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Liquidity Stress Testing with Second-Round Effects: Application to the Czech Banking Sector*

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Abstract

We build a macro stress-testing model for banks' market and funding liquidity risks with a survival period of one month. The model takes into account the impact of both bank-specific and market-wide scenarios and includes second-round effects of shocks due to banks' feedback reactions. The model has three phases: (i) the formation of a balance-sheet liquidity shortfall, (ii) the reaction of banks on financial markets, and (iii) the feedback effects of shocks, such as secondary deposit outflows for reacting banks and additional haircuts on securities. During each phase, we recount the liquidity buffer and examine whether banks hold a sufficiently large amount of liquid assets to be able to survive the liquidity tension in their balance sheets. The framework is applied to the Czech banking sector to illustrate typical calibrations and the impact on banks.

1. Introduction

The recent global financial crisis illustrated the importance of including liquidity risk within stress-testing frameworks, especially when the US bank Lehman Brothers went bankrupt in the fall of 2008 and many US and European banks were hit by severe funding shocks. Liquidity stress tests that had been occasionally applied before the crisis often used very mild shocks, underestimating the impact of a typical liquidity-crisis feedback loop between banks and markets that has the potential to considerably increase liquidity stress. The loop mechanics typically evolve as follows: a decline in funding liquidity (such as a systemic retail or wholesale bank run) would force banks to liquidate assets, effectively decreasing market liquidity and causing asset prices to fall. This would in turn affect liquidity buffers at all banks in the system, leading to a need to liquidate additional assets and causing further falls in asset prices and in market liquidity. Eventually, an initial mild liquidity shock can lead to a downward liquidity spiral (Brunnermeier and Pedersen, 2009; Geršl and Komárková, 2009).

Furthermore, stress testers have been criticized for conducting solvency and liquidity stress tests separately, with no link between them, although in reality shocks to solvency (increase in market and credit risk) and to liquidity are typically intertwined. This holds not only for system-wide shocks (such as a decline in the value

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of certain assets that are used as liquidity buffers, e.g. government bonds), but also for individual banks within the system, as banks that suffer high losses from market and credit risk would typically experience more severe bank runs.

This article describes a liquidity stress-testing framework that includes an adverse feedback loop.[1] The contribution of the article is in three areas. First, we show how to structure the stress-testing framework so that it overcomes the problem of the typical pre-crisis liquidity stress tests. We build a framework that includes endogenous reactions of banks (so-called feedback effects) to the first round of initial shocks, creating an additional wave of liquidity shocks in the second round. Our work was inspired by van den End (2008), Aikman *et al.* (2009) and Nier *et al.* (2008), who try to quantify the relationship between the value of assets held by banks in their liquidity buffers and market liquidity that gets impaired once the assets are liquidated in the market during periods of stress. Second, we show how solvency and liquidity stress-testing frameworks can be interlinked, similarly as in Aikman *et al.* (2009), so that a complete stress-testing exercise can encompass mutually consistent shocks to liquidity, market, credit and other risks. Third, the framework is applied to 2013 end-year data for the Czech banking sector to illustrate typical calibrations and the impact on banks. Many countries, especially in Central, Eastern and Southeastern Europe, share many similarities with the Czech banking sector and thus the selected calibration might offer a useful guidance for building modern liquidity stress tests for their sectors. We also test the robustness of our approach by altering selected assumptions and changing the shock calibration.

The Basel Committee of Banking Supervision (BCBS) has designed a new liquidity regulation within Basel III based on two measures—the Liquidity Coverage Ratio (LCR) and the Net Stable Funding Ratio (NSFR)—of which the former is in principle a liquidity stress test (BIS, 2010, later revised in BIS, 2013). While we do not explore how banks in the Czech Republic score on this new measure, as its introduction into regulatory practice happened in the EU only in 2015, we do compare some of the LCR parameters (such as deposit outflow rates) with our calibration. It should also be emphasized that the LCR neither assumes any haircuts on high-quality domestic government bonds (while we do) nor does it include any second-round effects.

As with any model, our model has some limitations. First, we do not take into account domino-type interbank contagion, which could happen in times of liquidity crises and bank runs provided that banks are interlinked through mutual exposures. However, our approach does feature a contagion mechanism within the second-round effects through common exposures of various institutions to the same asset class (such as government bonds). Second, the data used for simulations are reasonably granular, but still imperfect with respect to capturing the liquidity risks precisely.

The structure of the article is as follows: Section 2 briefly discusses the related literature. Section 3 is devoted to the methodology of liquidity stress testing, while Section 4 presents the data and simulations for the banks in the Czech Republic. Section 5 concludes the article.

[1] A variation of this model is used at the Czech National Bank (CNB), the central bank of the Czech Republic, for its annual top-down liquidity stress-testing exercise (CNB, 2014). The model presented here differs in several areas from the official CNB model and the results of our empirical simulations thus differ from the results in official CNB publications.

2. Related Literature

A number of studies investigate liquidity, liquidity risk and the market-banking liquidity relationship within the financial system. Nikolaou (2009) introduces various types of liquidity (funding, market and monetary) and explains the strong, complex and dynamic linkages among them. In normal times, these linkages promote a virtuous circle in financial system liquidity, guaranteeing the smooth functioning of the financial system. In turbulent times, the linkages remain strong but become propagation channels of liquidity risk in the financial system, leading to a vicious circle between low funding and low market liquidity. Adrian and Shin (2009) and Praet and Herzberg (2008) provide the theoretical and practical foundations for banks' market-banking liquidity relationship under stress—the mark-to-market effects on banks' balance sheets, which lead to a downward liquidity spiral in asset prices and contagious defaults of banks through market linkages. Similarly, Brunnermeier and Pedersen (2009) show that under certain conditions market and funding liquidity are mutually reinforcing and lead to liquidity spirals. They also empirically document that market liquidity can suddenly dry up, has commonality across securities, is related to volatility, and is subject to "flight to quality". Cifuentes *et al.* (2005), Nier *et al.* (2008) and IMF (2009) focus on additional channels through which liquidity risk can be spread across the whole system, namely through direct exposures among financial institutions. Liedorp *et al.* (2010) test interconnectedness in the interbank market as a channel through which banks affect each other's riskiness, showing that interbank funding exposures to other banks in the system exhibit significant spillovers.

Alternative liquidity stress-testing frameworks have been described in, for example, Ong and Cihak (2010) and Schmieder *et al.* (2011). Van den End (2008) includes second-round effects of market disturbances on banks that are determined by the number and size of reacting banks as well as by the similarity of reactions. Nier *et al.* (2008) and Aikman *et al.* (2009) analyze the relationship between asset prices and sales of assets by banks. Wong and Hui (2009) developed a stress-testing framework to assess the liquidity risk of banks, where liquidity and default risks can stem from the crystallization of market risk arising from a prolonged period of negative asset price shocks. They present three channels through which asset price shocks are transformed into banks' liquidity risk: (i) mark-to-market losses increase banks' default risk and induce deposit outflows; (ii) the ability to generate liquidity from asset sales evaporates due to the hampered market liquidity; and (iii) due to more stressful financial environments, the likelihood of drawdowns on banks' irrevocable commitments increases. IMF (2011) also presents a stress-testing framework for liquidity risk as a standard solvency stress test with an innovation in the form of an added systemic liquidity component. They analyze two channels for a systemic liquidity event—a frozen interbank money market due to higher counterparty and default risks or due to liquidity hoarding by banks and investors, and a fire sale of assets. The feedback effect is simulated by an attempt by banks to meet immediate obligations by selling assets, which affects the market liquidity of the assets, further tightening funding liquidity (through higher withdrawal rates). The solvency stress-testing framework of the CNB is discussed in detail in Geršl and Seidler (2012) and Geršl *et al.* (2013).

2. Methodology

In our article, we built upon the approach presented mainly in van den End (2008), but we develop it further. Our framework thus differs in many dimensions and fits better to the Czech banking sector (van den End's model was calibrated to the conditions of the Dutch banking system). First, van den End (2008) uses both stocks and flows data for his simulations, whereas, due to a lack of reported data, we rely only on stocks data. However, we do model a significant part of inflows and outflows based on a set of assumptions in line with the Basel III LCR. Second, while the shocks in van den End's first round are designed in the case of liquid assets as haircuts, our framework additionally takes into account an increase in the loan portfolio (also due to the use of credit lines), which increases the financing needs. Third, there are differences related to the assumptions regarding banks' reactions and the trigger for those reactions. In van den End (2008), the responses of banks to markets are triggered if the decline in the liquidity buffer after the first round of shocks breaches a predefined threshold, which is the same for all banks. The reactions are assumed to take the form of sales of tradable securities, the issuance of additional securities or the substitution of some assets or liabilities with other items. In our article, we do not allow any increase in the liability side of banks' balance sheets when banks react and our trigger for reactions by banks is endogenous—the banks are assumed to react and sell on markets when they run out of cash and receivables from the central bank, which may differ across banks. Fourth, in van den End (2008), the extent to which banks use particular instruments to react against shocks is determined by the relative importance of items on the balance sheet. Here, we assume a certain order of items that will be liquidated, which is based on the relative liquidity of the items and is the same for all banks. Fifth, we endogenize the market liquidity so that it is a function of the way banks react in the markets, while in van den End's paper the market liquidity was an exogeneously assumed parameter. Finally, the calibration of the second-round effects uses a different functional form, reflecting a smaller scale of tradable securities in banks' portfolios and thus an increased probability that most reactions will be concentrated in the domestic government bond market.

The methodology is useful for a top-down stress test using bank-level data at a reasonable granularity. It examines whether banks' liquidity buffer is sufficient in relation to liquidity shocks. It proceeds in three subsequent steps: (i) the formation of a balance-sheet liquidity shortfall (first round of shocks), (ii) the reaction of banks, and (iii) the feedback effects of shocks (second round of shocks). The stress test assumes a horizon of one month, similarly to the LCR.

The initial liquidity buffer LB_0 of each bank is defined as

$$LB_0 = \sum_{i=1}^{5} L_{Bi} \tag{1}$$

where i is a particular balance-sheet item, B is a particular bank and L is assets included in the liquidity buffer: (1) cash, (2) claims on the central bank (including required reserves), (3) short-term claims due within a particular time horizon, (4) domestic government bonds, and (5) foreign government bonds, all expressed in units of the domestic currency. We assume a relatively conservative definition of the liquidity buffer because no securities other than government bonds are included. While in principle banks could sell other securities (for example, covered bonds) in the market, there is no really liquid domestic market except the government bond market, so those securities are better treated as illiquid and subject to a considerable haircut if they need to be liquidated. This is our own definition of a liquidity buffer and it is not the same as the definition of the liquidity reserve (i.e. high-quality liquid assets) in the current regulatory framework centered around the LCR.

The inclusion of claims on the central bank into the liquidity buffer needs to reflect whether the central bank's policies and instruments allow them to be drawn down in times of stress. In the Czech Republic, a large part of these claims are due to collateralized reverse repo operations through which the CNB withdraws surplus liquidity in the banking sector. These operations have a two-week maturity and are organized three times a week, ensuring that banks have access to liquidity throughout the month as individual tranches mature and can thus be used as a buffer almost continuously. In the case of a liquidity mismatch, the CNB bills (not included in the buffer!) received as collateral can be used for intraday or O/N borrowing from the central bank against virtually zero haircut. The remaining part of the claims are required (about 2% of primary deposits) and voluntary reserves. Given that the CNB uses a 30-day averaging scheme for required reserves, banks can have the reserves at their disposal throughout the month, with the exception of the end-of-reserve-period day, on which they need to top up the account. However, they can borrow from the central bank O/N using the CNB bills. Our framework is flexible enough to change the assumption about the possible use of required reserves.

Banks hold the liquidity buffer to be able to provide liquidity on demand both to depositors (deposit withdrawals) and borrowers (drawdown of credit lines, extension of credit). Such assets—usually short-term and low-risk in nature—are costly to hold because they do not provide a high return compared with alternative uses of funds. Therefore, banks try to avoid holding a large amount of unnecessary low-return liquid assets. According to Kashyap *et al.* (2002), banks can hold the liquidity buffer at lower cost if depositors' need for liquidity is not strongly correlated with borrowers' need for liquidity. In other words, depositors are unlikely to withdraw funds from their accounts at the same time that firms are tapping bank credit lines. In fact, many studies have shown that during past episodes of market stress, the funds that investors pulled out of markets flowed primarily into the banking sector (Saidenberg *et al.*, 1999; Gatev *et al.*, 2009; Kashyap *et al.*, 2002), but argument broke down in the recent crisis. Mora (2010) shows that during the 2007–2009 crisis, the banks most vulnerable to liquidity drawdowns did not have bigger deposit inflows and had to rely more on other sources of borrowing (such as issuance of securities or wholesale funding) and liquid assets to fund commitments.[2]

3.1 The First Round of Shocks

The first round of liquidity stress includes five simultaneous shocks: (a) a bank run (deposit outflows); (b) falling prices of marketable securities (both government

[2] There are several reasons for banks not to hold adequate amounts of liquid assets (Banque de France, 2008): (i) liquidity is costly, (ii) liquidity shortages are very low-probability events, and (iii) there is a perception that central banks will step in and provide liquidity support if and when it is needed (the moral hazard argument).

securities and other securities); (c) pressure on the assets side to continue financing clients by means of drawdowns of credit lines and the necessity of rolling over a part of the loan portfolio; (d) drying-out of funding markets (impossibility of borrowing funds); and (e) a decrease in the value of short-term claims on clients (both banks and non-banks) due to deterioration of the creditworthiness of the counterparties. This combination of shocks is a typical feature of systemic liquidity crises and is in line with the setup of the LCR (BCBS, 2013). During the stress test, one can choose which shocks to use as well as their calibration.

A liquidity shortfall (R_1) is calculated as

$$R_1 = C*c + D*r + E*g \qquad \text{with } R_1 \geq 0 \tag{2}$$

where C represents the total committed credit lines in the off-balance sheet, with the parameter c being the rate of drawdown of those lines; D represents deposits with maturity of up to one month, with r being the average deposit withdrawal rate; and E represents the total loan portfolio, with g being the monthly credit growth of that portfolio.[3]

While most countries have deposit insurance schemes that cover up to 100% of deposits, there may still be a case for bank runs due to the following reasons: First, not all deposits are under the deposit insurance limit, and deposits over the limit are not explicitly guaranteed in the event of a bank failure. Second, there are fixed costs associated with extracting deposits from banks that fail. Third, depositors may worry that the deposit insurance fund will not be large enough in the event of a bank failure (Mora, 2010), especially if the government itself suffers from a loss of confidence.

A decline in the value of liquid marketable assets held in banks' balance sheets is additionally assumed, reflecting the impaired market liquidity resulting from increased uncertainty regarding the market value of some instruments (such as government bonds). Simultaneously, banks can only use a part of the short-term claims. This effectively decreases the available liquidity buffer LB_0 to LB_1:

$$LB_1 = \sum_{i=1}^{5} L_{Bi} * \left(1 - b_{1i}\right) \tag{3}$$

where b_{1i} is the haircut for the individual liquid assets in the buffer, with haircuts on cash (b_1) and claims on central banks (b_2) being always equal to zero. The decrease is also applied to instruments that are classified as held to maturity, which are normally not marked to market, as banks would need to sell them for the current prices (rather than for the book value) if they were to generate cash to cover their liquidity shortfall.

The next step is to compare the size of the liquidity shortfall (R_1) with the available (but already impaired) liquidity buffer (LB_1). If $LB_1 \geq R_1$, the bank survives the first round of shocks just with its liquidity buffer. Such a bank gradually starts liquidating its liquid assets to close the liquidity shortfall. Other banks that lack sufficient liquid assets must also liquidate less liquid (marketable) or illiquid (loan-

[3] One could also extend the deposit withdrawals for term deposits beyond one-month maturity. However, we assume that a liquidation of a term deposit is associated with a large penalty, thus depositors would start by withdrawing the demand and short-term deposits first.

type) assets. Such liquidation is usually very costly because less liquid and illiquid assets are often subject to large haircuts. This is because illiquid assets, such as the retail or corporate loan portfolio, are rarely traded and it can take more than a month to receive a good price for it. Due to their uniqueness, it could be difficult to find a market for these items and to determine what their fair value might be. To compensate for this uncertainty and illiquidity, the model assumes much larger haircuts on these illiquid assets compared to less liquid or liquid assets.

3.2 The Reaction of Banks

In general, all banks "react" during the first round to liquidity stress, but—depending on the calibration—some banks may only use cash or reduce their claims on the central bank or other short-term claims to cover the liquidity shortfall, with no impact on market liquidity. Other banks may need to sell some of their assets (such as government bonds) in the financial markets, which is what we mean by "reacting". The test assumes that all funding sources are shut off due to a freeze in both the short-term and long-term credit markets and an increase in banks' liabilities is thus excluded. The only permitted method banks can use is liquidation of assets.

In general, the banks' reaction is expressed by

$$\sum_{i=1}^{5} L_{Bi} * \left(1 - b_{1i}\right) * p_i + \sum_{i=6}^{9} I_{Bi} * \left(1 - b_{1i}\right) * q_i = R_1 \tag{4}$$

where L_{Bi} stands for the five assets in the liquidity buffers used to fund the liquidity shortfall, while I_{Bi} stands for other assets, i.e. assets outside the liquidity buffer. The latter include two less liquid but still marketable assets (other bonds including covered bonds and equity instruments) and two illiquid assets (claims with maturities over the maturity horizon and other assets such as fixed assets). The b_{1i} are the haircuts for the individual assets with which banks can react, whereby for illiquid assets such as loan portfolios the haircuts are applied only if they are liquidated to cover the liquidity shortfall.

The degree to which the individual assets are liquidated is captured by the proportion ratios p_i and q_i, which are between 0% and 100%. It is assumed that for their reaction banks first use assets included in the liquidity buffer and—should the buffer not be sufficient—subsequently other available assets. We assume that banks rank assets according to their liquidity and would use them also in this order: cash, claims on the central bank, claims on demand, domestic government bonds, claims due within a horizon (other than on demand), foreign government bonds, and remaining assets not belonging to the liquidity buffer—the two less liquid assets (other bonds and equity instruments) and the two illiquid assets (long-term loans and other assets). In total, there are nine broad balance sheet items with which banks can react—five within the buffer and four outside it.

The haircuts b_{1i} are determined exogenously as parameters of the test. the variables p_i and q_i are determined endogenously within the framework and can be either 100% (for those items used entirely to cover the shortfall), a number between 0% and 100% for the one particular item (be it within or outside the liquidity buffer) that is the last item used to cover the shortfall, and 0% for the remaining asset items down the liquidity ladder.

The banks' response will close the liquidity shortfall, depleting their liquidity buffers to the level of LB_2:

$$LB_2 = LB_1 - \sum_{i=1}^{5} L_{Bi} * (1 - b_{1i}) * p_i = \sum_{i=1}^{5} L_{Bi} * (1 - b_{1i}) * (1 - p_i) \tag{5}$$

However, this will simultaneously lead to a second round of shocks through two channels. First, it causes systemic risk through the simultaneous response of the banks on the financial markets and, second, it increases the reputational risk of each responding bank. The increase in these two risks feeds back to the banks' balance sheets, creating a feedback effect.

As to the systemic risk, an idiosyncratic liquidity shock[4] concerning a single bank can very quickly spread to others through the high degree of market and balance-sheet interconnectedness. In order to generate the required cash, a single bank has to sell assets, which may start weighing on prices. Other market participants who have followed similar trading strategies may also begin selling, but this may be widely anticipated by the rest of the market, which has little incentive to be on the buying side. As a result, liquidity providers close their positions, waiting for the inventory to be wound down and triggering sharp falls in the prices of instruments (Praet and Herzberg, 2008). A similar episode is simulated in the framework as excessive one-sided pressure from banks on the financial market (e.g. all banks want to sell bonds), which leads to an additional decline in market liquidity and thus an additional decrease in the market value of liquidated assets.

A bank's reputational risk consists of signaling its liquidity problems. Banks do not usually like offering over-the-odds (a premium) for trading in the market, as this could advertise their weakness, known as the stigma effect (Goodhart, 2008). Armantier *et al.* (2011) provided empirical evidence for the existence, magnitude and economic impact of the stigma associated with discount window liquidity provision by the Federal Reserve. They found, *inter alia*, that during the height of the 2007–2010 crisis, banks faced higher borrowing rates the day after borrowing from the discount window, as they suffered from a special stigma premium. In our model, we assume that the reputational risk materializes in additional deposit outflows for banks that signal liquidity problems by selling in the markets.

3.3 Feedback Effects and the Second Round of Shocks

The third step of the methodology involves calculation and application of the second round of shocks stemming from the market reaction of banks to the first round of shocks. The systemic risk has a feedback impact on the liquidity buffer items as well as on the other assets outside the buffer through a decline of market liquidity in various financial markets and a decrease in asset prices, leading to larger haircuts b_{2i}. These affect all banks (i.e. also those which did not react by selling) due to the systemic effects via the decreased market liquidity and are calculated as:

$$b_{2i} = b_{1i} + (1 - b_{1i}) * \frac{1}{2} \ln(1 + F_i) \qquad \text{where } F_i \in \langle 0,1 \rangle \tag{6}$$

[4] Such as losses in a particular activity, a hedge that has gone wrong and operational problems leading to higher demand for cash (Brunnermeier and Pedersen, 2009).

The larger haircuts are calculated for all six types of assets with which banks can react, both within and outside the buffer (leaving aside cash, balances with the central bank and short-term claims). This leads to a decline of the liquidity buffer to the level of LB_3:

$$LB_3 = \sum_{i=1}^{5} L_{Bi} * \left(1 - b_{2i}\right) * \left(1 - p_i\right), \quad b_{2i} \geq b_{1i} \tag{7}$$

We assume that all marketable items in the liquidity buffer (i.e. both types of government bonds) need to be repriced by the new haircuts, while assets outside the liquidity buffer are repriced only if they are securities (the two types of less liquid assets—other bonds and equities). This means that if a bank covers the initial liquidity shortfall by selling illiquid assets such as a portfolio of loans, the part sold would be subject to the haircut b_{1i} and the part retained would still be booked on the balance sheet at its original book value. However, should an additional liquidity shortfall occur (such as additional deposit outflows), the bank would be able to sell the remaining part of the loan portfolio only with the original extended haircut b_{2i}, which may reflect several banks selling those illiquid assets during the reaction phase with downward pressure on their price. Moreover, this extended haircut would also affect all other banks should they decide to sell their illiquid assets.

The factor F_i reflects the feedback effect through the systemic risk. We assume that F_i for a particular asset is larger (i.e. the market liquidity in that particular segment is lower) if (i) more banks react in the markets by selling this asset, (ii) the total amount liquidated in that market is large, (iii) reactions on the markets are more similar, i.e. banks are concentrated in one market, for example. For all three of these factors, we construct indicators with values between zero and one and calculate the factor F as an average of these indicators. The concrete variables are (i) the number of banks reacting in the particular market out of all banks; (ii) the total volume sold in that market by all banks as a ratio of the volume of this asset held by all banks; (iii) the total volume sold in that market by all banks as a ratio of the total volumes sold in all markets in which banks react.

The feedback effect stretches the original haircut. The selected logarithmical form and the use of the parameter 0.5, which decreases the sensitivity of prices to sales, ensures that even if F_i is equal to one, the new haircut would reach a reasonable number below 100% (for example, if the initial haircut is 50%, the maximum new haircut is 67%; if the haircut is 25%, the new one is 50%, i.e. doubling the original value). If F_i is equal to zero (for example if no bank reacts with the given asset), the new haircut is equal to the initial haircut.

A bank that reacts in order to fund its liquidity shortfall faces reputational risk in terms of second-round deposit withdrawals. The withdrawal rate is bank-specific and linked to the intensity of the reaction—the more a bank sells off its assets in the markets, the higher second-round withdrawal rate it faces. More specifically, we set the upper bound U for the withdrawal rate and assume that the bank with the highest ratio of its sales to its total assets will face the withdrawal rate equal to the upper bound, with rates for other banks being set up proportionately to the most active bank.

Given that the additional withdrawals create yet another liquidity shortfall for the reacting banks, we let those banks react again in the second round (in the same way as in the first round) and liquidate their remaining assets to close the new liquidity gap, albeit now at the increased haircuts b_{2i}. This leads to a final liquidity buffer after the second-round reactions LB_4, which is lower than LB_3 for reacting banks (unless it was already depleted in the first round) and equal to LB_3 for banks that did not react and thus did not face the reputation risk. We stop after the second-round reactions, but, in principle, one could continue with the third- and higher-round effects, given the expected impact of the second-round reactions on market prices.

4. Application of the Model to the Czech Banking Sector

The Czech banking sector features relatively high liquidity. The loan-to-deposit ratio is comfortably below 100% and one of the lowest in the EU. Banks hold the rest of their assets mainly in the form of government bonds, short-term interbank deposits and deposits in the central bank. Thus, rather than providing liquidity to the banking system, the Czech National Bank absorbs liquidity via its open market operations. A specific segment of the banking sector is building societies, which collect deposits under specific and legally regulated building savings plans and use the funds to grant housing loans. By design, the liquidity risk of these institutions should be mitigated by the relatively long maturity of their liabilities (usually five- to six-year savings contracts where the minimum period of the term deposit is five or six years) matched to long-term assets (the housing loans arising from these contracts). However, past developments have aggravated liquidity risk in this segment, as most of the savings contracts have run beyond the minimum number of years and are thus redeemable with a three-month notice period. However, they are not vulnerable to liquidity risk at the one-month horizon.

We used end-2013 data on both on-balance and selected off-balance sheet items (committed credit lines) reported to the CNB for all 23 banks incorporated in the Czech Republic (i.e. excluding branches of foreign banks) to run simulations within the described framework.

Table 1 shows selected distributional characteristics of the initial liquidity buffer (expressed as a percentage of assets) and its composition of various items among the banks. *Table 2* shows the buffer size and its composition for the banking sector as a whole and its various segments (large banks, medium-sized banks, small banks and building societies).[5]

The aggregate initial liquidity buffer was about 37% of total banking sector assets at the end of 2013 and was mostly composed of domestic government bonds and claims on the central bank. However, the relevance of the various items differs among banks. For example, small banks and building societies hold more than a half of their liquidity buffers in government bonds, whereas claims on the central bank are the most important item in the buffers of medium-sized banks.

We have run several scenarios. The first one is designed following the typical CNB calibration as reported in its Financial Stability Reports (CNB, 2014) as well as the calibration of the Basel III LCR (*Main Scenario*). For this one, we also illustrate how to link selected parameters of the liquidity stress test with the results of a solvency stress test. The second one is a very severe scenario modelled in line with

[5] The definition and assignment of individual banks into the four segments follows the official CNB classification.

Table 1 Composition of Czech Banks' Liquidity Buffers (in % of assets, end-2013)

	Min	25th percentile	Median	Mean	75th percentile	Max
Liquidity buffer	2.5	24.0	32.5	35.1	43.4	85.4
Cash	0.0	0.0	0.1	0.6	0.8	2.3
Claims on central bank	0.0	2.4	7.6	12.5	17.2	67.9
Short-term claims	0.5	3.3	6.2	6.9	9.8	20.2
Czech government bonds	0.0	7.2	11.1	14.2	18.2	38.7
Other government bonds	0.0	0.0	0.0	0.9	2.0	3.4

Source: Authors' calculations based on CNB data.

Table 2 Composition of Liquidity Buffers for the Main Segments (in % of assets, end-2013)

	Banking sector	Large banks	Medium-sized banks	Small banks	Building societies
Liquidity buffer	36.7	39.7	32.9	37.6	20.5
Cash	0.8	1.2	0.6	0.6	0.0
Claims on central bank	10.2	13.6	13.4	9.6	2.2
Short-term claims	5.4	6.3	8.7	4.9	4.4
Czech government bonds	12.6	16.7	9.8	21.1	14.0
Other government bonds	1.1	1.9	0.4	1.3	0.0

the harsher values of parameters in the Basel III LCR as well as in line with selected country-level experience (*Severe Scenario*). Finally, the remaining scenarios reflect "reverse stress tests"—these are selected scenarios that would bring the banking sector down, which we define as a situation in which banks with at least 50% of the sector's assets would completely deplete their liquidity buffers.

Table 3 shows the parameters of the two scenarios in comparison with the recommended LCR calibration. The parameters of the *Main Scenario* are in line with the LCR calibration, taking into account that the majority of deposits in the Czech banking sector are retail deposits and most credit lines are granted to non-financial corporations. This scenario is harsher on the initial haircut for government bonds as well as other bonds because, out of the private bonds, Czech banks usually hold covered bonds.

The parameters for the *Severe Scenario* are harsher along all dimensions and go largely beyond the LCR calibration in several areas (such as government bonds). This is before the second-round effects hit the banks in our model.

Two parameters of the *Main Scenario*—the deposit withdrawal rate and haircut on assets sold before maturity (long-term loans and fixed assets)—are linked to the results for individual banks in the most adverse scenario in the solvency stress tests conducted by the CNB (CNB 2014), in line with the CNB practice. *Table 4* shows how we arrived at the calibration. The underlying intuition is that banks that incurred accounting losses in the solvency stress test face a greater deposit outflow than profitable banks. In sales of illiquid assets, account is taken of the quality of the bank's loans as measured by the overall credit portfolio risk costs.[6]

[6] Risk costs are calculated as new net provisions expected within a year over the stock of performing loans.

Table 3 Calibration of the Scenarios

	Parameter	Main Scenario	Severe Scenario	LCR calibration
Deposit withdrawal rate (average for banks)	r	11%	20%	3% – 10% for retail deposits 5% – 100% for wholesale deposits
Drawdown of credit lines	c	10%	20%	5% for retail customers 10% for corporations and sovereigns 40% for financial institutions 100% for securities firms and SPVs
Credit growth (excluding loans from credit lines)	g	5%	10%	50% of claims on non-financial clients with maturity of up to one month (roughly 4% credit growth for the Czech banking sector)
Share of short-term claims that will become unavailable	b_3	20%	40%	depends on what part of claims becomes non-performing
Initial haircut on Czech government bonds	b_4	25%	40%	0%
Initial haircut on other government bonds	b_5	30%	50%	0% – 15% depending on the credit quality of the sovereign
Initial haircut on other bonds (outside the liquidity buffer)	b_6	30%	50%	15% for covered bonds and corporate bonds with credit rating AA- and higher 25% for mortgage-backed securities with credit rating AA and higher 50% for corporate bonds with rating between A+ and BBB-
Initial haircut on equity instruments (outside the liquidity buffer)	b_7	30%	50%	50%
Haircut on long-term loans if sold before maturity (average for banks)	b_8	49%	60%	…..
Haircut on fixed assets if sold	b_9	49%	60%	…..

Source:Authors calculations.

Table 4 Calibration of the Deposit Withdrawal Rate and Haircuts on Loans and Fixed Assets

Estimated Return on Assets	Deposit Withdrawal Rate
< -2%	15%
-2% – -1%	13%
-1% – 0%	11%
0% – 1%	9%
1% – 2%	7%
> 2%	5%
Estimated risk costs	**Haircut on loans and fixed assets sold before maturity**
< 1%	25%
1% – 2%	45%
2% – 3%	55%
> 3%	65%

Source: Authors' calculations.

Figure 1 shows the evolution of the liquidity buffer for the banking sector as a whole from LB_0 to LB_4 in the *Main Scenario*. The initial haircuts decrease the liquidity buffer from 36.7% of assets to 29.2%, and banks were hit by a liquidity shortfall of about 8% of assets (deposit withdrawals, extension of credit and materialization of a part of credit lines). Banks used a part of their buffer to close the liquidity shortfall, decreasing the liquidity buffer to the level of 24.9%. The reactions caused second-round systemic effects in terms of larger haircuts on securities. After repricing with higher haircuts, the liquidity buffer further declined to 23.2%. A total of 11 reacting banks were hit by second-round deposit withdrawals due to reputational effects (with the upper-bound parameter of second-round withdrawal rate U set to 10%, i.e. the bank that had to sell the largest proportion of its assets faced a 10% withdrawal rate and other banks proportionately lower rates), causing an additional yet not very large shortfall of about 0.3% of assets. After the reacting banks closed this shortfall by selling additional assets, the final liquidity buffer slightly declined to 23% of assets. Two banks (with a roughly 6% share in the total assets of the banking sector) fully exhausted their liquidity buffers.

Figure 2 depicts the evolution of the liquidity buffer for the banking sector for the *Severe Scenario*.

The overall liquidity buffer declines to the level of 9.5% after all rounds of shocks, with 17 reacting banks being hit by second-round deposit withdrawals due to reputational effects, causing an additional liquidity shortfall of -1.5% (with an unchanged upper-bound parameter U of 10%). In this scenario, ten banks (with a roughly 30% share in the total assets of the banking sector) fully exhausted their liquidity buffers.

Detailed results for both scenarios by bank segments are included in the *Annex*. Overall, both scenarios support the high degree of resilience of Czech banks to liquidity shocks, although there are a couple of banks that are more sensitive to liquidity stress. These banks usually start with much lower liquidity buffers and very often rely on a specific business model, for example focusing on a particular customer

Figure 1 Evolution of the Liquidity Buffer in the Main Scenario (%; share in total assets)

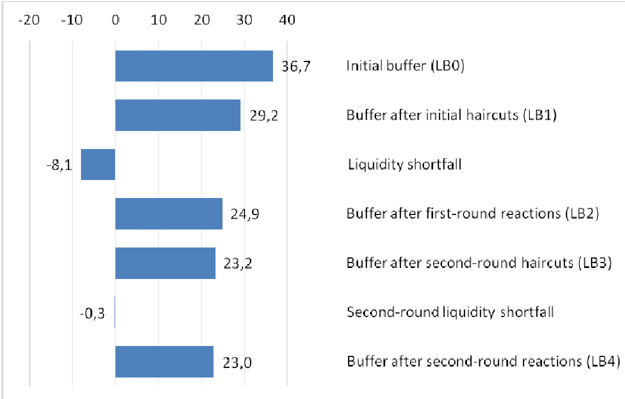
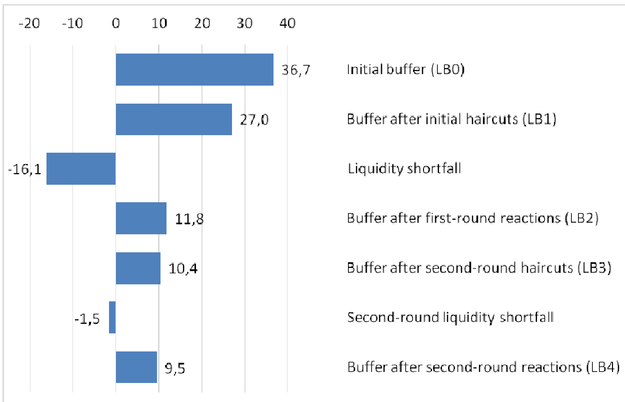


Figure 2 Evolution of the Liquidity Buffer in the Severe Scenario (%; share in total assets)



segment or type of loans. Typically, these banks are usually part of larger banking groups, so that potential liquidity stress could be mitigated by emergency liquidity support from the group.

Table 5 compares the initial and second-round haircuts on securities and other assets for both scenarios. Clearly, government bonds are, by definition, the asset with which banks react first after using cash and claims on the central bank, so there is an excess supply of bonds leading to an extended haircut. This increases from 25% to 39% in the *Main Scenario* and from 40% to 56% in the *Severe Scenario*.

Finally, we ran a "reverse stress test", i.e. we looked for a set of scenarios that would bring down the whole banking sector. We define the point at which the banking sector is "down" as a situation in which banks with at least 50% of the banking sector assets have fully depleted their liquidity buffers. As there can be many scenarios that lead to such an outcome, we present a few of them. We start with the *Severe Scenario* and adjust the parameters on (a) initial deposit withdrawals,

Table 5 Initial vs. Second-Round Haircuts

	Parameter	Main Scenario		Severe Scenario	
		Initial haircut	New haircut after reactions	Initial haircut	New haircut after reactions
Haircut on Czech government bonds	b_4	25%	39%	40%	56%
Haircut on other government bonds	b_5	30%	30%	50%	52%
Haircut on other bonds (outside the liquidity buffer)	b_6	30%	31%	50%	52%
Haircut on equity instruments (outside the liquidity buffer)	b_7	30%	30%	50%	51%
Haircut on long-term loans if sold before maturity (average for banks)	b_8	49%	51%	60%	63%
Haircut on fixed assets if sold	b_9	49%	49%	60%	60%

Table 6 Scenarios from the Reverse Stress Test

	Parameter	Scenario I	Scenario II	Scenario III	Scenario IV
Deposit withdrawal rate (average for banks)	r	**25%**	20%	20%	20%
Drawdown of credit lines	c	20%	**50%**	20%	20%
Credit growth (excluding loans from credit lines)	g	10%	10%	10%	10%
Share of short-term claims that will become unavailable	b_3	40%	40%	**85%**	40%
Initial haircut on Czech government bonds	b_4	40%	40%	40%	**50%**
Initial haircut on other government bonds	b_5	50%	50%	50%	50%
Initial haircut on other bonds (outside the liquidity buffer)	b_6	50%	50%	50%	50%
Initial haircut on equity instruments (outside the liquidity buffer)	b_7	50%	50%	50%	50%
Haircut on long-term loans if sold before maturity (average for banks)	b_8	60%	60%	60%	60%
Haircut on fixed assets if sold	b_9	60%	60%	60%	60%

(b) drawdown of credit lines, (c) share of short-term claims unavailable, and (d) initial haircuts on domestic government bonds to bring down the banking sector's liquidity. *Table 6* shows such scenarios, with the parameters that were manipulated *vis-à-vis* the *Severe Scenario* in the bold printed cells. Along many dimensions, these sets of parameters comprise very harsh liquidity stress scenarios with a very low probability, corroborating the strong resilience of the Czech banking sector against liquidity tensions.

5. Conclusion

This article described a liquidity stress-testing framework with an endogenous adverse feedback loop. The pre-crisis stress-testing frameworks very often neglected the feedback effects due to the reaction of banks to initial shocks and thus underestimated the extent of liquidity stress. Our framework captures endogenous reactions of banks to the first round of initial shocks in terms of selling securities in the markets, thus creating an additional wave of liquidity shocks via a decrease in market liquidity in the second round. These additional liquidity shocks come in two forms—as additional haircuts on marketable securities due to systemic risk and as additional deposit withdrawals for reacting banks due to reputational risk. We also show how solvency and liquidity stress-testing frameworks can be interlinked, so that a complete stress-testing exercise can encompass mutually consistent shocks to liquidity, market, credit and other risks. A lack of this link was another failure of the pre-crisis stress-testing models.

We apply our approach on all 23 banks incorporated in the Czech Republic, using 2013 end-year data on both on-balance and selected off-balance sheet items. The Czech Republic is a small open economy with banking sector assets of around 130% of GDP, with a relatively strong liquidity profile demonstrated by low loan-to-deposit ratios and surplus liquidity, which is regularly withdrawn from the market *via* central bank operations. We used two basic scenarios—the *Main Scenario*, calibrated in line with the Czech National Bank's usual scenarios and in line with the Basel III Liquidity Coverage Ratio parameters, and the *Severe Scenario*, calibrated as a very harsh stress test. We also ran a so-called reverse stress test, looking for scenarios that would bring down the whole banking sector, which we defined as a situation in which banks with at least a 50% share of the sector's total assets completely deplete their liquidity buffers.

The outcomes of the model showed that the Czech banking system as a whole seems to be resilient against liquidity shocks. However, we were able to find harsh scenarios where a number of banks lost their initial liquidity buffers, partly also due to the second-round effects. This proves that even in a banking sector with sufficient liquidity as a whole, there is heterogeneity among banks and thus a potential for liquidity shocks to spread through the system via feedback effects.

ANNEX

Table A1 Results for the Scenarios by Segments of Banks (in % of assets)

Main Scenario	**Large banks**	**Medium-sized banks**	**Small banks**	**Building societies**	**Banking sector**
Initial buffer (LB0)	39.7	32.9	37.6	20.5	36.7
Buffer after initial haircuts (LB1)	36.9	30.5	33.6	17.7	29.2
Liquidity shortfall	10.6	8.9	15.2	3.7	8.1
Buffer after first-round reactions (LB2)	27.6	23.3	20.1	13.7	24.9
Buffer after second-round haircuts (LB3)	25.6	22.5	18.2	12.2	23.2
Second-round liquidity shortfall	0.0	0.7	4.1	0.0	0.3
Buffer after second-round reactions (LB4)	25.6	21.9	15.2	12.2	23.0
Severe Scenario	**Large banks**	**Medium-sized banks**	**Small banks**	**Building societies**	**Banking sector**
Initial buffer (LB0)	39.7	32.9	37.6	20.5	36.7
Buffer after initial haircuts (LB1)	34.7	28.4	30.6	15.5	27.0
Liquidity shortfall	21.3	18.0	24.2	7.8	16.1
Buffer after first-round reactions (LB2)	12.2	13.7	8.9	6.9	11.8
Buffer after second-round haircuts (LB3)	10.6	12.9	7.6	5.8	10.4
Second-round liquidity shortfall	1.8	1.1	6.2	0.0	1.5
Buffer after second-round reactions (LB4)	9.2	13.1	5.8	5.8	9.5

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