decision variable enhances comprehension of the depositor demand behaviour, whereas focusing on deposit outflows as a decision variable facilitates comparison with the bank's second decision variable, i.e. the change in market funding (which we will define momentarily). For subsequent modelling, we opt for deposit outflows as the bank's decision variable.

Funding costs from corporate deposits

The cost of funding for banks through corporate deposits depends on the stock of deposits K_i and the deposit rate $r_{K,i}$. The formula is given by

$$f_{K,i} = r_{K,i} \cdot K_i \tag{5}$$

We assume that the bank's corporate deposit funding remains unchanged with the introduction of a D€, implying it is a constant value. Additionally, we posit that banks have no market power in the pricing of wholesale deposits. Instead, they apply the credit-risk-pricing approach (which is widely used in the banking industry). Corporations possess complete information. Hence, they accurately assess the credit risks of banks. With regard to corporate deposits, government bonds can be considered a benchmark asset. We utilise the yield on German government bonds (“BUNDS”) as a proxy for the time value of money.[12] Consequently, bank i offers a deposit rate to corporations that encompasses both the yield on German government bonds and the marginal costs associated with the bank's credit risk.

The deposit rate $r_{K,i}$ can be expressed by

$$r_{K,i} = y + pd_i \cdot lgd_i. \tag{6}$$

The yield on German government bonds is denoted by y . The product of the bank's 1 year probability of default (pd_i) and the Loss Given Default (lgd_i) represents the expected loss over 1 year due to the bank’s default risk.[13]

The variable pd_i is endogenous and plays a pivotal role in the model. We assess the impact of changes in a bank's liquidity position on its probability of default using logistic regression. Consistent with the well-establishd literature on logistic regression analyses to predict bank’s failure using CAMELS variables[14], we measure the bank's liquidity position as its share of reserves (i.e. cash and cash equivalents) to total balance sheet assets, denoted by CA_i

$$pd_i = \frac{\dfrac{pd_{0,i}}{1-pd_{0,i}} \cdot \left(\dfrac{CA_i}{CA_{0,i}}\right)^{\gamma}}{1+\dfrac{pd_{0,i}}{1-pd_{0,i}} \cdot \left(\dfrac{CA_i}{CA_{0,i}}\right)^{\gamma}}. \tag{7}$$

The initial probability of default, which is valid before the bank reacts to the introduction of the D€ by adjusting the interest rate paid on deposits and possibly issuing bonds, and the reserves over total assets for bank i are denoted by pd_0 and $CA_{0,i}$, respectively. The regression coefficient is denoted by γ . Equation (7) is derived from a logistic regression model as demonstrated in the work of Fink, Krüger, Meller and Wong (2016).

Bank’s reserves over total assets, in turn, depend on banks options to increase liquidity, i.e. reduce deposits outflows d_i and increase market funding b_i

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[12] We acknowledge that the deposit facility rate could be considered as an alternative proxy for the risk-free rate for corporate (sight) deposits. However, we chose short-term BUNDS instead to minimize the impact of recent monetary policy developments on our model.

[13] Typically, (sight) deposits may carry further components, such as a liquidity premium, reflected as a discount to the interest rate. However, this is not relevant for our model. In the model, corporate deposits play a specific role, influencing outcomes only through the market discipline channel, i.e., $pd(d, b)$, where risk repricing occurs when the bank's liquidity buffer weakens. As a result, what matters for the optimization is the sensitivity of the corporate deposit rate to changes in the liquidity buffer, not the overall level of the deposit rate. Introducing a liquidity premium, such as p, as a discount to the risk-free rate (i.e., $y - p$), would simply shift the level of the deposit rate without affecting the optimization results for d and b.

[14] The CAMEL variables, which stand for Capital, Asset Quality, Management, Earnings, and Liquidity, originated in 1979 with the introduction of the Uniform Financial Institutions Rating System (UFIRS) for U.S. banks.

$$CA_{0,i} = \frac{C_i}{A_i}, \quad CA_i(b_i, d_i) = \frac{C_i + b_i - d_i}{A_i + b_i - d_i}. \tag{8}$$

Here, C_i is the initial level of cash reserves for bank i and A_i is its initial total assets.

Funding costs from bond issuances

The bond market provides banks access to long-term funding. The variable $f_{B,i}$ describes the costs from bank issuances and depends on the level of outstanding bond debt and the coupon rate to be paid on the bond, i.e.

$$f_{B,i} = r_{B,i} \cdot (B_i + b_i), \tag{9}$$

with $b_i = 0$ or $b_{\min,i} \leq b_i \leq d_i$.

In this formula, $r_{B,i}$ describes the coupon rate of the bond. B_i denotes the initial stock of bond debt, and b_i is the change in bond issuances set by bank i. We assume that banks seeking to fund themselves through the bond market must adhere to a minimum issuance volume $b_{\min,i}$. This assumption reflects the economic inefficiency of funding with small amounts in the bond market.[15] We further assume that the bank does not overcompensate deposit outflows through inflows generated by an increase in issuance of bonds; in other words, the bank will at most fully offset deposit outflows. Noticeably, the (new) coupon rate $r_{B,i}$ is applied not only to the new issuances b_i but also to the initial stock B_i. Given the steady-state assumption, we posit that in the long-term, the initial stock will be replenished and its coupon rate will align with the funding costs determined by the new coupon rate $r_{B,i}$.

Similar to the wholesale deposit market, we assume that in the bond market banks have no market power apply the credit-risk-pricing approach when pricing coupon rates. Bond investors have complete information and accurately assess the credit risks of issuing banks. In addition, as bond financing involves long maturities, investors are also exposed to (market) liquidity risk of the bond, i.e. the risk, which relates to the inability of trading at fair prices with immediacy. Finally, on bond markets, government bonds serve as a benchmark asset. Therefore, we use the yield on German government bonds as a proxy for the risk-free coupon rate.

Against this backdrop, the issuing bank i offers a coupon rate that covers the yield of the German government bond and marginal costs associated with the credit risk for bank i and liquidity risk of the bond issued by bank i.

The coupon rate $r_{B,i}$ can be calculated as

$$r_{B,i} = y + pd_i \cdot lgd_i + l. \tag{10}$$

[15] Consequently, small banks have limited access to the bond market. Savings banks and cooperative banks are given a special consideration in the model. As central institutions are responsible for the liquidity management within their banking network, they can aggregate the funding needs of their respective savings and cooperative banks and accordingly raise funds in the capital market. This division of responsibilities enhances the market access of savings banks and cooperative banks compared to small commercial banks. Therefore, for savings banks and cooperative banks a lower minimum issuance volume is introduced than for commercial banks (see Section 4 for further details).

The variable l is the bond's liquidity risk. We quantify the bond's liquidity risk based on the widely used empirical measure of market liquidity, suggested by Amihud (2002). It considers the average daily price impact of trading by calculating the ratio of absolute daily returns to daily trading volume. If even small trading volumes are associated with large price changes, the Amihud measure is large and indicates illiquid markets. We consider the price impact ratio λ as a modified version of the Amihud measure and restrict attention to falling prices, as applied in Krüger, Roling, Silbermann, and Wong (2025). Based on a given price impact ratio, we can determine the relative daily price decline of a bond for various simulated daily issuance volumes in the bond market.

Accordingly, we define the bond's liquidity risk as a linear function, similar to Greenwood (2015)

$$l = \lambda \cdot \kappa \cdot \left(b_i + \sum_{i \neq j}^{N} b_j \right). \tag{11}$$

The variable l describes the price decline of the bond for increasing issuances volume across all banks. Since our model considers a long-term horizon and the simulated aggregated issuance volume is gradually introduced to the market over an extended period, we apply the scaling factor κ to the total issuance volume when calculating the (daily) price impact.[16] The liquidity risk, being contingent on the aggregate issuance volume of banks, introduces strategic interdependencies into the set of bank-individual decision-making problems. These interdependencies are characterized by strategic substitutability (akin to a Cournot competition framework), as increased bond issuance of one bank increase bond funding costs for others.

<u>Interest income on central bank reserves</u>

A withdrawal of bank deposits into a D€ results in a corresponding decrease in the bank's cash reserves held at the central bank and remunerated at the deposit facility rate, thereby reducing bank's interest income. In contrast, an increase in bond funding results in an inflow of cash reserves and increases bank's interest income.

Accordingly, the change in interest income on reserves is denoted by

$$f_{C,i} = r_C \cdot (C_i + b_i - d_i)$$

The deposit facility rate set by the central bank is denoted by r_C .

2.3 Banks' optimisation problem

Having described the different cost components of the banks' decision making, we now formulate bank i's optimisation problem as

[16] We employ a scaling factor to reflect that the simulated total new issuance volume of the banking sector is not placed in the market on a single day, but rather (evenly) distributed over a longer period, say of 1 month or 1 quarter.

$$
\begin{aligned}
& f_i(b_i, d_i) \rightarrow \min! \quad \forall i \in N \\
& s.t. \quad 0 \le d_i \le d_{\max,i} \\
& \qquad b_i = 0 \quad or \quad b_{\min,i} \le b_i \le d_i \\
& C_i + b_i - d_i \ge 0 \\
& LCR_i \ge 1
\end{aligned} \tag{12}
$$

According to the constraints of problem (12) bank's cash reserves must be above the minimum (regulatory) requirements, which are defined by the Liquidity Coverage Ratio (LCR). It is defined by

$$LCR_i = \frac{HQLA_i + \Delta HQLA_i}{Outflows_i + \Delta Outflows_i}, \tag{13}$$

with $HQLA_i$ being the initial stock of high-quality liquid assets and $Outflows_i$ the initial expected net outflows over a period of 30 calendar days according to the requirements regulating the LCR. These two quantities are derived from regulatory reports.

$\Delta HQLA_i$ is the sum of changes in incoming and outgoing cash reserves from (unsecured) borrowing and deposit outflows. i.e.

$$\Delta HQLA_i = b_i - d_i \tag{14}$$

$\Delta Outflows_i$ is the change in the expected net outflows due to the change in deposit outflows weighted by the regulatory run-off rates, i.e.

$$\Delta Outflows_i = -d_i \cdot \mu \tag{15}$$

with μ being the run-off rate for stable deposits.[17]

In order to approximate an equilibrium, we apply a heuristic approach, which iteratively works through the set of all banks and determines a solution with minimal costs for each bank conditional on the funding strategies of the other banks. The algorithm terminates as soon as the strategy vectors and aggregate variables for the banking system such as the average ROE and liquidity buffers converge.

3 Theoretical Analysis

Due to the complexity of the objective function – particularly the component that models deposit outflows described in equation (3) and the bank's probability of default described in equation (7) – theoretical analyses are significantly impeded. Consequently, based on the original objective function, we introduce a simplified objective function to facilitate the theoretical analysis (Section 3.1). In Appendix 8.3, we demonstrate that the simplified approach produces results comparable to those of the original approach outlined in Section 5. Furthermore, we conduct a detailed analysis of the marginal effects on

[17] The regulatory run-off rate is set to 3%, reflecting the standard value for stable deposits in the LCR framework. In our model, we focus on long-term bonds with maturities exceeding 30 days. Consequently, their future repayments are not included in the outflows considered for the LCR calculation.

the bank's funding costs to gain a deeper understanding of the influence exerted by the market discipline channel and the remuneration channel (Section 3.2). Based on an illustrative example of a retail bank, we visualize the objective function for different combinations of funding strategies (Section 3.3). Finally, we conduct an equilibrium analysis and show that at least one Nash equilibrium always exists (Section 3.4).

3.1 Reduced Model

We approximate the concave outflow function using anchored linear regression and we use an exponential function to approximate the logistic probability of default function for enhanced analytical tractability (see Appendix 8.2). Accordingly, the funding costs and underlying components are formulated as follows, with variables that have been transformed compared to the original optimisation problem denoted by a '~' above the respective symbol:

$$\tilde{f}_i = \tilde{f}_{D,i} + \tilde{f}_{K,i} + \tilde{f}_{B,i} - f_{C,i}$$

The funding costs of retail deposits are defined as $\tilde{f}_{D,i} = \tilde{r}_{D,i} \cdot \left(D_i - d_i\right)$, incorporating the deposit rate $\tilde{r}_{D,i} = r_{0,i} + \tilde{r}_{1,i}$ The approximating linear function of deposit outflows is

$$\tilde{d}_i\left(\tilde{r}_{1,i}\right) = D_i \cdot \left(\varphi_{hl,i} - \eta_{hl,i} \cdot \tilde{r}_{1,i}\right),$$

for $0 \leq \tilde{r}_{1,i} \leq r_{\max,i}$.

The two parameters $\eta_{hl,i}$ for the aggregate interest rate sensitivity across depositors and $\varphi_{hl,i}$ for the maximum outflow of deposits are introduced to approximate the concave function described by (3) by a linear function, for more details see Appendix 8.2. After rearranging the terms we obtain:

$$\tilde{r}_{1,i}\left(\tilde{d}_i\right) = \frac{\varphi_{hl,i} - \dfrac{\tilde{d}_i}{D_i}}{\eta_{hl,i}} \tag{16}$$

for $0 \leq \tilde{d}_i \leq \varphi_{hl,i} \cdot D_i$.

The funding costs of corporate deposits are given by $\tilde{f}_{K,i} = \tilde{r}_{K,i} \cdot K_i$, where $\tilde{r}_{K,i} = y + \widetilde{pd}_i \cdot lgd$. The approximating exponential function of the probability of default is

$$\widetilde{pd}_i = e^{-\tilde{\gamma}_i \cdot CA_i}. \tag{17}$$

The parameter $\tilde{\gamma}_i$ describes the bank-specific curvature of the function and is determined by bank's initial probability of default (see Appendix 8.2). It is influenced by its initial liquidity buffer and other relevant risk factors, such as capital ratios.

The costs of bond funding is written as $\tilde{f}_{B,i} = \tilde{r}_{B,i} \cdot (B_i + b_i)$ with the coupon rate $\tilde{r}_{B,i} = y + \widetilde{pd}_i \cdot lgd + l$. The function describing the interest income on reserves remains unchanged and is given by $f_{C,i} = r_C \cdot \left(C_i - b_i + d_i\right)$.

Furthermore, the simplified approach abstracts from market frictions, i.e. the minimum bond issuance volume requirement is not considered. As a result, the constraint for bond issuances simplifies to $0 \le b_i \le d_i$. This ensures that the domain of feasible decision parameters b_i, d_i remains connected, thereby facilitating the theoretical analysis.

Having described the new different components of the reduced model, we now formulate bank i's optimisation problem, analogous to the original problem in (12), as

$$
\begin{aligned}
&\tilde{f}_i(b_i, d_i) \to \min! \quad \forall i \in N \\
&s.t. \quad 0 \le d_i \le \varphi_{hl,i} \cdot D_i \\
&\qquad 0 \le b_i \le d_i \\
&\qquad C_i + b_i - d_i \ge 0 \\
&\qquad LCR_i \ge 1.
\end{aligned}
\tag{18}
$$

Obviously, in both problems (12) and (18) all constraints are described by linear inequalities in b_i, d_i. The constraint for the LCR_i can be rewritten as $HQLA_i + b_i - d_i \ge Outflows_i + d_i \cdot \mu$.

3.2 Marginal effects analysis

The partial derivatives of bank's funding costs with respect to deposit outflows d_i [18] and bank i's new issuance of bonds b_i for a given new issuance volume of bank bonds of the other banks are given by:

$$
\begin{aligned}
\frac{\partial \tilde{f}_i(b_i, d_i)}{\partial b_i} = &-\gamma_i \cdot e^{-\gamma_i \cdot \frac{C_i + b_i - d_i}{A_i + b_i - d_i}} \cdot \frac{A_i - C_i}{(A_i + b_i - d_i)^2} \cdot (K_i + B_i + b_i) \cdot lgd + e^{-\gamma_i \cdot \frac{C_i + b_i - d_i}{A_i + b_i - d_i}} \cdot lgd \\
&-r_C + \lambda \cdot \kappa \cdot \left(B_i + 2 \cdot b_i + \sum_{i \ne j}^{N} b_j \right) + y
\end{aligned}
\tag{19}
$$

and

$$
\begin{aligned}
\frac{\partial \tilde{f}_i(b_i, d_i)}{\partial d_i} = &\gamma_i \cdot e^{-\gamma_i \cdot \frac{C_i + b_i - d}{A_i + b_i - d_i}} \cdot \frac{A_i - C_i}{(A_i + b_i - d_i)^2} \cdot (K_i + B_i + b_i) \cdot lgd \\
&+ r_C - \frac{D_i - d_i}{\eta_{hl,i} \cdot D_i} - r_0 - \frac{\varphi_{hl,i} - \frac{d_i}{D_i}}{\eta_{hl,i}}
\end{aligned}
\tag{20}
$$

In equation (19) and (20), the first line in each of the expressions represents the marginal effect of the market discipline channel with respect to the change in credit risk costs, whereas the second line denotes the marginal effect of the remuneration channel. Since equation (19) accounts for bank's liquidity inflows and equation (20) accounts for bank's liquidity outflows, the terms in the first two lines refer to a

[18] In order to keep the calculations simple we leave out the tilde-superscript for the decision variable d_i in the modified function for the interest rate and for the parameter γ_i in the modified function for the probability of default. This convention will be applied consistently throughout the remainder of the paper.

decrease in funding costs in equation (19) and to an increase in funding costs in equation (20). The magnitude of the first line in Equations (19) and (20) is nearly identical. While equation (20) solely considers the effect of changes in the probability of default (price effect), Equation (19) additionally accounts for the impact of changes in the bond issuance volume (volume effect), i.e. $e^{-\gamma_i \cdot \frac{C_i+b_i-d_i}{A_i+b_i-d_i}} \cdot lgd$.

Given that the remuneration channel is less effective in a low interest rate environment compared to a high interest rate environment, banks are more likely to tolerate higher outflows in a low interest rate environment, ceteris paribus.

The term in the third line of equation (19) demonstrates the transmission channel with respect to the bond's liquidity risk. It depends on bank's stock of bonds $B_i + b_i$ and the aggregated volume of banks' bond issuances $b_i + \sum_{i \neq j}^{N} b_j$, each weighted by the (scaled) price impact $\lambda \cdot \kappa$. As the marginal effect of the market risk increases in b_i, it limits the maximum feasible value of b_i at the optimum.

The term in the fourth line represents the transmission channel in relation to the time value of money, as measured by the yield on German government bonds. Since this channel leads to higher funding costs in a high interest rate environment compared to a low interest rate environment, banks are more inclined to prefer funding through bond issuances in a low interest rate environment, ceteris paribus.

In equation (20), the third and fourth lines describe the reduction in the cost of retail deposit funding associated with a marginal increase in deposit outflows. The third term captures a price effect, specifically a reduction in deposit rates in response to a marginal increase in deposit outflows, which in turn results in a downward revaluation the bank's stock of retail deposits $(D_i - d_i)$. The term in the fourth line reflects a quantity effect as funding costs decrease for marginal decreasing deposit quantities.

3.3 Visualisation of the Funding Objective Function

Using the illustrative example of a bank from the small to medium-sized category, Figure 2 visualises the non-linear relationship between the two funding strategies d_i and b_i (relative to total assets) and the increase in funding costs (relative to Common Equity Tier 1 (CET1) capital) for a holding limit of €5,000.[19] Banks increase their market funding to partially compensate for deposit outflows. These outflows are also (moderately) restricted by raising deposit interest rates. One reason why banks prefer issuing new bonds over raising deposit interest rates is due to the relatively low interest rate sensitivity of depositors at this level of holding limits. This implies that banks would need to significantly increase deposit interest rates to effectively limit deposit outflows, whereas they can achieve the same objective more efficiently through additional bond funding.

Three key points are highlighted in Figure 2:

- Points marked in blue and red: These represent trivial adjustments of funding strategies for adapting to a D€.

[19] The increase in funding costs is the difference between the funding costs with a D€ and the assumed holding limit (here: €5,000) and the funding costs without a D€ (or with a D€ and a holding limit of €0).

- Blue point: The bank raises deposit interest rates sufficiently to prevent any outflows to a D€. While the liquidity buffer and default probability remain unchanged compared to the initial state without a D€, increase in funding costs are relatively high due to the increased deposit interest rates (1.83% of CET1).
  - Red point: The bank fully compensates for deposit outflows by increasing market funding. Funding costs are also relatively high here, primarily because liquidity costs rise with increased bond issuance (1.95% of CET1).[20]
- Point marked in green: This marks the optimal point where the bank chooses the optimal combination the two funding strategies, and the increase in funding costs are minimised (1.76%).

Notably, if the bank remains passive upon the introduction of a D€, neither raising deposit interest rates nor expanding market funding, the bank's funding costs would be highest at this point, due to its low liquidity buffer and high probability of default resulting from large deposit outflows. Since the passive strategy fails to meet the regulatory minimum requirements of the bank, thereby falling outside the permissible range, this point is no longer visible in Figure 2. The figure demonstrates how banks can adapt to an environment with a D€. For example, for a holding limit of € 5,000, selecting the point marked in green, the bank's optimal funding strategy can reduce the bank's funding costs considerably, compared to the trivial adjustments (points marked in blue and red) or a passive approach.

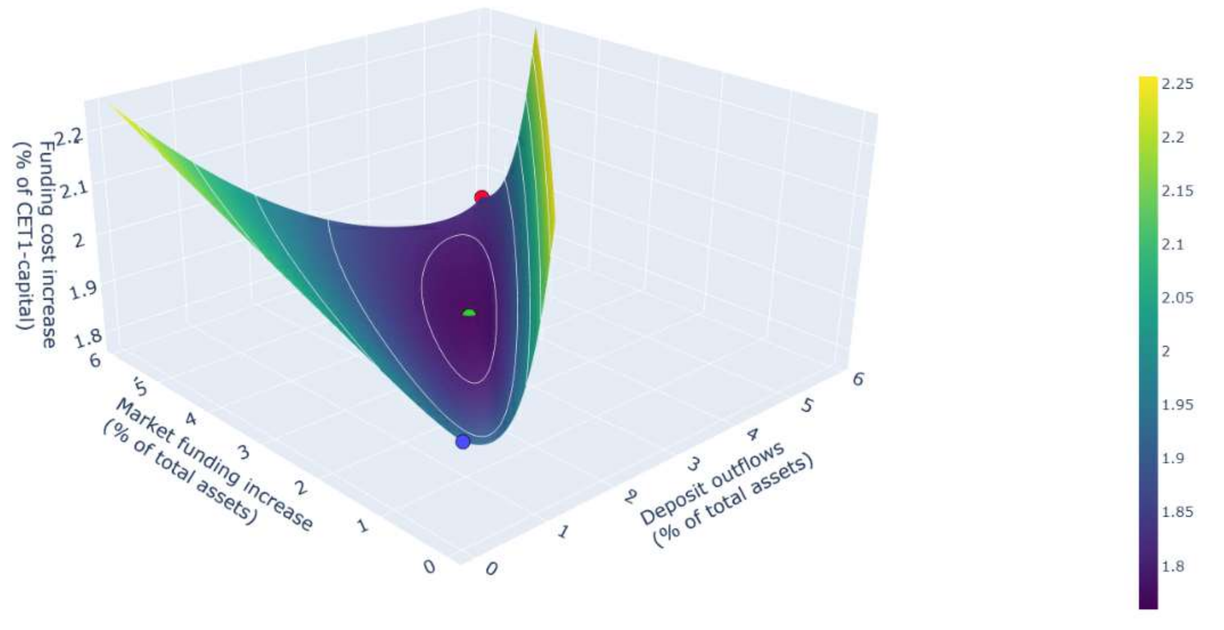

Figure 2: Non-linear relationship between the two funding strategies and funding costs.

3.4 Equilibrium analysis

The optimisation problems (18) for each bank are not independent of each other. Rather, they are linked through the costs for bond issuances $r_{B,i}$, in particular the liquidity risk arising from simultaneously issuing bonds, see formulae (10) and (11). Since costs are not only determined by the action of each

[20] This analysis, which focuses on a single stylised retail bank, assumes that other banks adopt a similar bond issuance strategy to that of the stylised bank.

individual bank i, but by the entire banking system, problems (18) cannot be solved independently of each other. Rather, they have to be looked at a system of concatenated optimisation problems, for which a Nash-equilibrium has to be determined. In this context a Nash-equilibrium refers to a set of N strategies (b_i, d_i), N being the number of banks in the banking system as before, such that each bank's individual strategy vector is optimal with respect to the problem (18) and the liquidity risk (11), which results from simultaneous action. More precisely, liquidity risk l incorporates the components b_i of the optimal strategy vectors of all other banks. The existence of an equilibrium can be linked to convexity certain properties of the objective function for each bank. For the proof of the theorem below, which is outlined in Appendix 8.4, we rely on well-stablished theory according to Debreu (1952), Fan (1952) and Glicksberg (1952). Most importantly, we provide a sufficient condition which ensures convexity for the functions $\tilde{f}_i$ there.

Theorem: At least one Nash-equilibrium for the system of concatenated optimisation problems (18) for all bank exists if each of the objective functions satisfies the criterion

$$SMM_i \geq 0, \tag{21}$$

which implies that all $\tilde{f}_i$'s are convex functions.

While we were not able to show convexity of the $\tilde{f}_i$'s in general, our criterion derived in Appendix 8.4 ensures convexity for at least 98.5 % of all banks in the sample. The coverage depends on the holding limit and the environment, either the low or high interest rate environment. Appendix includes a table showing the respective percentage of banks for which SMM_i is non-negative. Besides the number of banks, the table also shows the percentage of the overall banking system covered, measured in terms of size of balance sheets as well as the total retail deposits. Especially, the latter two measures demonstrate that the share of banks for which we were note able to show convexity is almost negligible.

As a general observation it should be mentioned that the criterion is independent of the liquidity vector l, otherwise convexity would not be a criterion solely depending on the characteristics of each individual bank. The expression for SMM_i which can be found in Appendix 8.4, does not include a reference to the bond's liquidity risk l as defined in formula (11).

In the practical application we observed that our algorithm leads to a unique solution in each application and for all tested parameter constellations. It did not show any behaviour of alternation between local optima. It showed a stable behaviour even if there remains a certain, though very low, residual uncertainty that an $\tilde{f}_i$ could not be convex, and the theory would therefore not be applicable under such circumstances. In a robustness check we left out banks for which convexity of the objective function could not be shown and compared the optimal decision parameters with those obtained from the initial application. No differences were observed.

4 Data and Parameter Specification

We rely on regulatory reporting data as of Q1 2025 at the banking group level. For banks not part of a banking group, we use reporting information at the solo level. Our sample consists of 1.156 banks. There are 104 banks without retail deposits. These banks were left out of the computer-based simulations because the D€ is irrelevant for them. Bank's regulatory and financial data, such as the initial stock of cash reserves, retail deposits, corporate deposits, bond financing and total assets, are obtained from the Common Reporting Framework (COREP) and the Financial Reporting Framework (FINREP). High-quality liquid assets and net outflows are taken from the regulatory LCR reports. For smaller local banks that do not submit the required financial data under FINREP, the data are sourced from the national monthly Balance Sheet Statistics (BISTA; 'Bilanzstatistik'). Table 2 presents the consolidated regulatory and financial data pertinent to the model.

Bank balance sheet aggregates		**Amount** [bn €]
Bond financing	$\sum B_i$	1,203
Corporate deposits	$\sum W_i$	1,013
Cash reserves	$\sum C_i$	975
Retail sight deposits	$\sum D_i$	1,498
High-quality liquid assets	$\sum HQLA_i$	1,813
Net Outflows	$\sum Outflows_i$	1,116
Total assets	$\sum A_i$	9.470

Table 2: Aggregated regulatory and financial data for the German banking system (N=1,156 banks)

Banks' initial probability of defaults are derived from their credit ratings assigned by the three major rating agencies, namely Fitch Ratings, Moody's, and Standard and Poor's.

The percentiles of the distribution of balances for sight deposits among depositors are derived from ad-hoc data requests conducted by the European Central Bank (ECB) and the Deutsche Bundesbank. These requests targeted large German banks classified as systemically important, with a reporting date of March 2024, as well as a sample of smaller banks deemed less systemically important, with a reporting date of January 2025. The data collection involved recording the number of depositors and the distribution of their balances per bank. The potential for double-counting individuals with accounts at multiple banks cannot be discounted. For savings banks and cooperative banks that were not part of the data request, average values from the data submissions of participating savings banks and cooperative banks were utilized to replace missing values. For other banks not included in the data request, the percentiles of the distribution of balances for sight deposits among depositors were obtained from surveys conducted by the German Panel on Household Finances (PHF) in March 2023. The percentiles describe a left skewed-distribution[21].

[21] For example, according to the percentiles obtained from the PHF around 50% of households cannot fully utilise a holding limit of € 3,000: $\omega_{10} = €50; \omega_{20} = €500; \omega_{30} = €1{,}000; \omega_{40} = €1{,}900; \omega_{50} = €3{,}000; \omega_{60} = €5{,}000; \omega_{70} = €7{,}900; \omega_{80} = €14{,}300; \omega_{90} = €30{,}000$.

Multiple simulations are conducted to consider different interest rate environments. For banks' initial deposit rate (before the introduction of a D€), we utilise regulatory reports from COREP on the funding costs of retail sight deposits for the groups of banks 'Commercial banks', 'Savings and cooperative banks', 'Central institutions', and 'Other banks'. We use data from the end of 2022 to represent a low to moderate interest rate environment, and data from the end of 2023 to represent a high interest rate environment. The level of the reported deposit rates fluctuates in response to the interest rate environment. For instance, the deposit rate for demand deposits averaged zero bps in the low-interest-rate environment and 60 bps in the high-interest-rate environment. Consequently, the potential proportion of depositors willing to hold a (non-interest-bearing) D€ is generally higher in a low-interest-rate environment compared to a high-interest-rate environment. Thus, in a low-interest-rate environment, larger deposit outflows, which impact the liquidity buffer, tend to strengthen the market discipline channel compared to a high-interest-rate environment (see equation (19) and (20)). For savings banks and cooperative banks, the change in the market discipline channel over the course of the interest rate cycle is less pronounced due to the relatively stable level of their deposit rates (prior to the introduction of a D€). For instance, during the current interest rate cycle, savings banks and cooperatives increased their deposit rates from zero to only 26 bps and 6 bps, respectively, compared to 212 bps for commercial banks. Coupon rates of German government bonds are obtained from Bloomberg for the end of 2023 and the end of 2022, in order to represent a high and low interest rate environment, respectively.

Depositor preferences, represented by the parameters α_i and β, are derived from Deutsche Bundesbank's Survey on Consumer Expectations of German households.[22] The parameters describe the slope and intercept of the function determining the share of deposits that are converted into a D€ depending on the prevailing deposit rate. Firstly, the survey assessed the preferred asset allocation (e.g. deposits, cash, etc.) of respondents with and without an (unremunerated) D€. Taking into account all respondents, the results indicate that the introduction of an unremunerated D€ would lead to a reduction in deposits by approximately 14 % at a deposit rate of 22 bps.[23] Focusing on the fraction of respondents who projected positive holdings of a D€, which might better reflect the broader population's behaviour once a D€ is more widely advertised and explained, deposits would reduce nearly as twice as much by approximately 27%. Secondly, the survey captures the share of depositors, who would hold a positive balance of D€ for various interest rate differentials between a bank deposit and a D€. Based on this surveyed data series, the level of deposit rates, at which no depositor would hold a D€ (or at which the share of deposits converted to D€ would be 0), is estimated to be around 82 bps (see Figure 3, left panel).

Based on the identified data points (i.e. 14 % (27 %) reduction in deposits at 22 bps, and 0 % reduction in deposits at 82 %) and under the assumption of a linear relationship, the dependency between deposit rates and deposit outflows can be quantified (see Figure 3). Using the identified linear relationship and the initial deposit rates derived from COREP data, the parameters α_i and β can be calculated (numerical examples are provided in Table 4).

[22] See Bidder, Jackson and Rottner (2024). According to the survey, around 20% of private depositors would be willing to shift their balances to a D€ during times of bank stress. We assume that 30% of retail deposits will be shifted to a digital euro in the long term (under normal conditions) if banks do not increase their deposit rates.

[23] The survey was conducted in April 2023, when the prevailing deposit rate was 22 basis points.

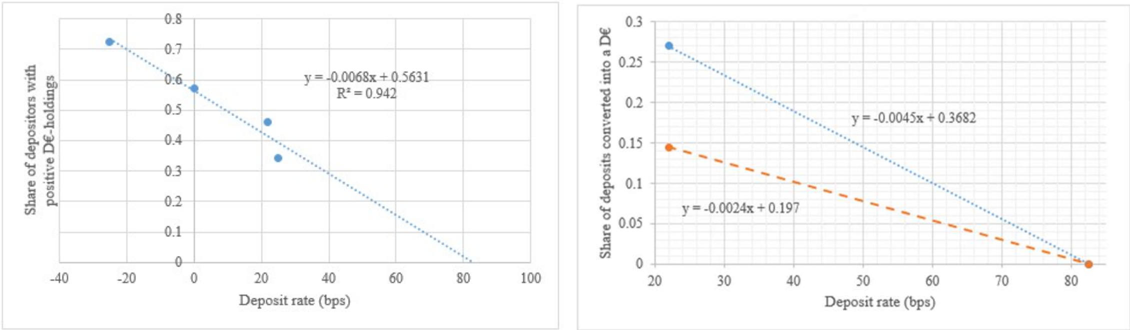

Figure 3: Determination of the parameters α and β. Left panel: The graph illustrates the relationship between deposit interest rates and the proportion of depositors holding a positive balance of D€. The y-axis represents the share of depositors with a positive balance of D€, while the x-axis denotes the deposit interest rates. The regression line suggests that at approximately 82 basis points, no depositor would hold a D€ (or the share of deposits converted to D€ would be zero). Right panel: The graph illustrates the relationship between deposit interest rates and the proportion of deposits converted into a D€. The y-axis represents the share of deposits converted into a D€, and the x-axis denotes the deposit interest rates. The regression lines illustrate the relationship between the share of deposits converted into a D€ and the deposit interest rates. The dashed regression line considers all survey respondents, while the dotted regression line focuses exclusively on depositors who would hold a positive balance of a D€.

In addition to a baseline scenario that considers all respondents, we also adopt an adverse scenario that only takes into account respondents who would hold a positive balance of a D€. This adverse scenario assumes that the demand for a D€ as a store of value will be relatively high. With this approach, we take into account the fact that, due to the limited number of data points, there is uncertainty regarding the actual preferences of depositors, ensuring that the simulated demand for a D€ is not underestimated.

In determining the parameter value for γ as the driver of the default probability for each bank, we draw upon the results of our regression analyses. Our logistic regression is conducted using an unbalanced panel with 146,396 observations from beginning of 2013 to end of 2021. The dependent variable equals one if a bank defaults within the next year as recorded by the Deutsche Bundesbank and zero otherwise. The independent variable is cash and central bank reserves over total assets. We use lagged independent variables in order to avoid endogeneity. Furthermore, we include banking group dummies. Most importantly, the cash ratio is significant at the 1% significance level and shows the expected signs. Consequently, a higher cash ratio reduces a bank's probability of default. The regression results can be found in Table 3.

In our simulation, we assume a system-wide transfer of a portion of retail deposits into a D€, which results in simultaneous reductions in the cash ratios of all banks. This scenario, which is uncommon and reflected in historical data only to a limited extent, implies that a decrease in cash reserves across the entire system would likely exacerbate the impact of a reduced cash ratio on an individual bank's probability of default. Therefore, the estimated coefficient from our regression analysis (-0.2) represents a less conservative approach. Having said this, we consider more conservative (smaller) values in the simulation to ensure the effects are not underestimated. Thus, the applied values for the parameter γ, ranging from -0.3 to -0.2, are chosen to reflect a cautious calibration guided by the magnitude of two times the standard error from the regression as a benchmark.[24]

[24] The existing literature includes empirical analyses that examine the relationship between a bank's probability of default and its liquidity position; see Cole and White (2011), Chiaramonte, Liu, Poli and Zhou (2016), Fink, Krüger, Meller and Wong (2016), Filippopoulou, Galariotos and Spyrou (2020), Chen, Chen and Huang (2021) and Alzayed, Eskandari, and Yazdifar (2023)). Most of these studies employ a broader definition of bank liquidity, often encompassing items due from other banks or liquid securities. Furthermoe, the analysis by Jahn

	Univariate	Multivariate
$pd_{i,t} = F(\varphi + \gamma_{CA} \cdot \ln(CA_{i,t-1}) + \gamma_1 \cdot X_{i,t-1} + \gamma_2 \cdot Z_{i,t-1})$		
Constant	-16.222*** (0.261)	-11.391*** (1.281)
ln(CA)	**-0.242***** (0.043)	**-0.208***** (0.042)
ln(CapA)		-2.033*** (0.275)
ln(TA)		-0.638*** (0.061)

*Table 3: Regression results. Note: $F(z) = e^z / (1+e^z)$ is the cumulative logistic distribution. Our unbalanced panel consists of 146,396 observations over 9 years (from beginning of 2013 to end of 2021) and the total number of banks is 1,535. The independent variables are the natural logarithm of cash and central bank reserves over total assets (CA), equity capital over total assets (CapA) and total assets (TA). We use lagged independent variables in order to avoid endogeneity. The dependent variable equals one if the bank defaults and zero otherwise. Distress events are systematically recorded by the Deutsche Bundesbank. There are six different types of distress events which are drawn from the German Banking Act (Kreditwesengesetz, KWG), see also Kick and Koetter (2007). The first three are early indications of potential future problems: annual operating profit contractions in excess of 25%, losses of 25% of regulatory, capital or more requiring a notification of the regulator according to section 24(1) KWG, and general notifications by banks that the existence of the bank might be at risk in line with section 29(3) KWG. Additional distress categories are capital injections received by banks from sector-specific insurance funds, restructuring mergers and revocations of a charter by a moratorium. We control for banking group as well as regional effects. Standard errors are given in parentheses and the 1% and 5% significance levels are indicated by *** and **, respectively. The bold numbers refer to the estimated coefficient of the cash ratio.*

Another key parameter of the model is the price impact ratio λ. For bank bonds, we apply the value 0.0001 per billion €, aligning with the value reported in Greenwood, Landier and Thesmar (2015).[25] For the baseline scenario, we set the scaling factor κ to 1/60 to reflect that the simulated total new issuance volume of the banking sector is not placed in the market on a single day, but rather (evenly) distributed over a period of 1 quarter, corresponding to 60 trading days. For the adverse scenario we set κ to 1/20, representing a more condensed issuance period of one month, equivalent to 20 trading days. This scenario reflects a more adverse market condition where bond issuances are concentrated within a shorter timeframe.

A minimum issuance volume of €100 million is assumed for commercial banks, and €5 million for savings banks and cooperative banks. This reflects the fact that central institutions are responsible for liquidity management within their banking network and can aggregate the funding needs of their respective savings and cooperative banks to raise funds in the capital market. Accordingly, a lower minimum issuance volume is introduced for savings banks and cooperative banks compared to commercial banks.[26]

and Kick (2012) demonstrate that higher cash reserves significantly reduce the probability of default for banks, as they provide a buffer against financial shocks and enhance financial stability.

[25] As a comparison, we also calculated the price impact ratio using the TACT module from Bloomberg, based on June/July 2025 data for bonds in the financial sector from developed markets. The resulting price impact ratio is an order of magnitude smaller, indicating that the value reported by Greenwood, Landier, and Thesmar (2015) is more conservative.

[26] In the context of our model, the assumption of a minimum issuance volume of €100 million for bonds of commercial banks is grounded in the prevailing market practices and regulatory environment in Germany. Unlike other countries such as the United States, where banks have the flexibility to issue smaller amounts of bonds, the German capital market traditionally favours larger issuances. This preference is driven by higher regulatory requirements and established market conventions that prioritise substantial bond volumes. Consequently, German commercial banks typically engage in larger bond issuances to meet these standards and market expectations.

The values of the model parameters are provided for both the baseline and adverse scenarios, across low and high interest rate environments in Table 4.

Parameter	**Baseline scenario**		**Adverse scenario**	
	Low interest Environment	**High interest Environment**	**Low interest environment**	**High interest environment**
Initial deposit rate $r_{D,i}$	CBs: 0.0017 CIs: 0.0019 SBs: 0 Co-ops: 0 OBs: 0.0008	CBs: 0.0229 CIs: 0.0129 SBs: 0.0026 Co-ops: 0.0006 OBs: 0.0058	CBs: 0.0017 CIs: 0.0019 SBs: 0 Co-ops: 0 OBs: 0.0008	CBs: 0.0229 CIs: 0.0129 SBs: 0.0026 Co-ops: 0.0006 OBs: 0.0058
Base utility α_i	CBs: 0.16 CIs: 0.15 SBs: 0.20 Co-ops: 0.20 OBs: 0.18	CBs: 0.10 CIs: 0.10 SBs: 0.13 Co-ops: 0.18 OBs: 0.10	CBs: 0.29 CIs: 0.28 SBs: 0.37 Co-ops: 0.37 OBs: 0.33	CBs: 0.10 CIs: 0.10 SBs: 0.25 Co-ops: 0.34 OBs: 0.11
Interest rate sensitivity β	23	23	45	45
Regression coefficient γ	-0.2	-0.2	-0.3	-0.3
Loss given default lgd	0.45	0.45	0.45	0.45
Price impact ratio λ	1e-13	1e-13	1e-13	1e-13
Scaling factor κ	1/60	1/60	1/20	1/20
Deposit facility rate r_C	0	0.0025	0	0.0025
German bond yield y	0.02	0.03	0.02	0.03
Minimum issuance volume for bonds $b_{\min}$	€5 million for savings banks and cooperative banks €100 million for commercial banks			

Table 4: Model parameter values for the baseline and adverse scenario under low and high interest rate environments. Note: The following abbreviations are used in the table: CBs = Commercial banks, CIs = Central institutions, SBs = Savings banks, Co-ops = Cooperative banks, OBs = Other banks. Illustrative calculation of the savings banks' base utility for the adverse scenario under the low interest environment: $0.0045 \cdot 0 + 0.37 = 0.37$.

5 Results

Figure 4 (left panel for all banks and right panel for primary institutions) illustrates the optimal funding strategies across banks at different holding limits ranging from €0 to €10,000 under the (adverse) high-interest scenario. It compares the allowed deposit outflows (represented by blue columns) with inflows resulting from increased bond funding (represented by yellow columns). Additionally, the figure illustrates the maximum potential deposit outflows (represented by light blue columns) in a maximum demand scenario where banks do not increase deposit rates and depositors withdraw the portion α_i (base utility) of their deposits or, if the holding limit is binding, all available deposits up to the holding limit. Figure 4 also shows the average increase in retail deposit interest rates across different holding limits (dotted line).

Four key observations can be made. First, the majority of deposit outflows across all banks can be attributed, as expected, to the primary institutions of the savings and cooperative bank sectors, as these banks predominantly rely on retail deposits for funding. Second, deposit outflows are only partially replaced by an increase of bond funding, i.e. up to 32% of deposit outflows are offset by additional bond funding. This illustrates that banks have a significant economical leeway to reduce their liquidity buffers in order to support their profitability. Third, for the range of holding limits considered, banks restrict deposit outflows just to a minimal extent by raising deposit interest rates. Consequently, the allowed deposit outflows are close to the maximum potential deposit outflows, with the ratio of allowed to potential deposit outflows ranging from 92% to 94%. One reason for the large ratio is the substantial initial stock of retail deposits. Retail deposits are typically the primary source of funding for banks. The total volume of retail deposits across all banks exceeds corporate deposits (bond funding) by approximately 32% (20%). Consequently, even small (permanently) increases in deposit rates result in noticeable rises in funding costs. Additionally, the interest rate sensitivity of depositors is relatively low, meaning banks would need to significantly raise their deposit interest rates to limit deposit outflows, rather than compensating through additional bond funding. This substantiates that increases in deposit rates may play a minor role compared to the expansion of market funding in the adaptation to a D€. Fourth, the magnitude of the increase in deposit rates (and the gap between optimal deposit outflows and maximum potential deposit outflows) varies depending on the holding limit. For low holding limits in place, some banks often find it more economically efficient to increase deposit rates rather than resort to bond funding. This preference is driven by the inefficiency of issuing small amounts in the bond market, a constraint that is captured by our model assumption of the minimum issuance volume requirement. Consequently, the mean increases in deposit rates initially rise up until a holding limit of €1,000 is reached, after which they begin to decline.

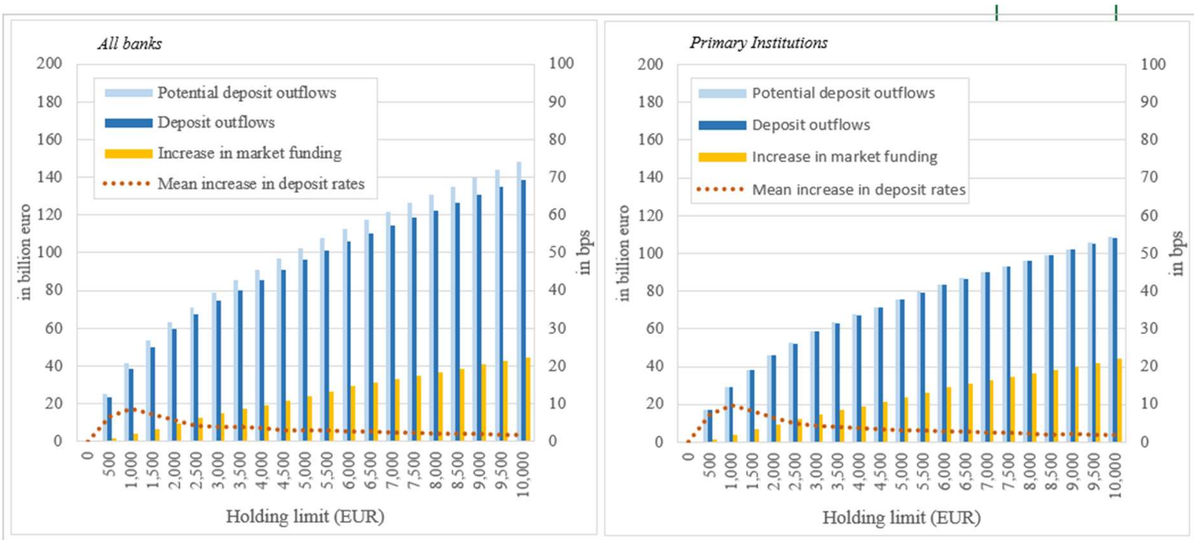

Figure 4: Optimal funding strategies across German banks under the adverse, high interest rate environment. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Columns: Potential deposit outflows (represented by light blue columns) describe outflows in a maximum demand scenario where banks do not increase deposit rates and depositors withdraw the portion α_i (base utility) of their deposits or, if the holding limit is binding, all available deposits up to the holding limit. Deposit outflows (represented by dark blue columns) and increase in market funding (represented by yellow columns) reflect quantities in equilibrium. Dotted line: Mean increase in deposit rates in equilibrium.

Under the adverse low interest rate scenario, the pattern of optimal funding strategies remains qualitatively similar. However, banks permit greater net deposit outflows, which are not compensated by additional bond issuances, as depicted in Figure 5. This is attributable to the negligible impact of the remuneration channel in a low-interest environment, which eliminates the incentive for banks to retain deposits.

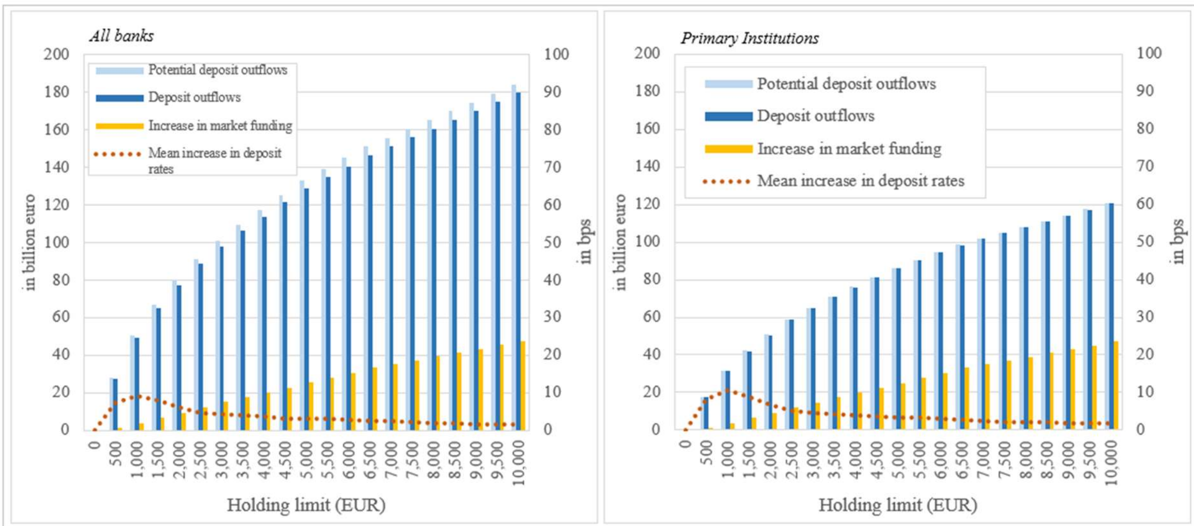

Figure 5: Optimal funding strategies across German banks under the adverse, low interest rate environment. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Columns: Potential deposit outflows (represented by light blue columns) describe outflows in a maximum demand scenario where banks do not increase deposit rates and depositors withdraw the portion α_i (base utility) of their deposits or, if the holding limit is binding, all available deposits up to the holding limit. Deposit outflows (represented by dark blue columns) and increase in market funding (represented by yellow columns) reflect quantities in equilibrium. Dotted line: Mean increase in deposit rates in equilibrium.

Figure 6 (left and right panel) demonstrates that smaller institutions within cooperative and savings bank networks can reduce liquidity (measured by the LCR) more significantly than the average in the banking system, as they are less dependent on wholesale funding, thereby supporting profitability. This analysis highlights that the effects of market discipline regarding the level of liquidity buffers and central bank reserves are less pronounced for savings banks and cooperative banks compared to commercial banks. While the funding model of most commercial banks relies on unrestricted market access, smaller institutions within the cooperative and savings bank networks primarily fund themselves through retail deposits. These deposits are typically covered by a deposit insurance scheme and are therefore considered as safe. Consequently, funding through insured deposits is subject to fewer market-disciplining effects compared to wholesale funding. Specifically, deposit rates do not react to changes in the liquidity buffer. As a result, savings banks and cooperatives can reduce their liquidity buffers more significantly. Specifically, with a holding limit of €3,000 and in a high-interest rate environment, savings banks and cooperatives decrease their liquidity buffers by 22 PP, whereas all banks on average reduce their buffers by only 5 PP. In a low interest rate environment, the reduction is even more pronounced, with savings banks and cooperatives decreasing their liquidity buffers by 25 PP, while all banks on average reduce their buffers by only 7 PP. As in a low-interest-rate environment, the remuneration channel is no longer effective, banks deplete their liquidity buffers more significantly than in a high-interest-rate environment. It is also noteworthy that savings banks and cooperative banks typically have a higher initial level of LCR compared to the average in the banking system, thereby providing them with greater flexibility to reduce their liquidity buffers.[27]

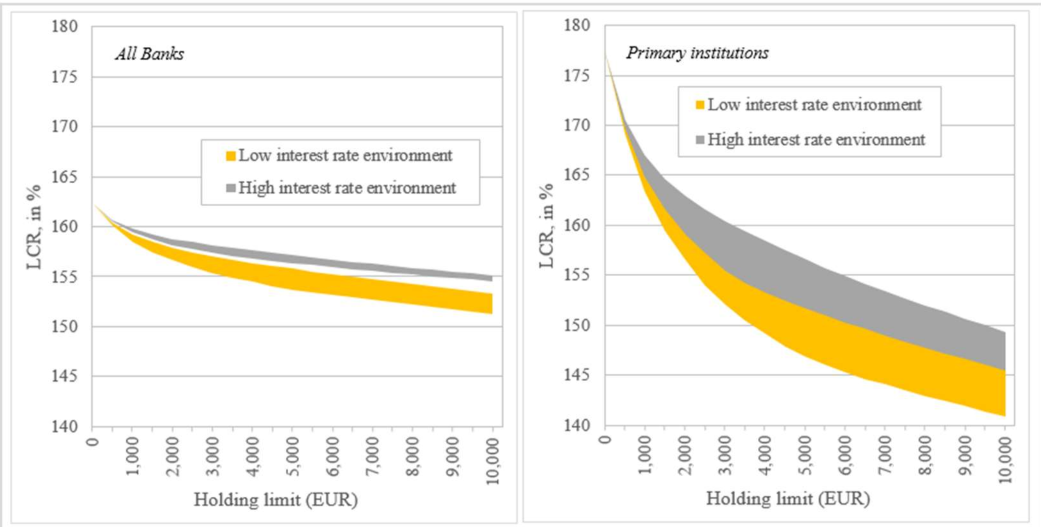

Figure 6: Effects on banks' liquidity buffer measured according to the LCR for alternative holding limits. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Note: The ranges (yellow and grey) illustrate the potential effects under optimal bank adjustments in both low-interest-rate and high-interest-rate environments. Both ranges reflect a continuum of scenarios bounded by the baseline scenario (upper boundary) and the adverse scenario (lower boundary).

[27] Interestingly, when analysing the distribution at the individual bank level, it becomes evident that adjustments to a D€ enhance the LCR for certain savings banks and cooperative banks. By replacing retail deposits with long-term bond funding, these institutions reduce maturity mismatches and improve their LCR, as long-term bonds are treated more favourably under regulatory standards than retail deposits. While this structural adjustment strengthens the LCR for many primary institutions, it leads to a moderate decline in ROE.

Figure 7 illustrates the increase in funding costs relative to equity and the consequent decline in ROE across various holding limits in all scenarios. The following two observations can be drawn. First, even in the most adverse scenario, the decline in ROE for the German banking sector resulting from increased funding costs remains relatively moderate for holding limits commonly discussed in regulatory expert circles (left panel). Specifically, the decline averages around 0.2 percentage points (PP) to 0.3 PP for a high interest rate environment and 0.1 PP for a low interest rate environment, each with holding limits ranging from €3,000 to €5,000. This effect is higher on average for primary institutions within cooperative and savings bank networks, ranging from 0.5 PP to 0.7 PP and 0.1 PP to 0.2 PP, respectively (right panel). Second, the simulated effects are unexpectedly more pronounced in a high-interest-rate environment compared to a low interest rate environment. This is primarily driven by the remuneration channel, which is more pronounced in a high-interest-rate environment. The withdrawal of deposits into a D€ reduces the bank's cash reserves held at the central bank, which are remunerated at the deposit facility rate. The resulting decline in interest income is more substantial when interest rates are elevated, amplifying the adverse impact on bank profitability. Another reason is that the initial level of deposit interest rates $r_{0,i}$ for savings banks and cooperatives, and consequently the base utility to hold a D€ measured by α_i is only marginally higher in periods of high interests compared to period of low interests. As a result, deposit outflows d_i exhibit only a marginal increase in low interest rate environments relative to high interest rate environments. Given that, for this particular group of banks, deposit outflows are only marginally higher in a low interest rate environment than those observed in a high interest rate environment, the effect of the market discipline channel is only slightly higher in a low interest rate environment compared to a high interest rate environment. In contrast, in high interest rate environments, the remuneration channel additionally comes into play, amplifying the adverse effects on ROE.

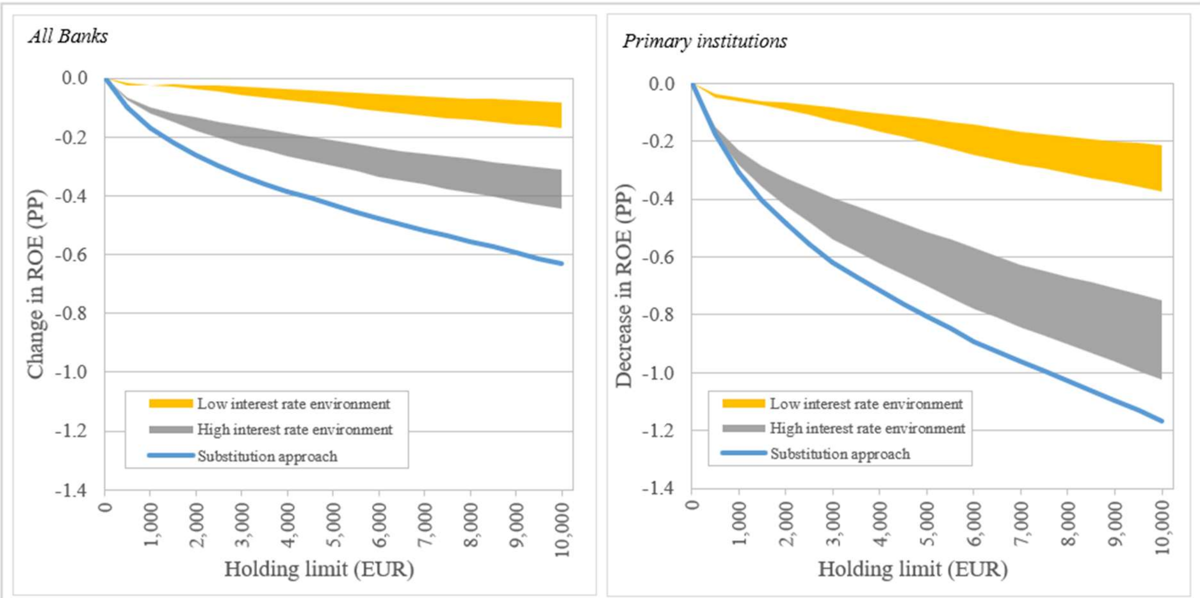

Figure 7: Effects on profitability due to increased funding costs for alternative holding limits. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Note: The ranges (yellow and grey) illustrate the potential effects under optimal bank adjustments in both low-interest-rate and high-interest-rate environments. Both ranges reflect a continuum of scenarios bounded by the baseline scenario (upper boundary) and the adverse scenario (lower boundary). The substitution approach demonstrates the effects if banks were to fully compensate for deposit outflows through market funding (in the adverse scenario within a high-interest-rate environment).

Figure 8 analyses the increase in funding costs (over equity) by disaggregating it into its individual components: the increase in (1) funding costs from retail deposits, (2) corporate deposits, and (3) bond funding, as well as (4) the change in interest income from central bank reserves. The top panel of the figure displays the cost components in a high-interest-rate environment, while the bottom panel presents them in a low-interest-rate environment, each for the adverse scenario. One main driver of the increase in costs in each interest-rate environment is the rise in bond funding costs. This rise is driven by the costs related to credit risk, with liquidity risk being a less significant factor. In a high interest rate environment, the biggest cost driver is the decrease in interest earnings on central bank reserves, which is negligible in a low-interest-rate environment. In both interest rate environments, the costs associated with retail deposits decrease. This decrease is due to a reduction in costs resulting from deposit outflows (volume effect), which more than offsets the increase in costs due to increased deposit rates (price effect). The reduction in costs is more pronounced in a high interest rate environment than in a low interest rate environment, as outflows of deposits remunerated at higher interest rates lead to greater cost reductions. Conversely, the increase in costs from corporate deposit funding is higher in a low interest rate environment than in a high interest rate environment. This is because, in a low interest rate environment, banks generally allow more deposit outflows, thereby increasing the bank's default risk and, consequently, the cost of corporate deposit funding.

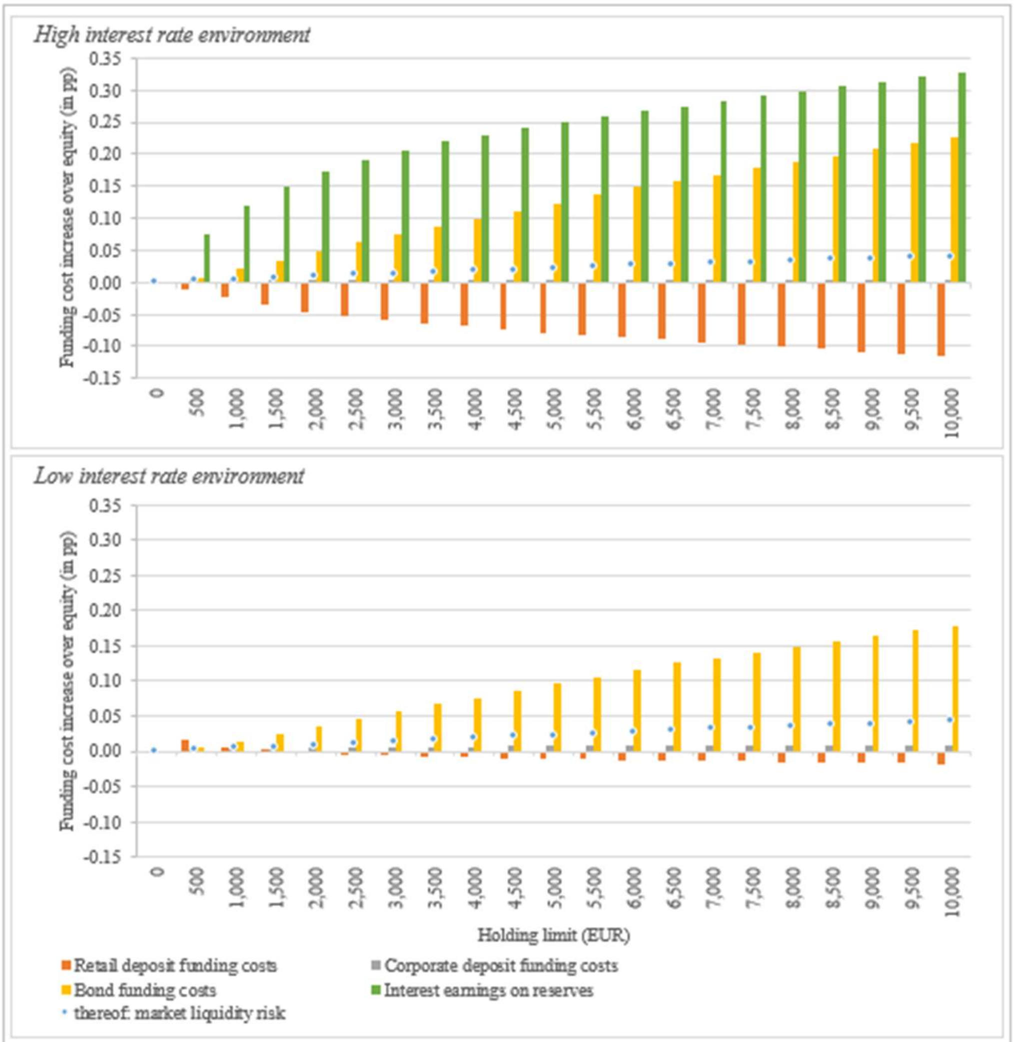

Figure 8: Individual components of increase in funding costs for different holding limits under the adverse scenario.

6 Conclusion

We present a novel model that examines the potential long-term impacts of the digital euro (D€) on bank profitability and liquidity, thereby contributing to the broader discourse on the implications of digital innovation for financial stability within financial markets. The model determines the optimal adjustment of banks' liquidity buffers and funding structures in the context of their strategic liquidity management, in response to the introduction of a D€. The study concludes that the introduction of a D€ requires adjustments within the banking sector. Banks can significantly reduce the potential increase in funding costs by actively adjusting their funding strategies. Simulations on the German banking system suggest that the overall impact on liquidity and profitability appear to be muted, for a holding limit in the range of €3,000, and even for adverse parameter settings. Accordingly, the ROE decreases by a value in the range of 0.2 percentage points, and the aggregate Liquidity Coverage Ratio declines by approximately 7 percentage points in the most adverse scenario, indicating that long-term effects appear to be limited. Notably, the effects of introducing a D€ are heterogeneous and impact various banking groups differently. While commercial banks with minimal reliance on retail deposits experience limited effects, the introduction of a D€ has the most significant impact on savings banks and cooperative banks, as they face the highest potential deposit outflows. However, they also have significant flexibility to adapt to the new environment. Unlike commercial banks, whose funding models often rely on unrestricted market access and are thus hesitant to reduce their liquidity buffer, savings banks and cooperative banks can more extensively reduce their liquidity buffers to support profitability. Additionally, savings banks and cooperative banks are better positioned than other small private banks to expand market funding by leveraging their central institutions. Furthermore, simulations reveal that increases in deposit rates may play a relatively minor role compared to the expansion of market funding in the adaptation to a D€, given the low interest rate sensitivity of depositors as derived from survey data. Finally, the resilience of the banking system to liquidity shocks depends on banks' liquidity buffers, which currently remain historically high. Hence, an on-going monitoring of effects, considering new macro-financial developments and changes in banks' liquidity positions, is essential.

While our model provides significant insights into the long-term implications of a D€ on liquidity and funding costs in the German banking system, there are several potential extensions. For example, one methodological and empirical extension of the model pertains to the calibration of the potential demand for a D€. While our model assumes a straightforward linear relationship between deposit interest rates and deposit outflows into a D€, alternative approaches offer a more nuanced representation of depositor behaviour and preferences. Notably, the study by Lambert, Larkou, Pancaro, Pellicani and Sintonen (2024) may exemplify such advanced methodologies. They apply a structural demand model to unique consumer-level survey data from the euro area to evaluate how different CBDC design options and individual preferences influence the demand for a D€. This data comes from three main sources: the Study on the payment attitudes of consumer in the euro area (SPACE), ii) the Household Finance and Consumption Survey (HFCS), and iii) Payment behaviour in Germany in 2021.

One theoretical model extension could be to treat lending (both prices and quantities) as bank's decision variables rather than a constant, integrating it into the bank's profit calculus. Under these circumstances, valuable insights could be gained regarding the provision of credit by the banking sector to the real economy. Furthermore, the market structure for retail deposits and bonds is likely not as stylised as assumed (i.e. bank monopoly in the deposit market and perfect competition among investors in the bond market) but rather a hybrid form. While banks still hold significant market power in the retail deposit market, some banks are already competing intensively for retail deposits among themselves (e.g., internet banks). Increased competition among banks for retail deposits may leave less room for banks to increase their deposit rates to counter potential deposit outflows into a D€. Moreover, the model currently assumes a simple pricing mechanism in the deposit market, where a bank pays a uniform deposit rate on all its deposits. To enhance the model, it could be extended to incorporate non-linear contracts, which are commonly observed in practice. For instance, interest on deposits could be contingent upon reaching a specified minimum deposit threshold. By adopting a more nuanced pricing strategy, the costs associated with restricting deposit withdrawals through deposit rate increases could be considerably lower than those currently simulated by the model.

A potential extension of the model addresses the impact on bank profitability due to reduced margins in payment services. On the one hand, the introduction of a D€ could intensify competition with private digital payment methods, leading to a decline in banks' payment service margins. On the other hand, a D€ might generate new revenue streams, for instance, by facilitating transactions that were previously conducted with physical cash, thereby allowing banks to earn a margin on these digital transactions. Analyses in this area are currently scarce due to limited data availability. The study by Gruber et al. (2024) provides an approach to estimate the impact on the net payment service income. Furthermore, it is essential to consider that the implementation of a D€ has the potential to foster innovation and growth through a more integrated European payments market as highlighted by Cipollone (2025), thereby potentially creating new revenue streams for banks. In this context, our findings represent a conservative scenario regarding the implications for banks' profitability, as our analysis is confined to funding costs. A broader perspective that incorporates positive macroeconomic effects would provide a more comprehensive understanding of the potential benefits. Another promising area of research is to explore additional funding strategies, specifically the increase in central bank funding. More broadly, incorporating the central bank as an active agent in the model could yield valuable insights. This approach would enable a detailed analysis of the interactions between monetary policy and the effects of a D€ on financial stability.

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8 Appendix

8.1 Determination of average withdrawal per depositor

In determining $\bar{w}_{hl,i}$, we assume that depositors follow the concept of relative asset allocation based on relative returns, inspired by Campbell (2006), and Guiso, Haliassos and Jappelli (2002), when allocating their liquid assets between sight deposits and a D€.

Let $\omega = [\omega_1, \ldots, \omega_p, \ldots, \omega_{10}]$ represent the percentiles of sight deposit balances for each bank.[28]

The average withdrawal $w_{p,hl,i}$ by depositors within a given percentile p, given a holding limit hl and a deposit rate increase $r_{1,i}$, is calculated by

$$w_{p,hl,i}(r_{1,i}) = \min\left\{hl, \omega_p \cdot \left(\alpha_i - \beta \cdot r_{1,i}\right)\right\} \tag{22}$$

for $0 \leq r_{1,i} \leq r_{\max,i}$.

In this formula parameters α_i, β represent the depositor preferences as introduced in Section 4. Accordingly, the relative share, which depositors in percentile p are willing to reallocate from their balance ω_p towards a D€, decreases linearly with increasing deposit rates $r_{1,i}$ and is capped at the holding limit hl. While β is the interest rate sensitivity of depositors to changes to deposit rates, α_i denotes the base utility[29] to hold the D€ as a store of value in an environment where equilibrium deposit rates $r_{0,i}$ would prevail in the absence of a D€. When the deposit rate reaches its maximum threshold, given by $r_{\max,i} = \alpha_i / \beta$ with $0 \leq \alpha_i \leq 1$ and $0 \leq \beta$, no depositor would have a benefit anymore from holding a D€ as an alternative to their sight deposits. As different groups of banks charge different deposits rates $r_{0,i}$ the parameter α_i is group-specific.[30] For instance, it is widely recognised that savings banks and cooperative banks benefit from a funding cost advantage due to their lower retail deposit rates compared to commercial banks. One might contend that the observed stickiness of depositors at these institutions will persist with the introduction of a D€. However, we adopt a conservative approach by assuming that the base utility α_i is higher for savings and cooperative banks than for commercial banks, as in an environment without a D€ deposit rates $r_{0,i}$ are lower for savings and cooperative banks than for commercial banks (see Section 4 for the determination of the parameter values). Additionally, we assume that the interest rate sensitivity β among depositors of different banks remains constant. The chosen approach

[28] The percentiles of the distribution of balances for sight deposits among households are obtained from surveys of the German Panel on Household Finances (PHF) from March 2023. For more details see Section 4. Based on this data collection 50% of households hold at most €3,000, and consequently nearly 50% of households cannot fully utilise a holding limit of €3,000.

[29] As our analysis focuses on normal times, i.e. the new steady state, we assume that the base utility of the D€ does not stem from risk considerations, such as being a 'safe-heaven-asset' in times of crisis. In fact, we assume that in normal times, deposits secured by a deposit insurance system exhibit similar risk characteristics as the D€. In fact, the reverse waterfall mechanism obviates the need to prefund a D€ account for payments, as any shortfall is immediately covered by the linked commercial bank account, assuming sufficient funds are available. One potential incentive to hold the D€ (unrelated to risk considerations), is the ability to make offline payments, incentivising larger amounts of electronic cash in one's e-wallet; see Lambert, Larkou, Pancaro, Pellicani and Sintonen (2024).

[30] Additionally, α_i is influenced by the interest rate environment, as the level of deposit rates fluctuates in response to changes in the interest rate environment.

implies that the introduction of a D€ will particularly affect the market power of savings banks and cooperative banks.

Interestingly, holding limits (in combination with depositors' strategy of relative allocation based on relative prices) impacts the effective interest rate sensitivity. While we assume the intrinsic interest rate sensitivity β among depositors is homogenous, the effective interest rate sensitivity (after applying the holding limit) differs among depositors depending on their level of account balances. This is because, given a specific holding limit, say €1,000, these thresholds are mostly binding for depositors with large balances, say €20,000. The effective interest rate sensitivity of this segment of depositors is lower than their intrinsic interest sensitivity since only a significant increase in deposit rates would prevent these depositors from fully utilising the holding limit and reduce their deposit outflows below €1,000 (or below 5% of their balances). Consequently, the effective interest rate sensitivity is lower for depositors with large balances than for depositors with low balances. With higher holding limits, the effective interest rate sensitivity increases, reducing the disparity between effective and intrinsic interest rate sensitivity.

The average outflow $\overline{w}_{hl,i}$ per depositor across all percentiles for bank i is given by

$$\overline{w}_{hl,i} = \frac{1}{10} \cdot \sum_{p=1}^{10} w_{p,hl,i}\left(r_{1,i}\right) \tag{23}$$

The average outflow $\overline{w}_{hl,i}$ is concave and decreasing in the variable $r_{1,i}$. Note that the average outflow is maximal for $r_{1,i} = 0$. For this reason the value $d_{\max,i}$, which describes the amount of deposits withdrawals in case the bank does not react at all to the introduction of D€, corresponds to the expression

$$d_{max,i} = \frac{1}{10} \cdot \sum_{p=1}^{10} w_{p,hl,i}\left(0\right) = \frac{1}{10} \cdot \sum_{p=1}^{10} \min\{hl, \omega_p \cdot \alpha_i\}.$$

This specific curvature is explained by the aforementioned fact that, depositors with large balances are effectively insensitive to small changes in deposit rates. At very high holding limits, the variable $\overline{w}_i$ approaches a linear function as the gap between intrinsic interest rate sensitivity and effective interest rate sensitivity narrows for depositors with large balances. The construction of the outflow function is illustrated in Figure 9.

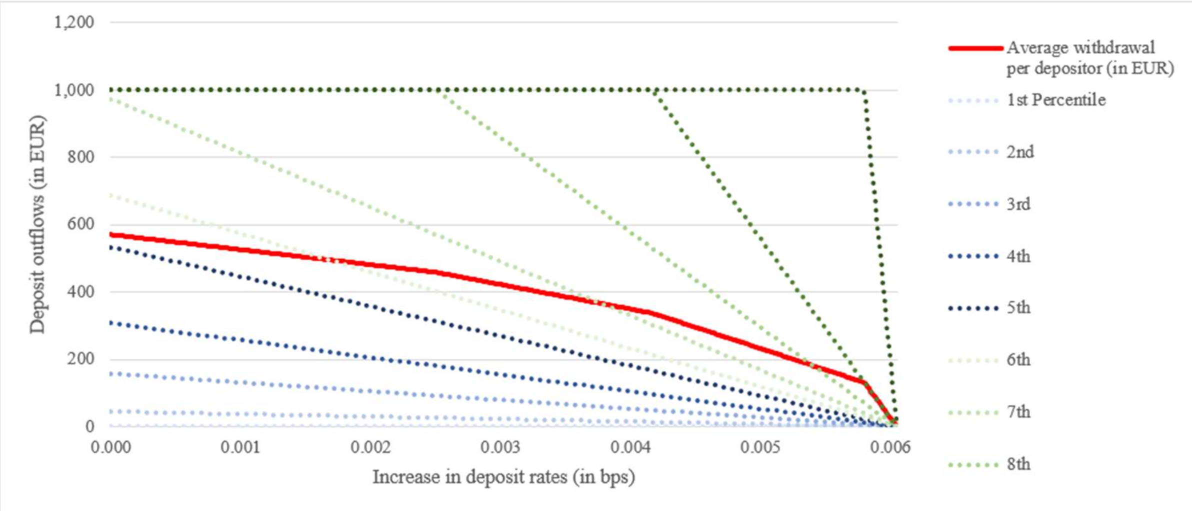

Figure 9: Outflow function according to Equations (22) and (23) for parameters α = 0.4, β=44.65, hl = 1.000€, ω=(25, 275; 750; 1,450; 2,450; 4,000; 6,450; 11,100; 22,150; 50,466). The dotted lines are $w_{p,hl,i}\left(r_{1,i}\right)$ and the red line is the average.

8.2 Simplified functions of outflows and probability of default

Outflow function

We approximate the concave deposit outflows function using anchored linear regression with a fixed anchor point at $r_{max,i}$.

Accordingly, we define $\tilde{d}_i(\tilde{r}_i)$ as

$$\tilde{d}_i\left(\tilde{r}_1\right)=D_i\cdot\left(\varphi_{hl,i}-\eta_{hl,i}\cdot\tilde{r}_{1,i}\right) \tag{24}$$

for $0 \leq \tilde{r}_{1,i} \leq r_{max,i}$.

The initial stock of bank's retail deposits is denoted by D_i . In an environment where equilibrium deposit rates $r_{0,i}$ would prevail in the absence of a D€, the maximum average withdrawal amount by bank i's depositors, described by $\varphi_{hl,i} \cdot D_i$, depends on the holding limit hl . The parameter $\eta_{hl,i}$ is the aggregate depositor's interest rate sensitivity. The parameters of the linear function $\tilde{r}_{1,i}\left(\tilde{d}_i\right)$ are defined in such a way that for $\tilde{r}_{max,i}=\alpha_i/\beta$ deposit outfows equal 0, i.e. both original and approximate function have the same threshold for which deposit outflows reach 0. The threshold value is group-specific.

Alternatively, Equation (24) can be rearranged so that deposit outflows is defined as the bank's decision variable instead of the deposit rate. In this case, the increase in deposit rates is obtained by

$$\tilde{r}_{1,i}\left(\tilde{d}_i\right)=\frac{\varphi_{hl,i}-\dfrac{\tilde{d}_i}{D_i}}{\eta_{hl,i}}$$

for $0\leq\tilde{d}_i\leq\varphi_{hl,i}\cdot D_i$.

In Figure 10, we compare the original deposit outflows function with its linear approximation (under the adverse, high interest rate scenario). The graph illustrates the behaviour of both functions for an illustrative bank and various holding limits, demonstrating that the linear approximation closely matches the original function for large holding limits. For very low holding limits, the approximation is much less accurate. However, the weak convergence has little impact on the accuracy of the simulation results compared to the simulations results based on the original outflow function, given that at very low holding limits, the magnitude of the initial shock and the resulting effects are inherently low (see Section 8.3). Similar to the original deposit outflow function discussed in Section 8.1, the aggregate interest rate sensitivity of depositors ($\eta_{hl,i}$) also increases in the linearly approximated deposit outflow function as the holding limits of a D€ increase. Notably, the average interest rate sensitivity is (in absolute terms) greater for the simplified function compared to the original concave function. This result arises because by construction both functions share the same x-axis intercept, while the y-axis intercept of the simplified function is higher than that of the original function (see Figure 10). Consequently, the slope of the simplified function declines more steeply than the average slope of the original function, reflecting a higher absolute sensitivity of deposit outflows to changes in interest rates.

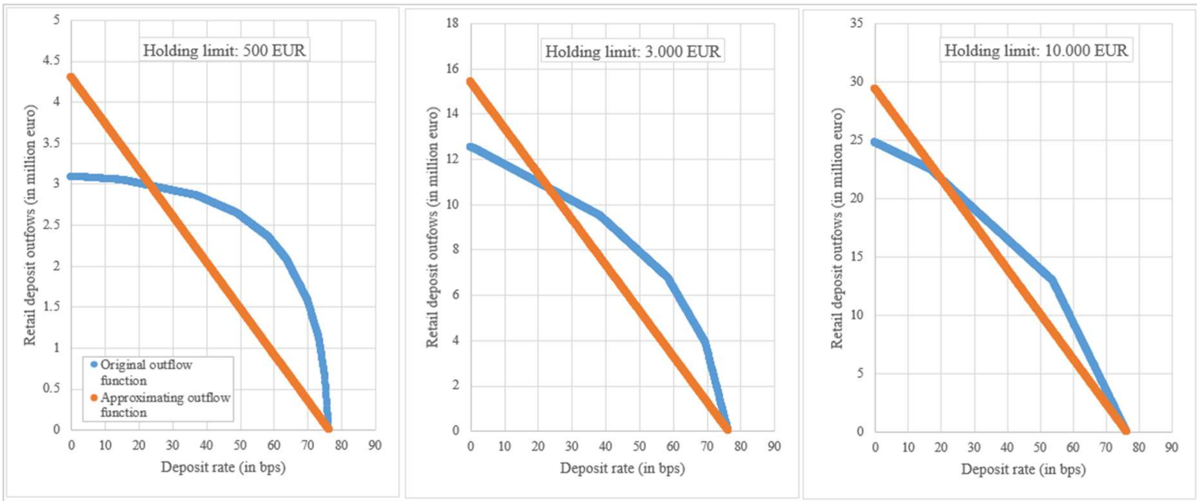

Figure 10: Approximation of deposit outflow function using the illustrative example of a bank from the small to medium-sized category under the adverse, high interest scenario.

Table 5 lists the mean and median values of the coefficients of the determination (R^2) and the root mean square errors (RMSE) across all banks for different holding limits to indicate how well the approximating functions fits the original functions.

Holding limit	Parameter		Baseline scenario: Low interest environment	Baseline scenario: high interest environment	Adverse scenario: Low interest environment	Adverse scenario: high interest environment
€500	R^2	Mean	0.06	0.21	-0.77	-0.50
		Median	-0.05	-0.13	-0.98	-1.22
	RMSE	Mean	4,114,014	3,532,613	5,658,912	4,576,992
		Median	1,516,552	1,396,107	2,060,435	1,957,638
€3,000	R^2	Mean	0.86	0.74	0.69	0.67
		Median	0.84	0.74	0.66	0.56
	RMSE	Mean	6,205,270	7493248	11,577,386	9,585,028
		Median	2,430,467	2824912	4,393,252	4,062,978
€10,000	R^2	Mean	1.00	0.96	0.95	0.86
		Median	1.00	0.95	0.94	0.87
	RMSE	Mean	685,614	4,040,771	9,590,519	11,078,824
		Median	320,133	2,100,364	3,887,672	5,472,657

Table 5: Coefficient of the determination (R^2) and root mean square errors (RMSE) across different scenarios.

Default probability function

We employ an exponential regression model to approximate the logistic function for estimating the probability of default. The resulting exponential function that represents the probability of default is given by:

$$\widetilde{pd}_i = e^{-\tilde{\gamma}_i \cdot CA_i}.$$

The parameter $\tilde{\gamma}$ represents the bank-specific curvature of the function. It is determined by the bank's initial probability of default, which depends on its initial liquidity buffer and other risk factors, such as capital ratios.

Table 6 provides the mean square errors (RMSE) of determination across all banks for different holding limits, indicating the fit quality of the approximating functions to the original functions. The median of the RMSE indicates a good approximation overall; however, the mean of the RMSE reveals that the default probabilities based on the exponential function for certain outlier banks are more conservative than the default probabilities based on the logistic function for lower cash ratios.

Parameter		Baseline scenario	Adverse scenario
RMSE	Mean	0.0229	0.0247
	Median	0.0004	0.0004

Table 6: Mean square errors (RMSE) across different scenarios.

8.3 Simulation results for the simplified approach

Compared to the simulations results presented in Chapter 5, the simulations are reproduced using the approximation functions for deposit outflows and default probability and presented in Figure 11 to Figure 15. Key findings of the simulation when using the simplified functions qualitatively align with those derived from simulations based on the original functions. Accordingly, Figure 11 and Figure 12 illustrate that, in both high and low interest rate environments respectively, deposit outflows (depicted by dark blue columns) are only partially offset - by less than 50% - through bond funding (depicted by light blue columns). This indicates that banks have enough leeway to reduce their liquidity buffers as a means to preserve profitability. Banks also rarely raise deposit rates to limit outflows, suggesting that increases in deposit rates may play a minor role compared to the expansion of market funding in the adaptation to a D€. A different pattern of equilibrium deposit rates can be observed under varying holding limits in both high and low interest rate environments. Namely, since the minimum bond issuance volume requirement $b_{\min,i}$ is not accounted for under the simplified approach, the deposit rate chosen under the simplified approach tends to be lower than that under the original approach when holding limits are relatively low.[31]

[31] Deposit rates begin to rise with larger holding limits only in the high interest rate environment, though the magnitude of the increase remains relatively small in absolute terms (amounting to a few basis points). The reason for the increase can be attributed to the increase in the aggregate interest rate sensitivity among depositors for larger holding limits, which is greater for the simplified function compared to the original concave function (see section 8.2). Consequently, this amplifies the importance of limiting deposit outflows by raising deposit rates relative to the increase in bond funding. In a low interest rate environment, no significant increase in deposit rates is observed for larger holding limits. This is because market funding becomes more cost-effective in a low interest rate environment compared to retail deposit funding, making it the preferred source for additional funding.

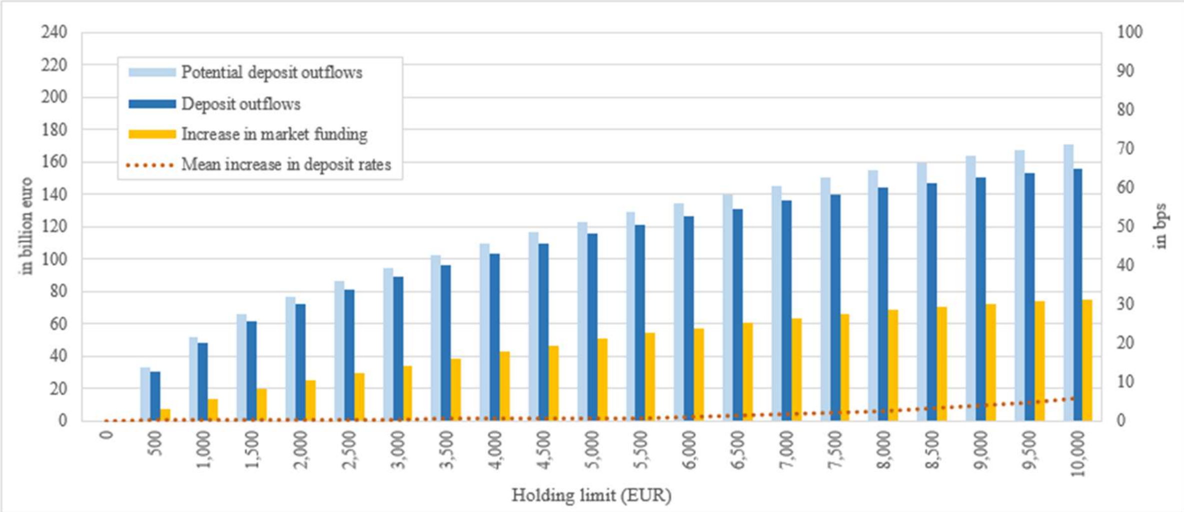

Figure 11: Optimal funding strategies across German banks under the adverse, high interest rate environment for the simplified approach. Columns: Potential deposit outflows (represented by light blue columns) describe outflows in a maximum demand scenario where banks do not increase deposit rates and depositors withdraw the portion α_i (base utility) of their deposits or, if the holding limit is binding, all available deposits up to the holding limit. Deposit outflows (represented by dark blue columns) and increase in market funding (represented by yellow columns) reflect quantities in equilibrium. Dotted line: Mean increase in deposit rates in equilibrium.

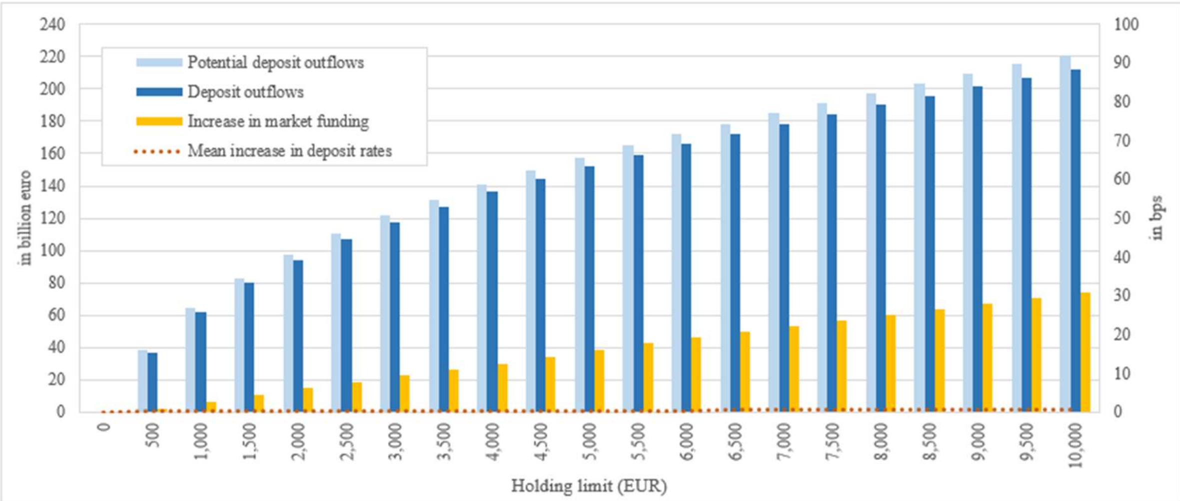

Figure 12: Optimal funding strategies across German banks under the adverse, low interest rate environment and for the simplified approach. Columns: Potential deposit outflows (represented by light blue columns) describe outflows in a maximum demand scenario where banks do not increase deposit rates and depositors withdraw the portion α_i (base utility) of their deposits or, if the holding limit is binding, all available deposits up to the holding limit. Deposit outflows (represented by dark blue columns) and increase in market funding (represented by yellow columns) reflect quantities in equilibrium. Dotted line: Mean increase in deposit rates in equilibrium.

When comparing Figure 6 with Figure 13, which show the LCR aggregated across all banks in Germany for different holding limits, the simulation results based on the approximated functions are qualitatively the same compared to those based in the original functions, albeit the effects are more pronounced. This is mainly attributable to the conservative nature of the approximating exponential function for default probability and linear outflow function, which amplifies the impact relative to the original specification.

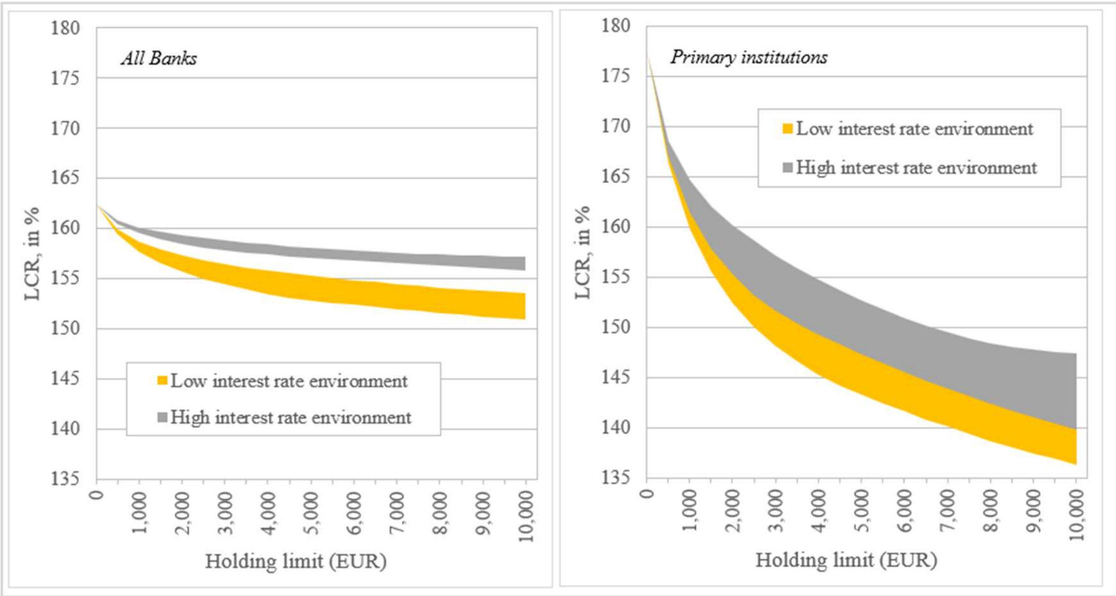

Figure 13: Effects on banks' liquidity buffer measured according to the LCR for alternative holding limits and the simplified approach. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Note: The ranges (yellow and grey) illustrate the potential effects under optimal bank adjustments in both low-interest-rate and high-interest-rate environments.

When comparing Figure 14 to Figure 15 with Figure 7 to Figure 8 in terms of the impact on funding costs and liquidity, a similar pattern emerges. The simulation results based on the simplified approach are qualitatively consistent with those derived from the original functions, although the effects appear stronger. This can be attributed to the linear approximation of the outflow function, which is more conservative (for small increase in deposit rates), thereby intensifying the observed impacts relative to the original model.

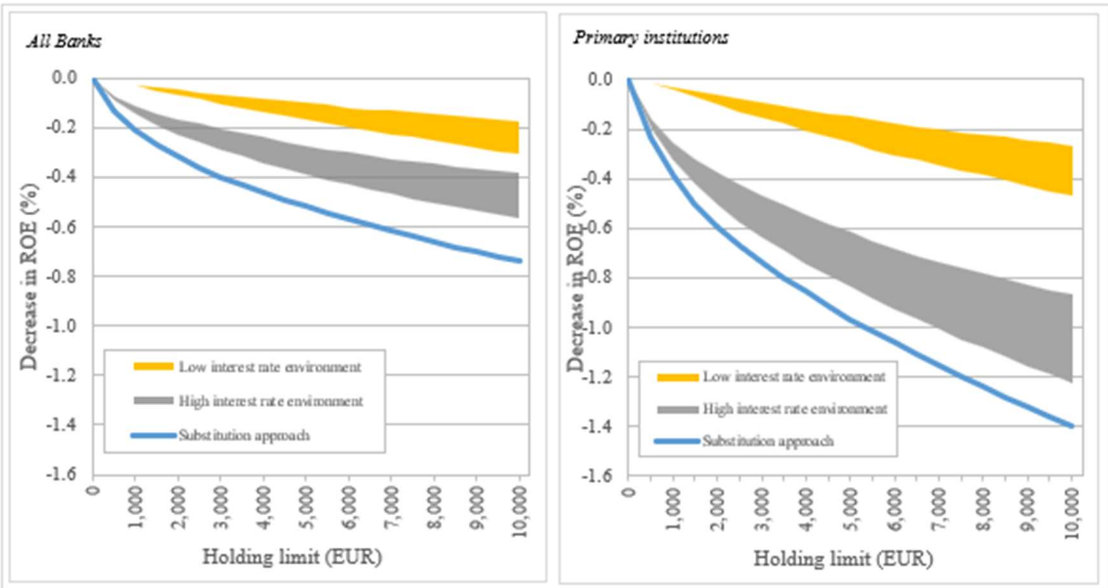

Figure 14: Effects on profitability due to increased funding costs for alternative holding limits and the simplified approach. Left panel: entire German banking system. Right panel: primary institutions consisting of savings banks and cooperative banks. Note: The ranges (yellow and grey) illustrate the potential effects under optimal bank adjustments in both low-interest-rate and high-interest-rate environments. The substitution approach demonstrates the effects if banks were to fully compensate for deposit outflows through market funding (in the adverse scenario within a high-interest-rate environment).

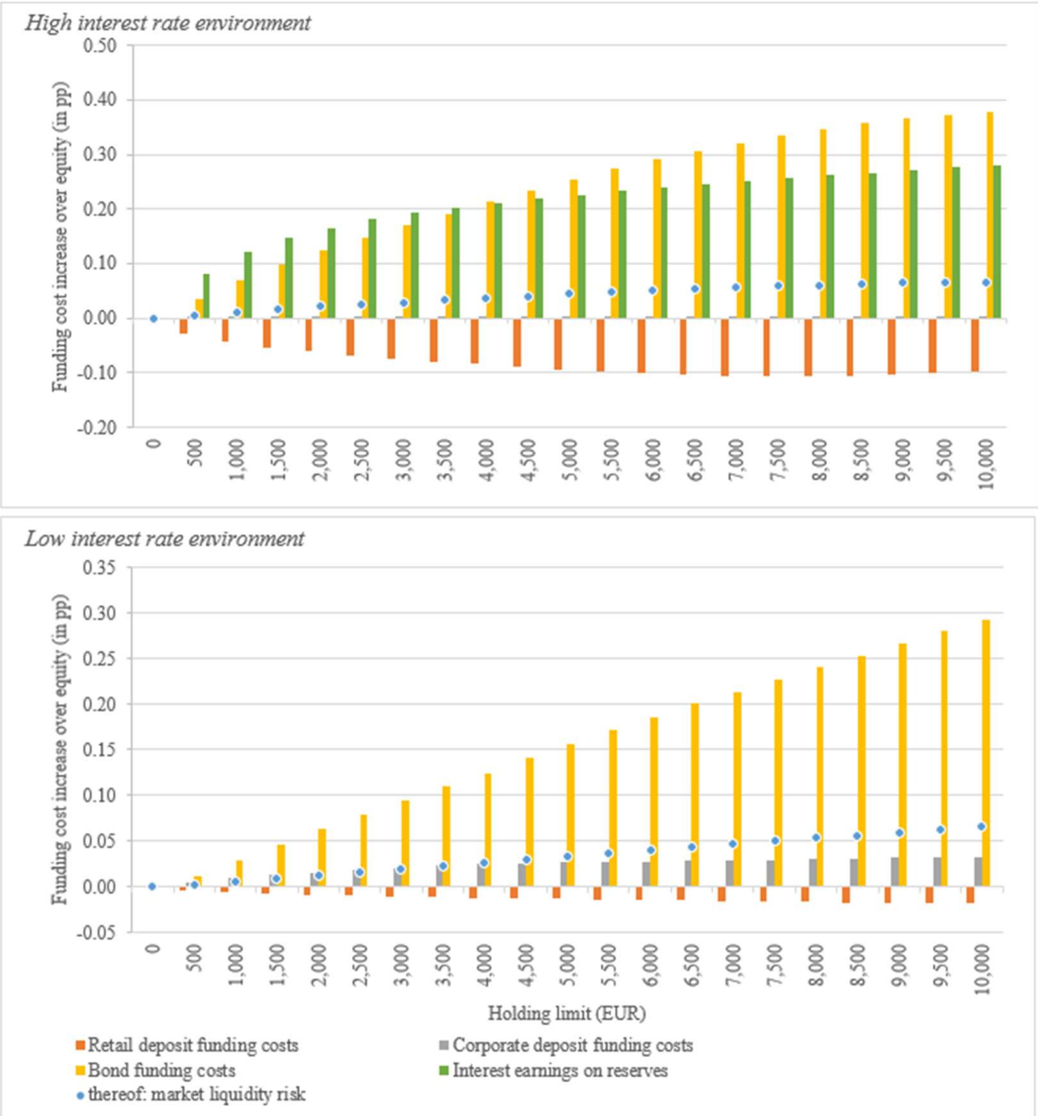

Figure 15: Individual components of increase in funding costs for different holding limits.

8.4 Proof of the existence of the equilibrium

We aim to prove that the game defined by the optimization problem (12) has at least one pure strategy Nash equilibrium. The proof is based on Debreu (1952), Fan (1952) and Glicksberg (1952) which requires the following conditions to hold for our optimisation problems (18):

1. Banks' funding strategies (d_i, b_i) are non-empty, compact and convex subsets of $\mathbb{R}^2$.
2. The objective functions $\tilde{f}_i(\cdot)$ are continuous in (d_i, b_i) *for all* $i \in \mathbb{N}$.
3. The objective functions $\tilde{f}_i(\cdot)$ are quasiconvex in (d_i, b_i) *for all* $i \in \mathbb{N}$.

It is evident that the first two criteria are satisfied. Specifically, the set of funding strategies (d_i, b_i) for each bank is non-empty, compact, and convex, which simply follows from the fact that the domains of feasible strategies can be described as intersection of halfspaces in the $\mathbb{R}^2$. Furthermore, the objective function is continuous and maps the funding strategy profile of all banks into the $\mathbb{R}^2$.

To meet the third criterion, we establish a condition that ensures the convexity of the objective function $\tilde{f}_i$ for our optimisation problems (18). Since every convex function is also quasiconvex, satisfying this condition automatically guarantees compliance with the third criterion. We rely on well-known theory which links convexity to the property of positive-definiteness of the Hessian matrix and the positivity of its main majors, for example see Boyd and Vandenberghe (2004).

However, before turning to the task of showing positivity of the main majors we introduce a variable transformation which significantly simplifies the necessary computations. Instead of the decision variables d_i and b_i, the two variables $v_{1,i}$ and $v_{2,i}$ are used. The substitution is provided in matrix notation below. It is not only a technical measure, but has an intuitive interpretation. The transformation combines the effect of both decision variables d_i and b_i on liquid assets. The difference $d_i - b_i$ describes the net liquidity outflow in the cash to assets ratio. For this reason, the bank's probability of default, which is determined by the cash-to-asset ratio, can be formulated as a function of only one variable. As a result, all computations involving the objective function and its first and second derivatives become much simpler. Since the transformation-matrix has full rank any properties of both the objective function as well as the domain of feasible strategies remain invariant w.r.t. the transformation, so that we can work with $\tilde{f}(v_{1,i}, v_{2,i})$ instead of $\tilde{f}(d_i, b_i)$. For the sake of consistency, we define the variable B_i as $V_{2,i}$.

$$\begin{pmatrix} v_{1,i} \\ v_{2,i} \end{pmatrix} = \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} d_i \\ b_i \end{pmatrix} \quad \text{and } B_i = V_{2,i} \text{ (variable substitution)}$$

$$\begin{aligned}
\tilde{f}_i\left(v_{1,i}, v_{2,i}\right) = & \left(r_{0,i} + \frac{D_i \cdot \varphi_{hl,i} - (v_{1,i} + v_{2,i})}{D_i \cdot \eta_{hl,i}} \right) \cdot \left(D_i - \left(v_{1,i} + v_{2,i} \right) \right) + r_R \cdot v_{1,i} \\
& + \left(y + e^{-\gamma_i \cdot \frac{C_i - v_{1,i}}{A_i - v_{1,i}}} \cdot lgd \right) \cdot K_i \\
& + \left(y + e^{-\gamma_i \cdot \frac{C_i - v_{1,i}}{A_i - v_{1,i}}} \cdot lgd - \kappa \cdot \lambda \cdot \left(v_{2,i} + v_{all} \right) \right) \cdot \left(V_{2,i} + v_{2,i} \right)
\end{aligned}$$

$$\tilde{f}_{v_{1,i}}\left(v_{1,i}, v_{2,i}\right) = \frac{2 \cdot \left(v_{1,i} + v_{2,i} \right) - D_i \cdot \left(1 + \varphi_{hl,i} + \eta_i \cdot r_0 \right)}{D_i \cdot \eta_i} + r_R + \gamma_i \cdot e^{-\gamma_i \cdot \frac{C_i - v_{1,i}}{A - v_{1,i}}} \cdot lgd \cdot \frac{A_i - C_i}{\left(A_i - v_{1,i} \right)^2} \cdot (K_i + V_{2,i} + v_{2,i})$$

$$\tilde{f}_{v_{2,i}}\left(v_{1,i}, v_{2,i}\right) = \frac{2 \cdot \left(v_{1,i} + v_{2,i} \right) - D_i \cdot \left(1 + \varphi_{hl,i} + \eta_i \cdot r_0 \right)}{D_i \cdot \eta_{hl,i}} + y + e^{-\gamma_i \cdot \frac{C_i - v_{1,i}}{A - v_{1,i}}} \cdot lgd + \kappa \cdot \lambda \cdot \left(V_{2,i} + 2 \cdot v_{2,i} + v_{all} \right)$$

$$\tilde{f}_{v_{1,i},v_{1,i}}\left(v_{1,i},v_{2,i}\right)=\frac{2}{D_i\cdot\eta_{hl,i}}+\gamma_i\cdot e^{-\gamma_i\cdot\frac{C_i-v_{1,i}}{A_i-v_{1,i}}}\cdot lgd\cdot\frac{A_i-C_i}{\left(A_i-v_{1,i}\right)^2}\cdot\left(\gamma_i\cdot\frac{A_i-C_i}{A_i-v_{1,i}}+2\right)\cdot\left(K_i+V_{2,i}+v_{2,i}\right)$$

$$\tilde{f}_{v_{1,i},v_{2,i}}\left(v_{1,i},v_{2,i}\right)=\frac{2}{D_i\cdot\eta_{hl,i}}+\gamma_i\cdot e^{-\gamma_i\cdot\frac{C_i-v_{1,i}}{A_i-v_{1,i}}}\cdot lgd\cdot\frac{A_i-C_i}{\left(A_i-v_{1,i}\right)^2}$$

$$\tilde{f}_{v_2,v_2}\left(v_1,v_2\right)=\frac{2}{D_i\cdot\eta_{hl,i}}+2\cdot\kappa\cdot\lambda$$

$$SMM_i=\left(\frac{2}{D_i\cdot\eta_{hl,i}}+2\cdot\kappa\cdot\lambda\right)\cdot\gamma_i\cdot e^{-\gamma_i\cdot\frac{C_i-v_{1,i}}{A_i-v_{1,i}}}\cdot lgd\cdot\frac{A_i-C_i}{\left(A_i-v_{1,i}\right)^3}\cdot\left(\gamma_i\cdot\frac{A_i-C_i}{A_i-v_{1,i}}+2\right)\cdot\left(K_i+V_{2,i}+v_{2,i}\right)$$
$$+\frac{4\cdot\kappa\cdot\lambda}{D_i\cdot\eta_{hl,i}}-\left(\frac{4}{D_i\cdot\eta_{hl,i}}+\gamma_i\cdot e^{-\gamma_i\cdot\frac{C_i-v_{1,i}}{A_i-v_{1,i}}}\cdot lgd\cdot\frac{A_i-C_i}{\left(A_i-v_{1,i}\right)^2}\right)\cdot\gamma_i\cdot e^{-\gamma_i\cdot\frac{C_i-v_{1,i}}{A_i-v_{1,i}}}\cdot lgd\cdot\frac{A_i-C_i}{\left(A_i-v_{1,i}\right)^2}$$

We rely on two different approaches to address the question which banks satisfy this condition. The first approach is to test non-negativity of the SMM_i on a 1,000x1,000-grid for $v_{1,i}$ and $v_{2,i}$ each ranging from 0 to $\min\left\{C_i, D_i\cdot\varphi_{hl,i}\right\}$ (using Python). In this **simulation-based approach** to test convexity the objective function for the respective bank can be classified as convex if SMM_i stays non-negative on the full grid.

The second, more **analytically-oriented approach** is based on the fact that the SMM_i is guaranteed to be non-negative when the parameter λ, representing the limited absorption capacity of capital markets, does not fall below a critical threshold. The second approach starts using lower and upper thresholds for the variable $v_{1,i}$ in the above expression for SMM_i depending on whether $v_{1,i}$ appears before or after the "minus" in the expression. In this way a lower bound for SMM_i is determined. Afterwards, the minimum value for the parameter λ is determined in such a way that SMM_i becomes non-negative. Under this second approach, convexity is then ensured if the threshold value turns out to be smaller than the value which is actually used for the simulation. Note that the threshold is influenced by the composition of banks' funding strategies, particularly the proportion of wholesale funding $K_i+V_{2,i}$. A higher reliance on wholesale funding increases the likelihood of satisfying the convexity condition.

We tested 1,156 - 104 = 1,052 banks[32] using these two techniques. Results are shown in Table 7 below:

[32] It also includes 104 banks with no initial stock of retail deposits ($D = 0$) and therefore have a trivial optimisation set. These banks are also included in the share of sample, which have a convex objective function.

Holding limit	Envi-ron-ment	Simulation-based approach			Envi-ron-ment	Analytically-oriented approach		
		Banks [%]	**Assets [%]**	**Deposits [%]**		**Banks [%]**	**Assets [%]**	**Deposits [%]**
€500	Low interest (7 b.)	99.39	99.83	99.59	Low interest (15 b.)	98.70	99.78	99.52
	High Interest (5 b.)	99.57	99.83	99.60	High Interest (17 b.)	98.53	99.77	99.49
€1,000	Low interest (5 b.)	99.57	99,83	99.60	Low interest (15 b.)	98.70	99.78	99.52
	High interest (5 b.)	99.57	99.83	99.60	High interest (17 b.)	98.53	99.77	99.49
€3,000	Low interest (5 b.)	99.57	99.83	99.60	Low interest (15 b.)	98.70	99.78	99.52
	High interest (4 b.)	99.65	99.83	99.60	High interest (17 b.)	98.53	99.77	99.49
€10,000	Low interest (3 b.)	99.74	99.95	99.91	Low interest (15 b.)	98.70	99.78	99.52
	High interest (2 b.)	99.83	99.95	99.92	High interest (17 b.)	98.53	99.77	99.49

Table 7: The figures illustrate the coverage of banks for which convexity can be shown using three different measures: number of banks, share of assets relative to the entire sample of bank, share of deposits relative to the entire sample of banks. If a bank is not classified as convex, it simply means convexity could not be proven using the non-negative second main minor criterion..