Bank Recapitalizations, Credit Supply, and the Transmission of Monetary Policy*

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Abstract

We integrate a banking sector in a standard New-Keynesian DSGE model, and examine how government policies to recapitalize banks after a crisis affect the supply of credit and the transmission of monetary policy. We examine two types of recapitalizations: immediate and delayed ones. In the steady state, both policies cause the banking sector to charge inefficiently low lending rates, which leads to an inefficiently large capital stock. Raising bank equity requirements reduces this dynamic inefficiency and increases social welfare. After the banking sector suffered large losses, a delay in recapitalizations creates banking sector debt-overhang. This debt-overhang leads to inefficiently high lending rates, which reduces the supply of credit and weakens the transmission of monetary policy to inflation (the transmission to output is largely unchanged). The welfare effect of raising bank equity requirements may then become negative. Overall, our analysis shows that different bank recapitalization policies may have considerable macro-economic implications.

Keywords: bank recapitalizations, credit supply, monetary policy transmission, bank equity requirements, NK-DSGE models.
JEL Classification: E30, E44, E52, E61.

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1 Introduction

One decade after the banking crisis of 2007-08, the recovery of bank credit supply in the euro area remains sluggish despite ongoing monetary accommodation. At the same time, bank credit supply in the U.S. has recovered much stronger. One major difference between the U.S. and the euro area was the policy response to undercapitalized banks. Following the crisis, U.S. authorities intervened rather swiftly to recapitalize the banking sector. By contrast, the recapitalization of the banking sector in the euro area was delayed by the sovereign debt crisis, and suffered from limited coordination at the European level.[1] While it seems plausible that different bank recapitalization policies lead to different economic outcomes, macro-economic models typically do not put these policies at the center stage. We fill this gap in the literature by developing a macro-economic model to analyze how immediate versus delayed bank recapitalizations after a crisis affect the supply of credit and the transmission of monetary policy.

We augment a New-Keynesian DSGE framework with a banking sector that issues equity and deposits to households and makes loans to capital producers.[2] The key friction that we build into the banking sector is a recapitalization that is received from the government if a negative productivity shock causes the income on loans to be insufficient to fully repay the deposits (the recapitalization is financed with a lump sum tax on the household). We refer to this difference between loan income and deposits as a *shortfall*. The government may either recapitalize the banking sector immediately after a shortfall, or with a delay of one period. Both recapitalization policies ensure that the depositors will always be fully repaid, so that the bank never defaults. In case of a delayed recapitalization, the profits made by the banking sector after a shortfall reduce the size of the recapitalization that will be received in the next period. Whether the government responds to a shortfall with an immediate recapitalization or with a delayed one is determined exogenously.[3]

We solve the model numerically and show that under both types of recapitalization policies, the banking sector charges inefficiently low lending rates in the steady state. These low lending rates reflect that the expected value of a future recapitalization effectively constitutes a subsidy, which the (competitive) banking sector passes on to its borrowers. Both recapitalization policies therefore

[1] In 2009, the largest U.S. banks were required by regulators to participate in the supervisory capital assessment program. As a part of this program, banks had to participate in a stress test to evaluate the adequacy of their capital buffers, and those banks that failed the test were forced to recapitalize. At the start of the European banking union in 2014, European banks were subject to a similar exercise as the European Central Bank published the results of its asset quality review.

[2] The structure of our model is similar to that of Smets and Wouters (2007), although we abstain from most of the real and nominal rigidities in order to isolate the effect of recapitalization policies. To analyze monetary policy, we retain price rigidities and persistence of the monetary policy interest rate.

[3] We focus on the timing of recapitalizations, immediate or delayed, and do not analyze other aspects such as their motivation or design. In practice, governments may choose to recapitalize large banks in distress because it considers them to be too-big-to-fail (e.g., O'hara and Shaw, 1990), or it may recapitalize smaller banks in distress because they are considered to be with too-many-to-fail (e.g., Acharya and Yorulmazer, 2007). Mariathasan and Merrouche (2012) find that recapitalizations are more successful if they are designed to increase common equity and are sufficiently large. Phillippon and Schnabel (2009) suggest to add warrants and conditions that limit moral hazard.

lead to over-lending and an inefficiently large capital stock. The effects of government safety nets on bank behavior have received ample attention in the literature, see, for example, Merton (1977), Kareken and Wallace (1978), Dam and Koetter (2012), Farhi and Tirole (2012) and Admati et al. (2013). Our model shows that lending rates decline by more if the banking sector expects to receive an immediate instead of a delayed recapitalization after a shortfall (as the former constitutes a larger subsidy). The extent of over-lending is also larger when expected future shortfalls are larger, which is the case when bank equity requirements are lower and when total factor productivity is more volatile.

The main contribution of the paper is to show that during the period in between a shortfall and a recapitalization, the banking sector effectively suffers from debt-overhang. In its classic form, debt-overhang describes the problem where a firm under-invests because the income on new investments is at least partially appropriated by its pre-existing debtholders instead of by its equityholders (Myers, 1977). In the context of the banking sector, the literature shows that pre-existing debt may render undercapitalized banks reluctant to issue new equity and may distort their lending decisions (e.g., Hanson et al., 2011, Thakor, 2014, Bahaj and Malherbe, 2016, Occhino, 2017 and Admati et al., 2018). In practice, however, banking sectors are less likely to suffer from debt-overhang in the traditional sense, as most bank debt is of short-maturity so that pre-existing debt claims are relatively small. Still, our model shows that a debt-overhang problem may arise during the period in between a shortfall and a recapitalization. The reason is that part of the income on new lending is effectively appropriated by the government, as this income reduces the expected value of the recapitalization that will be received in the next period. During the period in between a shortfall and a recapitalization, the banking sector therefore charges inefficiently high lending rates, which implies a reduction in the supply of credit.

The debt-overhang in the banking sector during the period in between a shortfall and a recapitalization also affects the transmission of monetary policy to bank lending rates.[4] An increase in the policy rate causes the banking sector to increase its lending rate more than one-for-one.[5] The reason is that part of the higher interest income on loans will be appropriated by the government and therefore cannot be used to cover the higher interest expenses on deposits. This effect results in a spread between lending rates and deposit rates, as in Goodfriend and McCallum (2007), Gerali et al. (2010), Gertler and Karadi (2011) and Curdia and Woodford (2016). The result is a weakened transmission of changes in the policy rate to inflation (and a largely unchanged transmission to output). This weaker transmission reflects that an increase in the policy rate, for example, leads to

[4]Monetary policy may affect bank lending rates through its impact on reserves (e.g., Bernanke and Blinder, 1988 and Kashyap and Stein, 1994), on equity (e.g., Van den Heuvel, 2002), and on risk-taking (Borio and Zhu, 2012). We do not model these channels, but follow the literature by letting the central bank directly set the interest rate on bank deposits. See Beck, Colciago and Pfajfar (2014) for a review of DSGE models that explore the role of financial intermediaries in monetary policy transmission.

[5]Gambacorta and Shin (2018) show empirically that the lending behavior of weakly capitalized banks responds more strongly to monetary policy.

a larger increase in the bank lending rate (the marginal cost of capital), and thereby exerts more upward pressure on firm prices and inflation.[6] The net effect on inflation remains negative due to the decline in wages (the marginal cost of labor), but less so than when the banking sector would not have suffered from debt-overhang.

A key property of our model is that higher bank equity requirements increase social welfare (by reducing dynamic inefficiency), even though equity requirements are privately costly for the banking sector.[7] We illustrate this property by numerically analyzing the transition dynamics associated with raising bank equity requirements (see also Meh and Moran, 2010, Angelini et al., 2014, Clerc at al., 2015, Nguyen (2015), and Mendicino et al. (2018)). In the steady state, higher equity requirements reduce the probability of future shortfalls and thereby reduce the expected value of future recapitalizations. Raising equity requirements therefore causes the banking sector to increase its lending rate, which reduces investment and output. Lifetime utility increases, however, as consumption and leisure increase in the short run before they arrive at their lower steady state values. The positive effect on lifetime utility is smaller, and may even be negative, when equity requirements are raised during the period in between a shortfall and a recapitalization. During this period the banking sector charges inefficiently high lending rates, which is aggravated by an increase in equity requirements. Hence, the welfare effects of increases in bank equity requirements may be modified by the timing of bank recapitalizations.

Our model is part of a broader class of DSGE models that focuses on how financial frictions interact with macroeconomic fluctuations, which builds on seminal contributions by Kiyotaki and Moore (1997) and Bernanke, Gertler and Gilchrist (1999). The incorporation of financial intermediaries in DSGE models is more recent, with key contributions by, amongst others, Goodfriend and McCallum (2007), Gerali et al. (2010), Gertler and Kiyotaki (2010), Gertler and Karadi (2011), Angeloni and Faia (2013), and Brunnermeier and Sannikov (2014). A typical source of amplification and propagation in such models is that banks cannot issue outside equity, but accumulate equity slowly through retaining earnings. We drop this assumption by allowing for outside equity, which ensures that the banking sector adds no dynamics to our model other than through the role of government recapitalization policies. This approach enables us to isolate the effect of recapitalization policies on the supply of bank credit and on the transmission of monetary policy. On the other hand, this parsimonious setup precludes us from analyzing how recapitalization policies interact with heterogeneity at the bank level (e.g., with respect to market power or risk profile) or with unconventional monetary policy. Analyzing these interactions would require a more enriched model of the banking sector and of the central bank, but this would be another paper.

[6] The positive effect of an increase in the nominal monetary policy interest rate on the marginal cost of capital is known as the cost channel of monetary transmission. Empirical evidence on the role of this channel for the effect of monetary policy on inflation is provided by, for example, Barth and Ramey (2001), Ravenna and Walsh (2006), Gaiotti and Secchi (2006), and Chowdhury, Hoffmann and Schabert (2006).

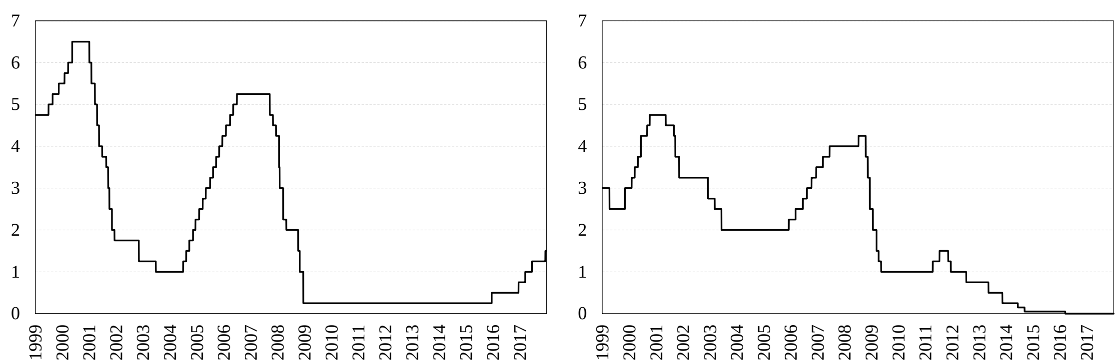
[7] Admati et al. (2013) emphasize the need to distinguish between the private and social costs of bank equity requirements.

The remainder of the paper is organized as follows. Section 2 discusses some stylized facts that motivate our analysis. Section 3 first models a banking sector without frictions, and then extends this benchmark with bank recapitalizations by the government. Section 4 calibrates the model, the section thereafter analyzes its properties, and the final section concludes. The Appendices describe the entire model and provide some auxiliary derivations.

2 Motivation

In response to the banking crisis of 2007-08, central banks aggressively reduced their monetary policy interest rates. Figure 1 illustrates that between September 2007 and the end of 2009, the U.S. Federal Reserve System (Fed) reduced its target interest rate by as much as five percentage points, until it arrived at the zero lower bound. About one year later, the European Central Bank (ECB) reduced its target interest rate as well, which fell by 3 percentage points in less than one year. The European sovereign debt crisis of 2010-12 and the ensuing recession then prompted a further decline in the ECB's interest rate, which arrived at the zero lower bound by the end of 2014. The ECB kept its interest rate at this low level until the end of 2017, while the Fed started to increase its interest rate from the end of 2015 onwards.

Figure 1: Monetary policy interest rates in the U.S. and EMU



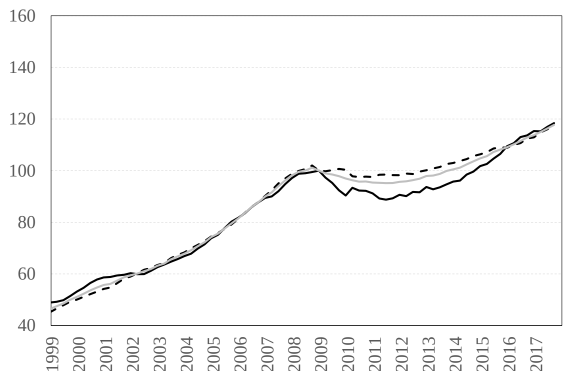
(a) United States

(b) Euro area

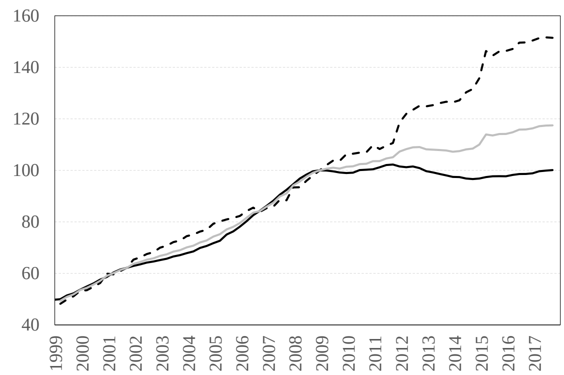
Note: the left panel displays the official target interest rate set by the United States Federal Reserve System, the right panel displays the target interest rate set by the European System of Central Banks. Source: Fed and ECB.

An important channel through which a reduction in central bank interest rates stimulates economic activity, is through its impact on the funding costs of banks. A decline in their funding costs enables banks to lower their lending rates, which increases the supply of credit and stimulates investment. Figure 2 illustrates how bank credit supplied to the non-financial private sector developed around the crisis (non-bank and total credit are shown for comparison). In the U.S. as well as in the euro area, the stock of bank credit reached a local maximum by the end of 2008. Until then, bank credit had grown at virtually the same pace in both regions, at an annual rate of about 7.5 percent on average. This pattern abruptly changed after the crisis, as bank credit growth in the euro area fell back to zero while bank credit growth in the U.S. turned sharply negative. While the growth of bank credit in the U.S. became positive again by mid-2012, amounting to an annual rate of about 2 percent on average since the end of 2008, the growth of bank credit in the euro area remained equal to zero. Hence, despite historically low monetary policy interest rates, the banking crisis triggered a large slowdown in bank credit growth, especially in the euro area.

Figure 2: Bank credit supply in the U.S. and EMU



(a) United States



(b) Euro area

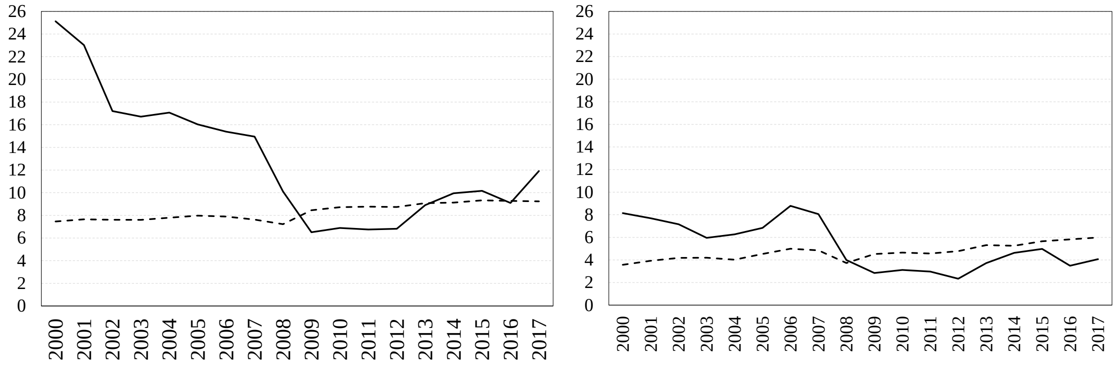
Note: the lines display the stock of credit to the non-financial private sector supplied by banks (solid black lines) non-banks (dashed black lines) and the aggregate of both (gray line). All series are based on data in local currencies, and are normalized to equal 100 by the end of 2008. Source: BIS Local Credit Statistics.

The large slowdown in bank credit growth after the crisis coincided with a large decline in the capitalization of the U.S. and euro area banking sectors. Figure 3 illustrates that in both regions, the market value of bank equity expressed as a percentage of bank assets fell considerably after the crisis. Since them, bank capitalization in the U.S. has started to recover while bank capitalization in the euro area has remained depressed (see also Sarin and Summers, 2016). As a result, since the end of 2008, the capitalization of euro area banks in terms of market values has been consistently below the capitalization in terms of book values, while prior to the crisis this was the other way around.[8] By contrast, the capitalization of U.S. banks in terms of market values has been higher than capitalization in terms of book values since 2013. The recovery of bank capitalization in both

[8]The regulatory requirement for bank capitalization is based on the book value of equity rather than the market value. The figure shows that book values of equity were relatively unresponsive to the crisis dynamics, as they declined only modestly in 2008 and gradually to improved thereafter. This improvement reflects that bank regulators raised minimum equity requirements after the crisis by adopting the Basel III reforms.

regions thereby follows a pattern that is similar to the recovery of credit growth, with both being much weaker in the euro area than in the U.S.

Figure 3: Bank capitalization in the U.S. and EMU



(a) United States

(b) Euro area

Note: the solid lines display the market value of bank equity divided by total assets, and the dashed lines display the book value of equity divided by total assets. The market value of equity is obtained by multiplying the book value of equity with the market-to-book ratio. Source: BIS (2018) and Thomson Reuters Eikon.

The slow recovery of the capitalization of the euro area banking sector after the crisis has often been blamed for the slow recovery of the European economy as a whole, and thereby for the prolonged need for the ECB to keep interest rates at historically low levels. Moreover, to the extent that the slow recovery of bank capitalization interferes with the monetary transmission mechanism, the positive effect of these low interest rates on economic activity may be smaller than usual. To examine these considerations more formally, the next section develops a model to analyze how the recapitalization of the banking sector after a crisis affects the supply of credit and the transmission of monetary policy.

3 Model

We integrate a banking sector in a standard New-Keynesian DSGE model with sticky prices and capital accumulation (this standard framework is described in Appendix A). Section 3.1 develops the benchmark version of the banking sector, which consists of a representative bank that operates without frictions. The model with the benchmark banking sector therefore has the same properties as the standard DSGE framework without banks. Section 3.2 introduces a friction in the benchmark version of the banking sector, which is a recapitalization that the government provides to the banking sector if the latter has suffered large losses. We develop two versions of the banking sector with recapitalizations. Section 3.2.1 develops a version where the recapitalization is provided immediately after large losses occur, and Section 3.2.2 develops a version where the recapitalization is provided with a delay. Except for these different recapitalization policies (i.e., no recapitalizations, immediate recapitalizations, or delayed recapitalizations), all versions of the model are the same.

3.1 The banking sector without frictions

The banking sector without frictions consists of a representative bank that intermediates between the household and the capital producing firm. The bank finances itself with deposits D_t and equity E_t from the household, which have expected returns equal to R_t^D and R_t^E.[9] The bank uses these funds to make loans L_t to the capital producer, against nominal lending rate R_t^L. Taking the returns on deposits and equity as given, the bank maximizes excess profits:

$$\max_{L_t, D_t, E_t} \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi_{t+1+\tau}^B\right). \tag{1}$$

where $\Lambda_{t+\tau} \equiv \beta^\tau \lambda_{t+\tau}/\lambda_t$ is the stochastic discount factor of the household (which is the owner of the bank, see Appendix A). The excess profit of the bank is defined as:

$$\Pi_{t+1}^B \equiv \frac{R_t^L}{\pi_{t+1}} L_t - \frac{R_t^D}{\pi_{t+1}} D_t - \frac{R_t^E}{\pi_{t+1}} E_t + \Pi_{t+1}^K, \tag{2}$$

where inflation $\pi_t \equiv P_t/P_{t-1}$ is defined as the change in the price level P_t. As the bank is the only financier of the capital producer, the excess profits of the capital producer Π_t^K are appropriated by the bank as well. This way, losses incurred by the capital producer (e.g., because of a negative productivity shock) reduce the excess profit of the bank.[10] The bank maximizes its excess profit subject to the balance sheet identity:

$$L_t \equiv D_t + E_t, \tag{3}$$

which may alternatively be interpreted as a production function for bank loans. In addition, the bank is subject to a regulatory minimum equity requirement:

$$E_t = \kappa L_t, \tag{4}$$

[9] The expected return on equity, also known as the cost of equity, is equal to the expected stream of dividend payments and capital gains on the equity of the bank. The distinction between dividend payments and capital gains is not important for our analysis. Implicitly, dividends at the end of time t are equal to shareholder value at the end of t minus shareholder value at the start of $t+1$. A negative value implies that the bank issues additional equity.

[10] The bank also receives any positive excess profits from the capital producer, which effectively converts the loan contract into an equity claim. This simplification is harmless for our purposes, as we focus on the effect of loan losses on bank behavior and do not study the capital structure of the firm.

where κ is exogenously determined by the bank regulator. We simplify the analysis by assuming that the equity requirement holds with equality.[11] Next, substituting the equity requirement, the balance sheet identity, and the profit function in the objective function, we obtain:

$$\max_{L_t} \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\frac{R^L_{t+\tau}}{\pi_{t+1+\tau}} L_{t+\tau} - \frac{R^D_{t+\tau}}{\pi_{t+1+\tau}} (1-\kappa) L_{t+\tau} - \frac{R^E_{t+\tau}}{\pi_{t+1+\tau}} \kappa L_{t+\tau} + \Pi^K_{t+1+\tau} \right). \tag{5}$$

Taking the derivative with respect to the choice variable L_t yields the first-order condition:

$$R^L_t = (1-\kappa) R^D_t + \kappa R^E_t, \tag{6}$$

where we used the fact that $\partial \mathbb{E}_t \left(\Pi^K_{t+1} \right) / \partial L_t = 0$. This condition states that the lending rate of the bank is equal to its weighted average cost of funds. As a result, the price of a bank loan is equal to the marginal cost of producing it.

3.2 Banking sector recapitalizations

We now extend the benchmark version of the banking sector with a recapitalization provided by the government (auxiliary derivations for this section can be found in Appendix D). The government provides such a recapitalization if the claims of depositors exceed the loan income of the bank, and thereby prevents the bank from becoming unable to fully repay its depositors. We refer to the difference between loan income and depositor claims as the shortfall:

$$\begin{aligned} S_{t+1} &\equiv \max \left(0; \frac{R^D_t}{\pi_{t+1}} D_t - \frac{R^L_t}{\pi_{t+1}} L_t - \Pi^K_{t+1} \right), \\ &= \max \left(0; \bar{\omega}_t - \omega_{t+1} \right) \frac{R^L_t}{\pi_{t+1}} L_t, \end{aligned} \tag{7}$$

which through the threshold $\bar{\omega}_t \equiv (1-\kappa) \frac{R^D_t}{R^L_t}$ depends on the bank equity requirement. Furthermore, as described in Appendix D, we defined $\omega_{t+1} \equiv \frac{R^K_{t+1} - \delta}{\mathbb{E}_t \left(R^K_{t+1} \right) - \delta}$. This stochastic variable is not a shock in itself, but is driven by (productivity) shocks that affect the excess profits of the capital producer. While $\mathbb{E}_t \left(\omega_{t+1} \right) = 1$, we simplify notation below by assuming that these productivity shocks are distributed such that ω_{t+1} is normally distributed with standard deviation σ_ω. Intuitively, (7) shows that a shortfall $S_{t+1} > 0$ can occur if the return on capital R^K_{t+1} is below expectation, and that such a shortfall will be larger when the equity requirement κ is lower. The reason is that a lower

[11] The frictionless bank is indifferent about its share of equity funding, as equity and deposits are perfect substitutes from the perspective of the household. Introducing a binding equity requirement therefore does not affect the dynamics of the model. By contrast, a bank that may receive a recapitalization from the government prefers its share of equity funding to be as small as possible, as we show in the next section. The minimum equity requirement will therefore hold with equality.

than expected return on capital gives rise to a loss for the bank, while a lower equity requirement reduces the ability of the bank to absorb such losses out of its equity buffers. The probability of a shortfall is eliminated for the special case where $\kappa = 1$, in which case the banking sector below is identical to the frictionless banking sector without recapitalizations. The model then has the same properties as the New-Keynesian DSGE framework without banks in Appendix A.

3.2.1 An immediate recapitalization

If a shortfall occurs, the bank receives a recapitalization from the government. We model this recapitalization as a transfer from the government to the bank, which the government finances by a lump sum tax on the household.[12] While the next section models the case where the recapitalization takes place with a delay, this section focuses on the case where the recapitalization takes place immediately. We model such an immediate recapitalization as a transfer that the bank receives from the government directly when it experiences a shortfall. The transfer at time $t+1$ is equal to the size of the shortfall S_{t+1}, so that the expected stream of excess profits is:

$$\begin{aligned} & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi^B_{t+1+\tau} + S_{t+1+\tau} \right) \\ = \quad & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi^B_{t+1+\tau} + \int_0^{\bar{\omega}_{t+\tau}} \left(\bar{\omega}_{t+\tau} - \omega_{t+1+\tau} \right) f(\omega_{t+1+\tau}) d\omega_{t+1+\tau} \frac{R^L_{t+\tau}}{\pi_{t+1+\tau}} L_{t+\tau} \right), \quad (8) \end{aligned}$$

where $f(\cdot)$ is the probability density function of a normal distribution with mean one and standard deviation σ_ω. Taking the derivative of the expected stream of excess profits with respect to L_t yields the first-order condition:

$$R^L_t = \frac{(1-\kappa) R^D_t + \kappa R^E_t}{1 + \Gamma(\bar{\omega}_t)}, \tag{9}$$

where we define $\Gamma(\bar{\omega}_t) \equiv \int_0^{\bar{\omega}_t} \left(\bar{\omega}_t - \omega_{t+1} \right) f(\omega_{t+1+\tau}) d\omega_{t+1} > 0$. This term indicates the size of the recapitalization that the bank expects to receive in the next period, expressed as a percentage of its current loan portfolio. The first-order condition shows that a bank charges a lower lending rate if it expects to be recapitalized by the government after experiencing a shortfall. A convenient way to calculate the magnitude of the effect on the lending rate is to use:

$$\Gamma(\bar{\omega}_t) \quad = \quad \bar{\omega}_t - 1 - \sigma_\omega \frac{f(0) - f(\bar{\omega}_t)}{F(\bar{\omega}_t) - F(0)}, \tag{10}$$

[12] In practice, the way in which governments finance bank recapitalizations is likely to be a source of economic inefficiencies in itself, as this may, for example, involve taxing wages and thereby distorting the labor supply decision. Alternatively, governments could finance recapitalizations in the same way as they sometimes finance deposit insurance schemes, by letting eligible banks pay a risk-based insurance premium. During previous crises, however, the cost of banking sector recapitalizations was typically borne by taxpayers.

where $F(\cdot)$ is the cumulative density function of a normal distribution with mean one and standard deviation σ_ω.

3.2.2 A delayed recapitalization

In practice, bank recapitalizations are politically unpopular, amongst others because they impose a large burden on taxpayers. Governments may therefore delay recapitalizations after a shortfall, hoping that the banking sector will recover by itself through its future profits. We therefore model a delayed recapitalization as a transfer to the bank in period $t+1$ after it experienced a shortfall in period t. The size of the delayed recapitalization is equal to the size of the shortfall (plus interest) minus any profits that the bank has made since the shortfall occurred. In this way, the transfer from the government to the bank is just enough for the bank to fully repay the depositors in $t+1$ while compensating them also for their losses in period t that resulted from the shortfall. The transfer that is required to ensure this is equal to:

$$\begin{aligned} & \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t - \max\left(0; \Pi_{t+1}^K + \frac{R_t^L}{\pi_{t+1}} L_t - \frac{R_t^D}{\pi_{t+1}} D_t\right)\right) \\ = \quad & \max\left(0, \bar{\omega}_t + \hat{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t - S_{t+1}, \end{aligned} \tag{11}$$

where the second max operator in the first line indicates the amount of profits made by the bank since it suffered the shortfall S_t. If there was no shortfall during period t, the threshold $\hat{\omega}_t \equiv (S_t/L_t)\frac{R_t^D}{R_t^L}$ defined in the second line is equal to zero. Using the definition of S_{t+1} in 7 then confirms that the recapitalization is equal to zero. The expected stream of excess profits associated with a delayed recapitalization equals:

$$\begin{aligned} & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi_{t+1+\tau}^B - S_{t+1+\tau} + \max\left(0, \bar{\omega}_{t+\tau} + \hat{\omega}_{t+\tau} - \omega_{t+1+\tau}\right) \frac{R_{t+\tau}^L}{\pi_{t+1+\tau}} L_{t+\tau}\right) \\ = \quad & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi_{t+1+\tau}^B - S_{t+1+\tau}\right) \\ + \quad & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\int_0^{\bar{\omega}_{t+\tau}+\hat{\omega}_{t+\tau}} \left(\left(\bar{\omega}_{t+\tau} + \hat{\omega}_{t+\tau} - \omega_{t+1+\tau}\right) \frac{R_{t+\tau}^L}{\pi_{t+1+\tau}} L_{t+\tau}\right) f(\omega_{t+1+\tau}) d\omega_{t+1+\tau}\right). \end{aligned} \tag{12}$$

Taking the derivative with respect to L_t yields the first-order condition:

$$R_t^L = \frac{(1-\kappa) R_t^D + \kappa R_t^E}{1 + F\left(\bar{\omega}_{t+1} + \hat{\omega}_{t+1}\right) \Gamma\left(\bar{\omega}_t\right) + \Gamma\left(\hat{\omega}_t\right)}, \tag{13}$$

where $F(\bar{\omega}_{t+1} + \hat{\omega}_{t+1})$ is the probability that if the bank experiences a shortfall in the next period, a recapitalization in the period thereafter will still be necessary. This will be the case if the bank does not make sufficient profits during the period following the shortfall to recover on its own. Furthermore, we define $\Gamma(\hat{\omega}_t) \equiv \int_{\bar{\omega}_t}^{\bar{\omega}_t+\hat{\omega}_t} (\bar{\omega}_t - \omega_{t+1}) f(\omega_{t+1+\tau}) d\omega_{t+1} \leq 0$, which negatively depends on $\hat{\omega}_t$ and therefore is smaller when there was a larger shortfall in the previous period.

Comparing the first-order condition to the one in (9) shows that relative to an immediate recapitalization, a delayed recapitalization drives up the lending rate in two ways. First, in this situation where the bank has not experienced a shortfall during the previous period, so that $\Gamma(\hat{\omega}_t) = 0$, the anticipation of a delayed recapitalization leads to a smaller decline in the lending rate than the anticipation of an immediate recapitalization. The reason is that $F(\bar{\omega}_{t+1} + \hat{\omega}_{t+1}) < 1$, which reflects that after a future shortfall the bank may become sufficiently profitable to render a delayed recapitalization unnecessary. Second, in the situation where the bank has experienced a shortfall during the previous period $\Gamma(\hat{\omega}_t) < 0$, which increases the lending rate as well. The reason is that during the period in between a shortfall and a delayed recapitalization, the income on loans reduces the size of the delayed recapitalization that the government will provide. This loan income is thereby partially appropriated by the government rather than by the shareholders of the bank, which the bank anticipates by charging a higher lending rate. A convenient way to calculate the magnitude of the resulting effect on the lending rate is to use:

$$\Gamma(\hat{\omega}_t) \quad = \quad \bar{\omega}_t - 1 - \sigma_\omega \frac{f(0) - f(\bar{\omega}_t + \hat{\omega}_t)}{F(\bar{\omega}_t + \hat{\omega}_t) - F(0)} - \Gamma(\bar{\omega}_t). \tag{14}$$

4 Calibration

Appendix B summarizes the model that results when integrating the banking block into the macroeconomic framework. We solve the model by taking a second-order approximation around the steady-state, and calibrate the model parameters as described in Table 1. As this calibration aims to follow common practice, we only discuss the parameters of the banking sector.[13] The bank equity requirement is calibrated at $\kappa = 0.04$, which reflects that the international Basel III Accord for bank regulation requires an equity buffer of at least three percent of total assets. In addition to this 'leverage-ratio' requirement, banks may be required to have higher buffers if they are systemically important or if their assets are relatively risky. Moreover, as a safe margin, banks tend to keep their equity ratios somewhat above the regulatory minimum. Calibrating the equity requirement at four percent therefore seems a reasonable choice.

[13] By calibrating $\theta \approx \infty$ we let intermediate goods producing firms be perfectly competitive. Calibrating $\gamma = 0$ implies that firms that cannot optimize their price leave their price unchanged. The central bank responds to inflation only, and adjusts interest rates gradually as we calibrate $\phi^R = 0.9$. Additionally, $\chi = 15.06$ is calibrated such that steady state labor supply in the frictionless version of the model equals 0.3. The rest of the parameter values are taken from Smets and Wouters (2007).

Given our calibration of the equity requirement, the banking sector in our model experiences a shortfall if the return on loans is less than minus four percent. Moreover, our calibration of the household discount factor gives rise to a the steady-state lending rate of about one percent per quarter in the frictionless version of the banking sector (so that the annual lending rate is about four percent). We therefore calibrate the standard deviation of the return on loans at $\sigma_\omega = 0.02$, so that a return on loans of minus four percent is $(-0.04 - 0.01)/0.02 = 2.5$ standard deviations away from the steady-state return. This calibration implies that the banking sector experiences a shortfall once in every 40 years (assuming that the return on loans is normally distributed). With the recent banking crisis fresh in mind, this seems to be a conservative estimate.

Table 1: Calibration of the model

Parameter	Description	Value
β	Household discount factor	0.99
σ	Rate of inter-temporal substitution	1
φ	Inverse of the labor supply elasticity	2
χ	Weight of labor in the utility function	15.06
κ	Bank equity requirement	0.04
σ_ω	Standard deviation of the return on bank loans	0.02
α	Share of capital in the production function	0.3
ρ^Z	Autoregressive coefficient for productivity shocks	0.67
δ	Capital depreciation rate	0.025
θ	Final good substitution elasticity	∞
ξ	Share of firms that cannot re-optimize their price	0.75
γ	Degree of price indexation	0
π^*	Steady state inflation rate	1
ϕ^R	Smoothing coefficient in the interest rate rule	0.9
ϕ^P	Response to inflation in the interest rate rule	1.5

5 Results

We first illustrate the dynamics of the model by focusing on the version where there are no frictions in the banking sector. The dynamics of this model are the same as those of the New-Keynesian DSGE model without a bank that is described in Appendix A. Figure 4 shows the impulse response functions for a one percent decrease in total factor productivity. This decrease in productivity leads to a decline in output, and therefore in consumption and investment. The lower investment reduces the size of the capital stock, so that deposits and equity decline in tandem. As firms hire less labor, the real wage goes down. At the same time, as firms need more capital and labor to produce one unit of output, they raise their prices so that inflation increases on impact. The central bank responds to the increase in inflation by raising the nominal monetary policy interest rate. This monetary contraction causes the bank to increase its nominal lending rate, but the real lending rate declines due to the higher inflation.

5.1 Monetary policy transmission

We now focus on the model with bank recapitalizations by the government (as described in Section 3.2). These recapitalizations altering the effect of changes in the nominal monetary policy interest rate on the nominal bank lending rate, and thereby affect the transmission of monetary policy. The effect on the bank lending rate is determined by the derivative:

$$\frac{\partial R_t^L}{\partial R_t^D} = \frac{1}{1 + F\left(\bar{\omega}_{t+1} + \hat{\omega}_{t+1}\right)\Gamma\left(\bar{\omega}_t\right) + \Gamma\left(\hat{\omega}_t\right)} > 0. \tag{15}$$

In the frictionless version of the banking sector this derivative is equal to one, as all interest rates in the model are the same. In the version with recapitalizations, however the transmission of monetary policy to bank lending rates may either be strengthened or weakened, depending on whether the denominator of (15) is smaller or larger than one.

If the banking sector has not experienced a shortfall during the previous period, a situation which could be defined as 'normal times', $\Gamma\left(\hat{\omega}_t\right) = 0$ so that $F\left(\bar{\omega}_{t+1} + \hat{\omega}_{t+1}\right)\Gamma\left(\bar{\omega}_t\right) > 0$ causes $\partial R_t^L / \partial R_t^D < 1$. This weakens the transmission of monetary policy to bank lending rates relative to the frictionless case. The reason is that an increase in the monetary policy interest rate leads to an increase in the interest rate on deposits. This higher cost of deposits just partially hast to be covered by a higher income on loans, as the remaining part is covered by the (immediate or delayed) recapitalization expected from the government. An increase in the deposit interest rate therefore leads to a less than one-for-one increase in the lending rate.

By contrast, if $\Gamma\left(\hat{\omega}_t\right) < 0$, which could be referred to as 'crisis times', the banking sector has experienced a shortfall during the previous period and is expecting a delayed recapitalization during the next period. If the shortfall was large enough to cause $\partial R_t^L / \partial R_t^D > 1$, the resulting transmission of monetary policy to bank lending rates is stronger than in the frictionless case. The reason is that an increase in the monetary policy interest rate causes the bank to increase its lending rate more than one-for-one, as the extra income on loans reduces the size of the delayed recapitalization that will be received from the government in the next period. The higher interest income on loans can therefore only partially be used to cover the higher interest expense on deposits, which implies that an increase in the deposit rate requires a relatively large increase in the bank lending rate.

5.1.1 Effects on output and inflation

A stronger transmission of monetary policy to nominal bank lending rates weakens the transmission of monetary policy to inflation. An increase of the nominal policy rate, for example, reduces aggregate demand and thereby reduces labor demand and wages, which enables firms to lower their prices. Part of this deflationary effect is offset, however, by the fact that a policy rate increase raises the cost of capital, which requires firms to increase their prices. A stronger transmission of a policy rate increase to bank lending rates strengthens this offsetting effect, which results in a weaker overall effect on inflation. The overall effect of a policy rate increase on inflation remains negative because the labor share in production is substantially larger than the capital share, so that the decline in wages dominates the increase in the cost of capital.

A stronger transmission of monetary policy to nominal bank lending rates leaves the transmission to output largely unaffected. The reason is that the larger effect on the nominal lending rate does not translate into a larger effect on the real lending rate, because of the weaker transmission of monetary policy to inflation. An increase in the nominal monetary policy rate, for example, leads to a relatively high nominal lending rate but also to a relatively high inflation rate. The net effect of an increase in the policy rate on the real lending rate is therefore largely unchanged.

Figure 5 illustrates the above results by displaying the effects of a negative productivity shock under three different circumstances. The first row describes the situation before a shortfall when recapitalizations are immediate, the second row describes the situation before a shortfall when recapitalizations are delayed, and the last row describes the situation between a shortfall (we calibrated $S/L = 0.01$) and a recapitalization. For comparison, each panel also displays the effect of the shock in the frictionless version of the banking sector. We focus on the effect of a negative productivity shock on the monetary policy interest rate, the inflation gap, and the output gap, which in most models are the main ingredients of the monetary policy rule. In addition, we report the effect of the shock on the spread between the nominal lending and deposit rate.

Focusing on the bottom row in the figure, which reflects the situation in between a shortfall and a recapitalization, a negative productivity shock leads to a relatively large increase in the monetary policy interest rate (compared to the model with the frictionless banking sector). This increase in the policy rate increases the spread between the lending rate and the deposit rate, which illustrates the stronger transmission of monetary policy to bank lending rates. At the same time, the large increase in the policy rate coincides with a relatively large increase in inflation, which illustrates the weaker transmission of monetary policy to inflation. The relatively large increase in the policy rate leads to a correspondingly large decline in the output gap, as the transmission of monetary policy to output is largely unaffected. The panels in the top row report the mirror image of these patterns, which illustrates that before a shortfall with immediate recapitalizations monetary transmission to lending rates is weaker while transmission to inflation is stronger. The middle row shows that these effects are dampened in the situation before a shortfall with delayed recapitalizations, as the impulse responses in this situation are about the same as in the model with the frictionless banking sector.

Figure 6 illustrates monetary transmission after a negative demand shock, which we model as a 1 percent in the household discount factor β. Households become more patient, reduce their consumption and increase their savings. Such a shock causes the output and inflation gap to move in the same direction rather than in opposite directions (which is the case after a negative productivity shock). The figure confirms the result that monetary transmission to bank lending rates is weaker before a shortfall and stronger between a shortfall and a recapitalization. As before, the transmission to inflation is therefore stronger before a shortfall and weaker in between a shortfall and a recapitalization.

5.2 Bank equity requirements

A key property of the model is that bank equity requirements typically increase social welfare, even though they require the banking sector to charge higher lending rates. The reason is that a higher equity requirement reduces the size of expected future shortfalls, and thereby reduces the magnitude of bank recapitalizations by the government. Banks anticipate such recapitalizations by charging inefficiently low lending rates, which leads to a dynamically inefficient equilibrium with an excessively large capital stock. Table 2 illustrates that the capital stock is particularly large (relative to the case where the banking sector is frictionless) if recapitalizations are provided immediately after a shortfall, but is also inefficiently large if recapitalizations are provided with a delay. By contrast, during the period in between a shortfall (as before calibrated at $S/L = 0.01$) and a recapitalization, banks charge inefficiently high lending rates so that the capital stock is inefficiently small. Raising bank equity requirements in this situation causes lending rates to become even higher, so that social welfare goes down.

Table 2: Comparison of steady states

	Y^*	K^*	C^*	R^{L*}
Frictionless banking sector (dynamically efficient)	-	-	-	4.00%
Before shorfall with immediate recapitalization	19.71%	58.36%	9.13%	0.55%
Before shortfall with delayed recapitalization	0.36%	0.87%	0.22%	3.95%
In between shortfall and recapitalization	-0.03%	-0.18%	0.00%	4.04%

Note: Y^*, K^* and C^* are expressed in percentage differences from the steady state of the model with the frictionless banking sector.

To illustrate the effect on social welfare of an increase in bank equity requirements, Figure 7 displays the response of the model variables to a permanent 0.5 percentage point increase in the bank equity requirement (i.e., from 4 to 4.5 percent). In the version of the model with a frictionless banking sector, such an increase leads to an increase in bank equity and a decrease in bank deposits and leaves all other variables unchanged. This result confirms that the frictionless banking sector does not violate the Modigliani-Miller (1958) conditions and capital structure is irrelevant. The figure shows, however, that this irrelevance property disappears when introducing bank recapitalizations into the model.

The figure reports transition paths to the new steady state for the situation before a shortfall when recapitalizations are delayed, and for the situation in between a shortfall and a recapitalization (we omitted the transition paths associated with an immediate recapitalization, which are an amplified version of the paths for the situation before a shortfall when recapitalizations are delayed). In both cases, an increase in the equity requirement leads to a higher real lending rate, which reflects that the magnitude of expected future recapitalizations declines. This higher lending rate reduces investment and initially raises consumption, but as the capital stock starts to shrink the economy ultimately becomes smaller and consumption ends up lower as well. As the figure illustrates, an increase in equity requirements has a larger impact on the economy during the situation in between a shortfall and a recapitalization. As a result, the monetary policy response in this situation has to be more accommodative as well.

Figure 8 shows that raising bank equity requirements increases household utility in the short-run and reduces utility in the long-run. The initial increase in utility reflects the initial increase in consumption and leisure, while the ultimate decline in utility reflects the lower consumption and leisure in the new steady state. If equity requirements are raised before a shortfall, lifetime utility increases on impact as the positive effect on short-run utility outweighs the negative effect on long-run utility. By contrast, if equity requirements are raised in between a shortfall (of $S/L = 0.01$) and a recapitalization, lifetime utility goes down. The reason is that bank lending rates in this situation are inefficiently high, which is aggravated by an increase in the equity requirement (if $S/L < 0.01$ the lending rate may still have been inefficiently low, in which case raising equity requirements would increase lifetime utility). Hence, the timing of an increase in equity requirements may importantly affect the impact of such an increase on social welfare.

6 Discussion

Despite large monetary expansions in both the U.S. and the euro area, the 2007-08 banking crisis was followed by a large decline in bank credit supply while inflation rates started to slide. These developments raised concerns amongst central bankers that inflation expectations would become de-anchored, which motivated unconventional monetary policy measures on both sides of the Atlantic. At the same time, bank regulators adopted the Basel III Accord, which aimed to restore the stability of the banking sector by raising bank equity requirements. The Basel negotiations were complicated, however, by concerns that raising equity requirements would weaken the economic recovery. Such concerns were especially prominent in the euro area, where bank recapitalizations and the economic recovery had been slowed down by the sovereign debt crisis. The recapitalization process came up to speed only by the end of 2014, when the ECB in its new role as European bank supervisor subjected banks to an asset quality review and a stress test. By contrast, in the same year, the bank recapitalization process in the U.S. came to its ending, as the Treasury recovered the last remaining funds that had been disbursed under the troubled asset relief program.

Our analysis turns out to validate the above concerns of central bankers and policy makers. After a banking crisis (in our model: a shortfall), monetary transmission to inflation is weakened as long as the banking sector has not been recapitalized. Central bankers may therefore find conventional monetary policy to be less effective than usual in preventing inflation from falling below its target level. The model also supports the intuition of bank regulators that raising equity requirements contributes to social welfare by improving bank stability. At the same time, the model shows that this intuition comes with a caveat if the banking sector has not yet been recapitalized. An increase in equity requirements may then reduce bank credit supply below its efficient level, which requires an additional monetary expansion and slows down the economic recovery. Bankers voiced similar concerns in their attempts to influence the Basel III negotiations, and argued that banks just could not raise outside equity as financial markets were disrupted by the crisis. The model highlights an alternative view, by showing that even when outside equity can be raised without frictions, banks only be willing to do so after a crisis at the cost of charging inefficiently high lending rates. In this way, they can compensate their shareholders for the fact that raising equity reduces the delayed recapitalization that they hope to receive from the government.

The U.S. approach of immediate bank recapitalizations is typically regarded as superior to the delayed European approach. The model confirms that a policy of immediate bank recapitalizations has important advantages in the aftermath of a crisis, but also shows that such a policy may in normal times imply a larger subsidy for the banking sector. The optimal recapitalization approach therefore seems time-inconsistent, as a policy of delayed recapitalizations has advantages before a crisis while a policy of immediate recapitalizations has advantages in its aftermath. A more efficient policy in the model is therefore to reduce the need for bank recapitalizations, as bank regulators have historically been doing by imposing minimum equity requirements. In addition, as part of the Basel III reforms, regulators have required banks to issue long-term debt liabilities that can be used to absorb losses after a crisis, an example of which are the contingent convertible bonds that banks are currently issuing. Such bonds are converted into equity when supervisors determine that bank equity has fallen below a predetermined threshold level. While such bonds are not in the model, the analysis suggests that delaying their conversion after a crisis may have similar consequences for credit supply and monetary transmission as delaying a recapitalization (both can give rise to debt-overhang). The insights from the model may therefore be relevant for the 'bail-in' debate as well.

7 Concluding remarks

We integrated a banking sector in a New-Keynesian DSGE model to examine how government policies to recapitalize banks affect the supply of credit and the transmission of monetary policy. We examined two types of recapitalizations after a crisis: immediate and delayed ones. In the steady state, both policies constitute a subsidy for the banking sector that causes banks to charge inefficiently low lending rates. The dynamic inefficiency that results can be mitigated by raising regulatory bank equity requirements, which cause banks to raise lending rates but increases social welfare. During the period in between a crisis and a recapitalization, the banking sector effectively suffers from debt-overhang (even in absence of long-term debt). The reason is that part of the income on new loans is appropriated by the government, as this income reduces the recapitalization that the bank expects to receive in the next period. Banks therefore charge inefficiently high lending rates during this period, which reduces the supply of credit and weakens the transmission of monetary policy to inflation (the transmission to output remains largely unchanged). Raising bank equity requirements under such circumstances may aggravate the problem of inefficiently high lending rates, and may thereby lower social welfare. The analysis illustrates that immediate and delayed bank recapitalization policies may have different macro-economic implications, both in the aftermath of a banking crisis and in normal times.

Figure 4: Response to a negative productivity shock when the banking sector is frictionless

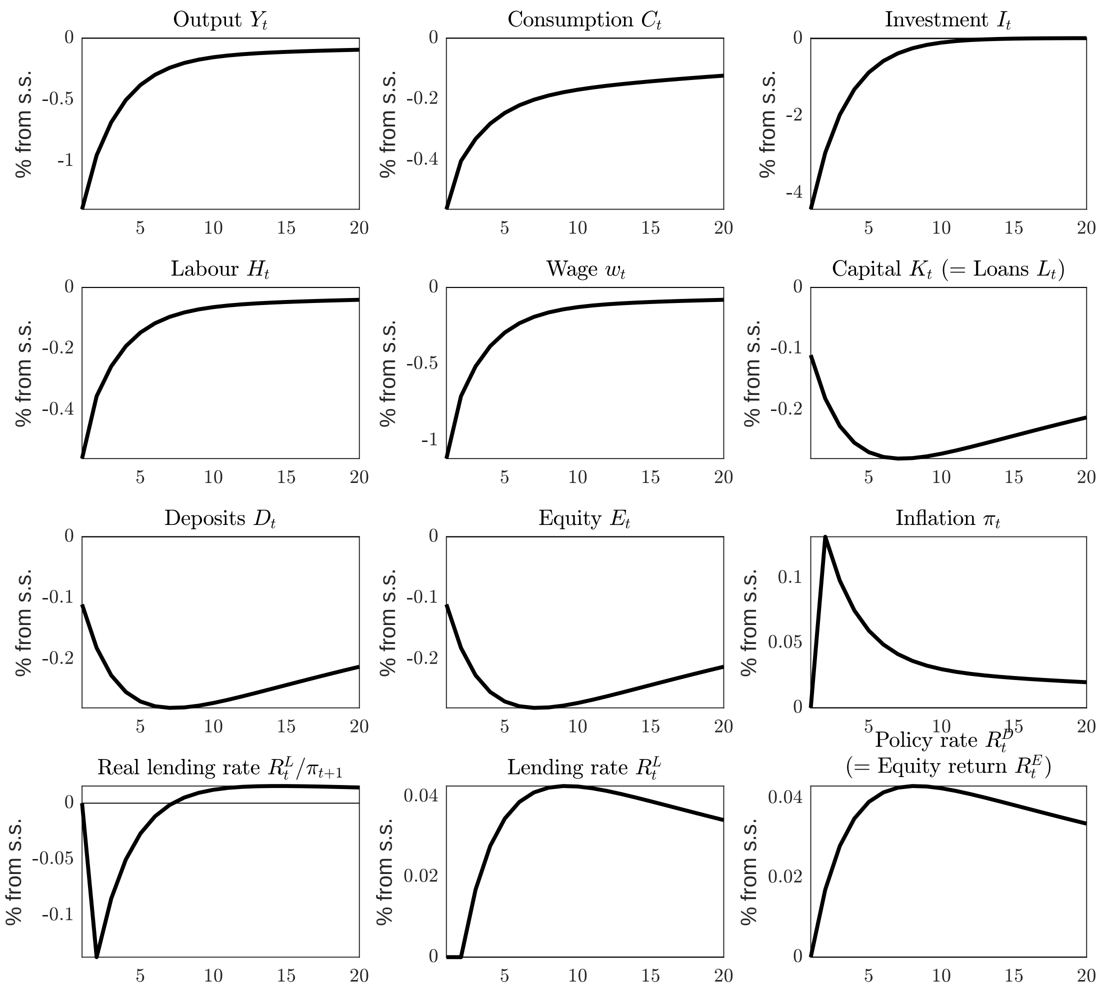
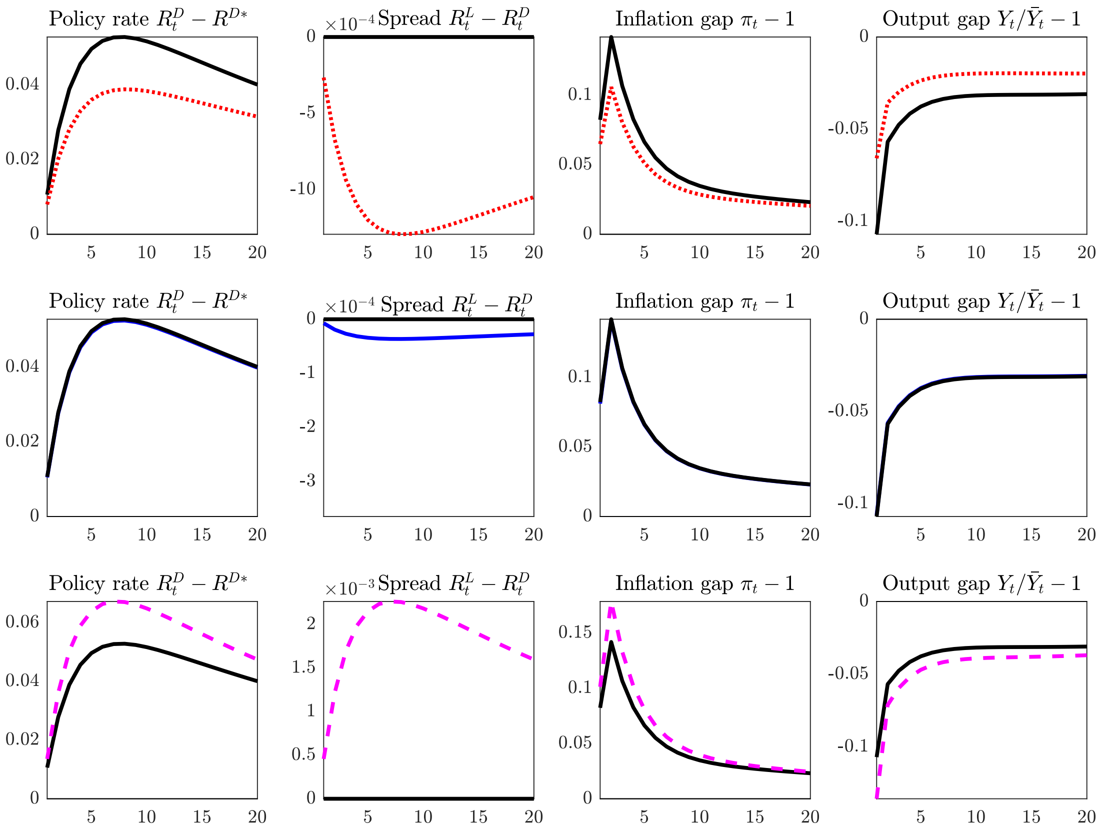
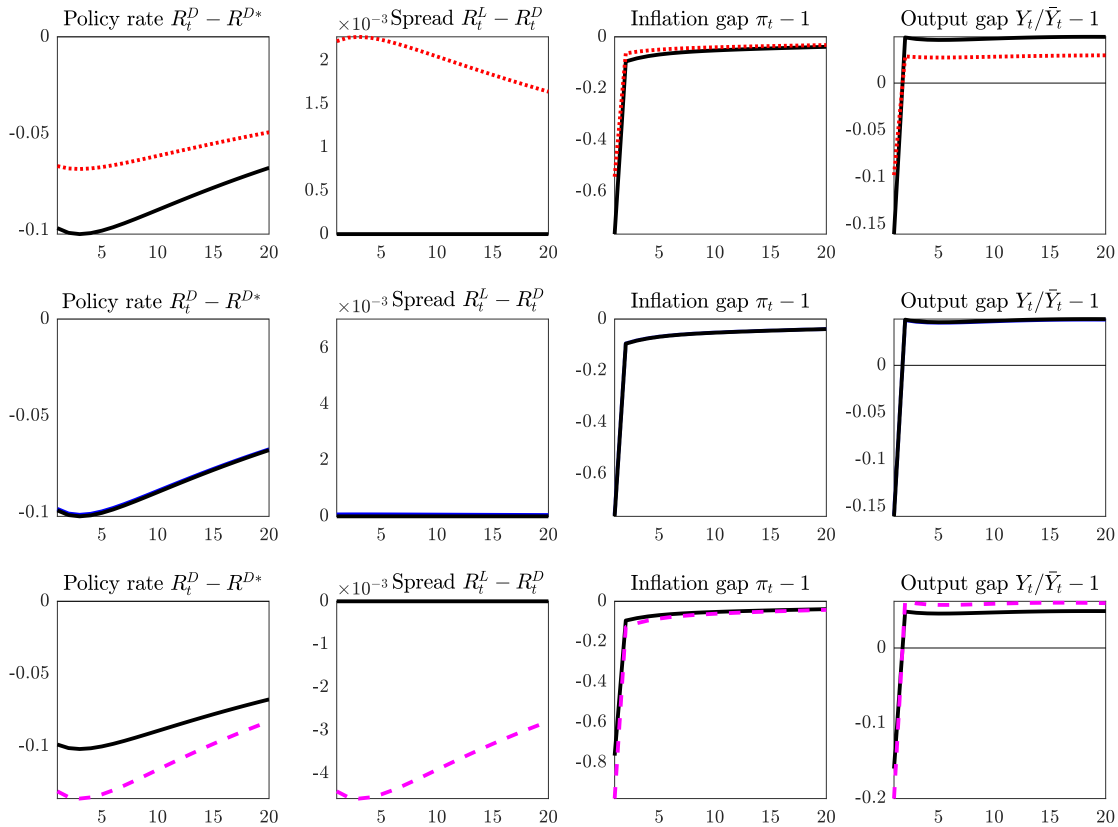


Figure 5: Monetary policy transmission after a negative productivity shock



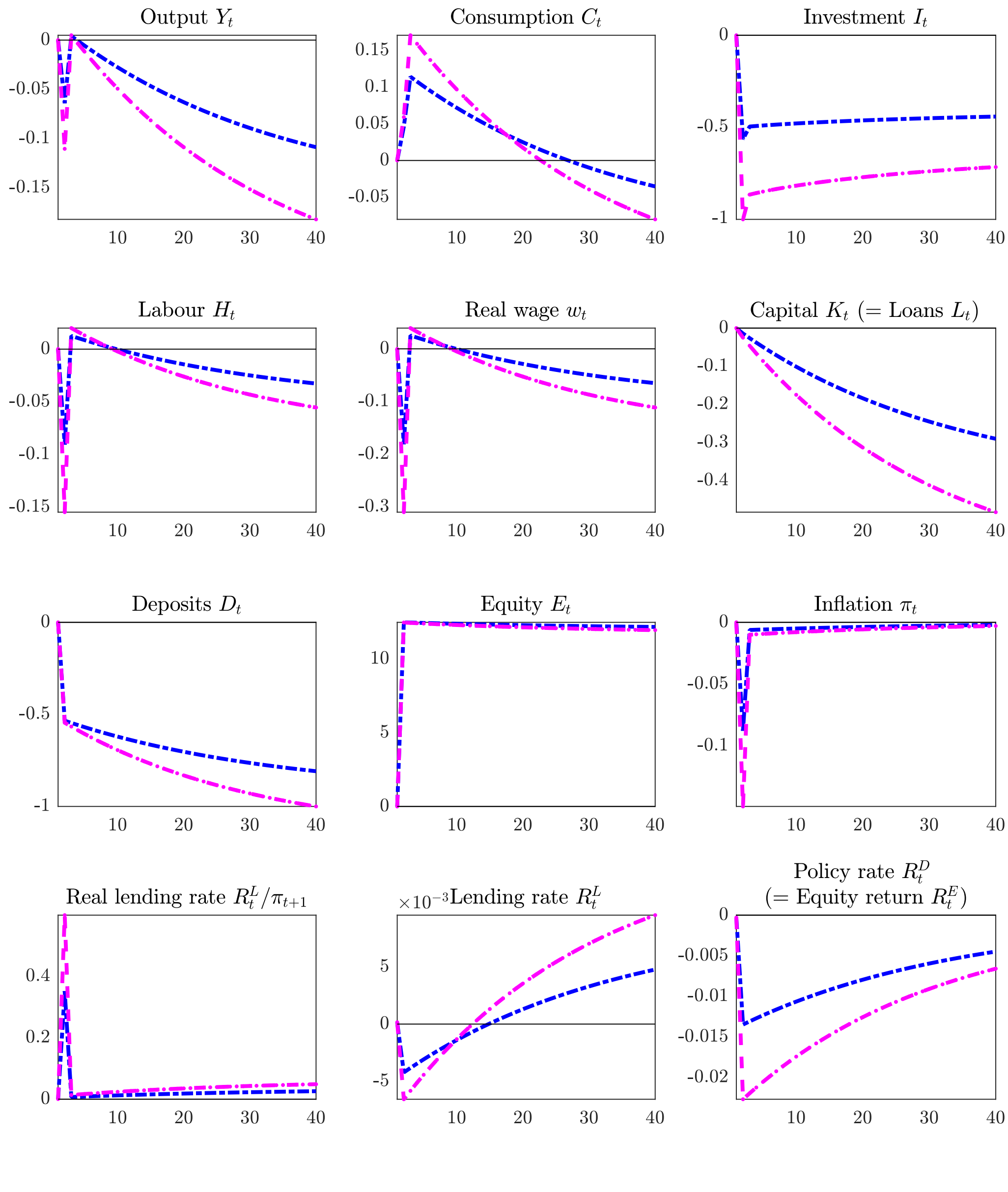
Note: the black line in each of the rows reflects the response for the case where the banking sector is frictionless without recapitalizations. The top row focuses on the case before a shortfall when recapitalizations are immediate, the middle row focuses on the the case before a shortfall when recapitalizations are delayed, and the bottom row focuses on the case between a shortfall and a recapitalization. In each of these four cases, to facilitate comparing the different panels, the monetary policy rule is calibrated such that the effect of the productivity shock on inflation is zero on impact. For the frictionless banking sector this implies a response to inflation of $\phi^P = 1.241$, while we calibrated ϕ^P at 1.182, 1.241, and 1.288 for the cases in the top, middle, and bottom row. Hence, ϕ^P is smaller when the transmission of monetary policy to inflation is stronger.

Figure 6: Monetary policy transmission after a negative demand shock



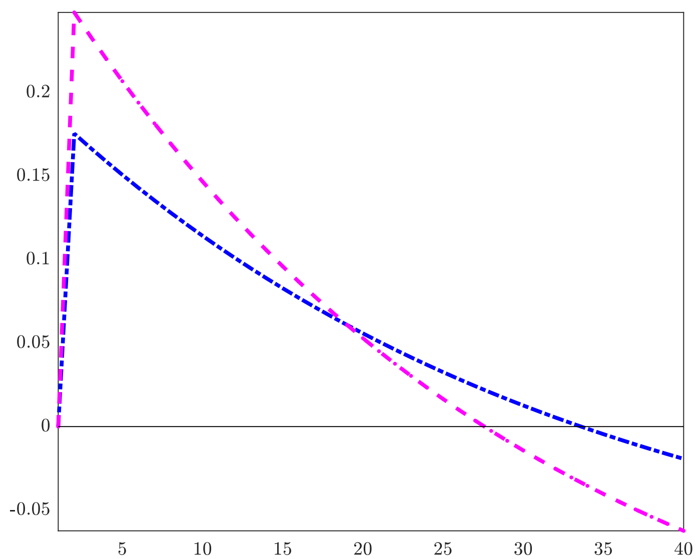
Note: the figure reports the response to an increase in β of one percent. The black line in each of the rows reflects the response for the case where the banking sector is frictionless without recapitalizations. The top row focuses on the case before a shortfall when recapitalizations are immediate, the middle row focuses on the the case before a shortfall when recapitalizations are delayed, and the bottom row focuses on the case between a shortfall and a recapitalization. The response to inflation in the monetary policy rule is calibrated as in Figure 5.

Figure 7: Response to a permanent increase in the bank equity requirement



Note: the figure reports the response to a permanent increase in κ of 0.5 percentage points. The blue line describes the case before a shortfall when recapitalizations are delayed and the pink line describes the case in between a shortfall and a recapitalization.

Figure 8: Utility after a permanent increase in the bank equity requirement



Note: the figure reports the response to a permanent increase in κ of 0.5 percentage points. The blue line describes the case before a shortfall when recapitalizations are delayed, and the pink line describes the case in between a shortfall and a recapitalization.

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Appendix A: A standard New Keynesian DSGE model

The household

The representative household maximizes its expected lifetime utility U_t:

$$U_t \equiv \mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} \left(u_{t+\tau} \right), \tag{16}$$

where β is the discount factor. The period utility function takes the following form:

$$u_t \equiv \frac{1}{1-\sigma} \left(C_t - \frac{\chi {H_t}^{1+\varphi}}{1+\varphi} \right)^{1-\sigma} \tag{17}$$

where C_t is consumption, H_t is the number of hours worked, $\sigma > 0$ is the rate of inter-temporal substitution, $\varphi > 0$ is the inverse of the labor supply elasticity, and $\chi > 0$ is the weight of labor in the utility function. The household can save in bank deposits D_t and in bank equity E_t, so that its budget constraint equals:

$$C_t + D_t + E_t = w_t H_t + \frac{R^D_{t-1}}{\pi_t} D_{t-1} + \frac{R^E_{t-1}}{\pi_t} E_{t-1} + \Pi_t, \tag{18}$$

where w_t denotes the real wage in the perfectly competitive labour market, R^D_t and R^E_t denote the returns on bank equity and bank deposits, and $\pi_t = P_t / P_{t-1}$ denotes inflation as a function of the price level P_t. The household in addition receives lump sum transfers $\Pi_t = \Pi^I_t + \Pi^F_t + \Pi^B_t + \Pi^G_t$, which consist of excess profits from the intermediate goods producing firms, the final goods producing firm, the bank, and transfers from the government (the excess profits from the capital producing firm enter in the profit function of the bank). Maximizing lifetime utility subject to the budget constraint yields the first-order conditions with respect to C_t, H_t, D_t, E_t:

$$\left(C_t - \frac{\chi {H_t}^{1+\varphi}}{1+\varphi} \right)^{-\sigma} = \lambda_t, \tag{19}$$

$$\chi {H_t}^{\varphi} = w_t, \tag{20}$$

$$\beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{R^D_t}{\pi_{t+1}} \right) = 1, \tag{21}$$

$$\beta \, \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{R^E_t}{\pi_{t+1}} \right) = 1, \tag{22}$$

where λ_t denotes the Lagrange multiplier for the budget constraint.

The firm

The household owns all firms in the economy. Firms therefore maximize the present value of their future profits discounted by the household discount factor. To preserve tractability we split the firm in three sub-firms. First we describe the capital producing firm, which is perfectly competitive. Next, we describe the final goods producing firm, which is perfectly competitive as well. Consequently, both firms have zero expected excess profits: $\mathbb{E}_t(\Pi^K_{t+1}) = 0$ and $\mathbb{E}_t(\Pi^F_{t+1}) = 0$. Finally, we describe the intermediate goods producing firms. These firms are monopolistically competitive and can set prices above marginal costs to maximize excess profits $\mathbb{E}_t(\Pi^I_{t+1}) > 0$. However, as they cannot update their prices every period, prices in the model are sticky.

The capital producing firm

The capital producing firm produces capital K_t, and supplies this capital to the intermediate good producing firms for a rental rate r^K_t. The capital producing firm must decide today how much capital it wants to supply in the next period. It finances this amount with a loan L_t from the bank, which it pays using the rental payments received during the next period. The capital producing firm maximizes its expected excess profits:

$$\max_{K_t, L_t} \mathbb{E}_t \left(\Pi^K_{t+1} \right). \tag{23}$$

Excess profits are equal to:

$$\Pi^K_{t+1} \equiv (1 + r^K_{t+1}) K_t - \delta K_t - \frac{R^L_t}{\pi_{t+1}} L_t, \tag{24}$$

where δ denotes the percentage depreciation of the capital stock, so that investment is defined as:

$$I_t \equiv K_t - (1 - \delta) K_{t-1}. \tag{25}$$

The balance sheet identity of the capital producing firm reads:

$$K_t \equiv L_t, \tag{26}$$

which can be substituted into the profit function. Taking the derivative with respect to K_t then yields the first-order condition:

$$\frac{R^L_t}{\mathbb{E}_t(\pi_{t+1})} = \mathbb{E}_t \left(R^K_{t+1} \right) - \delta, \tag{27}$$

where $R^K_t \equiv 1 + r^K_t$. As a result, expected excess profits are equal to zero: $\mathbb{E}_t(\Pi^K_{t+1}) = 0$.

The final goods producing firm

The final goods producing firm is perfectly competitive. It combines a continuum of differentiated intermediate goods $Y_t(j)$ produced by intermediate firm $j \in [0,1]$ into a final good denoted by Y_t, which it then sells to the household. As there are no inter-temporal effects the profit function is static and equals:

$$\Pi_t^F \equiv Y_t - \int_0^1 \frac{P_t(j)}{P_t} Y_t(j) dj, \tag{28}$$

where $P_t(j)$ is the price of the j^{th} intermediate input and P_t is the price for which the final good is sold. The firm maximizes these profits subject to the production technology:

$$Y_t = \left[\int_0^1 Y_t(j)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}, \tag{29}$$

where $\frac{\theta-1}{\theta}$ reflects the steady-state mark-up of the intermediate goods producing firms. Substituting this expression into the profit function and calculating the first-order condition with respect to $Y_t(j)$ yields:

$$Y_t(j)^{-\frac{1}{\theta}} = \frac{P_t(j)}{P_t} \left[\int_0^1 Y_t(j)^{\frac{\theta-1}{\theta}} dj \right]^{-\frac{1}{\theta-1}}. \tag{30}$$

Raising both sides of this expression to the power $-\theta$ and substituting the expression for the production technology gives the demand curve for intermediary good $Y_t(j)$:

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\theta} Y_t. \tag{31}$$

Substituting this expression in the profit function yields the aggregate price index:

$$P_t = \left[\int_0^1 P_t(j)^{1-\theta} dj \right]^{\frac{1}{1-\theta}}, \tag{32}$$

where we used that $\Pi_t^F = 0$ because of perfect competition.

The intermediate goods producing firms

The intermediate goods producing firms use capital supplied by the capital producing firm and labor supplied by the household. Each intermediate goods producing firm j is monopolistically competitive, and uses these inputs to produce intermediate good $Y_t(j)$. For convenience, we split the profit maximization problem of each firm in two parts. First, the firm determines its optimal ratio of labor demand H_t to capital demand $K_t^d = K_{t-1}$, by minimizing the total costs to produce an intermediate good amount $Y_t(j)$. The solution to this cost minimization problem provides the marginal cost of the intermediate goods producing firms. Then, in a second step, intermediate goods producing firms maximize their profits by setting the optimal price.

Cost minimization

The first step involves minimizing total costs:

$$\min_{K_t^d(j), H_t(j)} w_t H_t(j) + r_t^K K_t^d(j), \tag{33}$$

subject to the production technology:

$$Y_t(j) = Z_t H_t(j)^{1-\alpha} K_t^d(j)^{\alpha}, \tag{34}$$

which is a standard Cobb-Douglas production function. Productivity Z_t is common across all firms and follows an autoregressive process: $\log(Z_t) = \rho^Z \log(Z_{t-1}) + \varepsilon_t^Z$, with autoregression parameter ρ^Z and where ε_t^Z is an i.i.d. Gaussian shock. We denote the Lagrangian multiplier associated with the production technology constraint by mc_t, which can be interpreted as the marginal cost of the intermediate goods producing firms. Taking the derivative of the Lagrangian with respect to $K_t^d(j)$ and $H_t(j)$ then yields the first-order conditions:

$$mc_t Z_t \alpha H_t(j)^{1-\alpha} K_t^d(j)^{\alpha-1} = r_t^K, \tag{35}$$

$$mc_t Z_t \left(1-\alpha\right) H_t(j)^{-\alpha} K_t^d(j)^{\alpha} = w_t. \tag{36}$$

Combining both first-order conditions gives the optimal ratio of labour to capital as a function of their respective costs:

$$\frac{\alpha}{1-\alpha} \frac{H_t(j)}{K_t^d(j)} = \frac{r_t^K}{w_t}. \tag{37}$$

Substituting the first-order conditions in the production function and rewriting the result shows that marginal costs equal:

$$mc_t = \frac{1}{Z_t} \left(\frac{w_t}{1-\alpha}\right)^{1-\alpha} \left(\frac{r_t^K}{\alpha}\right)^{\alpha}. \tag{38}$$

Price setting

In the second step, intermediate goods producing firms determine their price. In each time period a firm can re-optimize its price with probability $1 - \xi < 1$. We define $\tilde{P}_t$ as the price optimally chosen at time t by firms that re-optimize their price. Those firms that cannot re-optimize adjust their price by the inflation rate from the previous period:

$$\hat{P}_t(j) = \hat{P}_{t-1}(j)\pi_{t-1}^{\gamma}, \tag{39}$$

where γ represents the degree of indexation. Using this expression we define $P_{t,t+\tau}$ (which does not depend on the index j) as the level at time $t+\tau$ of a price that was last re-optimized at time t:

$$P_{t,t+\tau} \equiv \tilde{P}_t \prod_{s=1}^{\tau} \pi_{t-1+s}^{\gamma} = \tilde{P}_t \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma}. \tag{40}$$

Firms that are allowed to re-optimize their price maximize the discounted value of expected profits. A firm that is allowed to re-optimize its price therefore faces the following optimization problem:

$$\max_{\tilde{P}_t(j)} \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{\tau} \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t(j)}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} - mc_{t+\tau} \right) Y_{t+\tau}(j) \right]. \tag{41}$$

where $Y_{t+\tau}(j)$ is the demand by the final goods producing firm for intermediate good j with price $P_{t,t+\tau}$. The demand in period $t+\tau$ follows from (31) and is given by:

$$Y_{t+\tau}(j) = \left(\frac{P_{t,t+\tau}(j)}{P_{t+\tau}} \right)^{-\theta} Y_{t+\tau} = \left(\frac{\tilde{P}_t(j)}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} \right)^{-\theta} Y_{t+\tau}. \tag{42}$$

Substituting the demand expression in the maximization problem and rewriting yields:

$$\max_{\tilde{P}_t(j)} \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{\tau} \frac{\lambda_{t+\tau}}{\lambda_t} \left(\left(\frac{\tilde{P}_t(j)}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} \right)^{1-\theta} - \left(\frac{\tilde{P}_t(j)}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} \right)^{-\theta} mc_{t+\tau} \right) Y_{t+\tau} \right]. \tag{43}$$

Maximizing with respect to $\tilde{P}_t(j)$ and multiplying the result by $\tilde{P}_t$ gives:

$$\mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{\tau} \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} \right)^{1-\theta} Y_{t+\tau} \right] \tag{44}$$

$$= \frac{\theta}{\theta-1} \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{\tau} \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^{\gamma} \right)^{-\theta} mc_{t+\tau} Y_{t+\tau} \right], \tag{45}$$

where we dropped the firm index j as all firms are identical at this point. Next we define:

$$F_t^1 \equiv \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^\tau \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^\gamma \right)^{1-\theta} Y_{t+\tau} \right], \tag{46}$$

$$F_t^2 \equiv \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^\tau \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^\gamma \right)^{-\theta} mc_{t+\tau} Y_{t+\tau} \right], \tag{47}$$

so that the first-order constraint in (45) can be rewritten as:

$$F_t^1 = \frac{\theta}{\theta - 1} F_t^2. \tag{48}$$

Define $\tilde{\pi}_t \equiv \frac{\tilde{P}_t}{P_t}$ allows us to write F_t^1 in recursive form as:

$$\begin{aligned}
F_t^1 &\equiv \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^\tau \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^\gamma \right)^{1-\theta} Y_{t+\tau} \right], \\
&= \left(\frac{\tilde{P}_t}{P_t} \right)^{1-\theta} Y_t + \mathbb{E}_t \left[\sum_{\tau=1}^{\infty} (\beta\xi)^\tau \frac{\lambda_{t+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+\tau}} \left(\frac{P_{t-1+\tau}}{P_{t-1}} \right)^\gamma \right)^{1-\theta} Y_{t+\tau} \right], \\
&= \tilde{\pi}_t^{1-\theta} Y_t + \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{1+\tau} \frac{\lambda_{t+1+\tau}}{\lambda_t} \left(\frac{\tilde{P}_t}{P_{t+1+\tau}} \left(\frac{P_{t+\tau}}{P_{t-1}} \right)^\gamma \right)^{1-\theta} Y_{t+1+\tau} \right], \\
&= \tilde{\pi}_t^{1-\theta} Y_t + \mathbb{E}_t \left[\sum_{\tau=0}^{\infty} (\beta\xi)^{1+\tau} \frac{\lambda_{t+1+\tau}}{\lambda_{t+1}} \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\tilde{P}_{t+1}}{P_{t+1+\tau}} \frac{\tilde{P}_t}{\tilde{P}_{t+1}} \left(\frac{P_{t+\tau}}{P_t} \frac{P_t}{P_{t-1}} \right)^\gamma \right)^{1-\theta} Y_{t+1+\tau} \right], \\
&= \tilde{\pi}_t^{1-\theta} Y_t + \mathbb{E}_t \left[\beta\xi \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\tilde{P}_t}{\tilde{P}_{t+1}} \left(\frac{P_t}{P_{t-1}} \right)^\gamma \right)^{1-\theta} \mathbb{E}_{t+1} \left[\sum_{\tau=0}^{\infty} (\beta\xi)^\tau \frac{\lambda_{t+1+\tau}}{\lambda_{t+1}} \left(\frac{\tilde{P}_{t+1}}{P_{t+1+\tau}} \left(\frac{P_{t+\tau}}{P_t} \right)^\gamma \right)^{1-\theta} Y_{t+1+\tau} \right] \right], \\
&= \tilde{\pi}_t^{1-\theta} Y_t + \mathbb{E}_t \left[\beta\xi \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\pi_t^\gamma}{\tilde{\pi}_{t+1}} \right)^{1-\theta} F_{t+1}^1 \right].
\end{aligned} \tag{49}$$

Using the same reasoning, we write F_t^2 in recursive form as:

$$F_t^2 = \tilde{\pi}_t^{-\theta} mc_t Y_t + \mathbb{E}_t \left[\beta\xi \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\pi_t^\gamma}{\tilde{\pi}_{t+1}} \right)^{-\theta} F_{t+1}^2 \right]. \tag{50}$$

The price index (32) can be rewritten as:

$$P_t^{1-\theta} = \int_0^1 P_t(j)^{1-\theta} dj. \tag{51}$$

Splitting between firms that cannot re-optimize their price and therefore update their price according the indexation rule and firms that can optimize their price yields:

$$P_t^{1-\theta} = (1-\xi)\tilde{P}_t^{1-\theta} + \xi \left(P_{t-1}\pi_{t-1}^{\gamma}\right)^{1-\theta}. \tag{52}$$

We divide by $P_t^{1-\theta}$ to get rid of the potentially non-stationary P_t variable and obtain:

$$1 = (1-\xi)\tilde{\pi}_t^{1-\theta} + \xi \left(\frac{\pi_{t-1}^{\gamma}}{\pi_t}\right)^{1-\theta}. \tag{53}$$

The government and central bank

There is no fiscal policy, except for the fact that the government may recapitalize the bank. As this is a zero sum game between the bank and the government, excess profits in the banking sector plus transfers from the government to the household are always equal to the excess profits of the frictionless bank:

$$\Pi_t^B + \Pi_t^G = \Pi_t^B, \tag{54}$$

which helps to simplify the household budget constraint. Furthermore, monetary policy involves the central bank setting the nominal interest rate on bank deposits by responding to inflation according to a Taylor rule:

$$\frac{R_t^D}{R^{D^*}} = \left(\frac{R_{t-1}^D}{R^{D^*}}\right)^{\phi^R} \left(\left(\frac{\pi_t}{\pi^*}\right)^{\phi^P}\right)^{1-\phi^R}, \tag{55}$$

where R^{D^*} is the steady state deposit rate and π^* is steady state inflation.

Market clearing

The supply of each intermediary goods producing firm j must equal the demand from the final goods producing firm:

$$Y_t(j) = Z_t H_t(j)^{1-\alpha} K_t^d(j)^{\alpha} = \left(\frac{P_t(j)}{P_t}\right)^{-\theta} Y_t. \tag{56}$$

Integrating over all intermediary firms and denoting the total supply of intermediary goods by Y_t^I yields the market clearing condition for the intermediary goods market (the final goods market clears by Walras' law):

$$Y_t^I \equiv \int_0^1 Y_t(j)dj = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\theta} djY_t = s_t Y_t, \tag{57}$$

where s_t can be written recursively as:

$$\begin{aligned} s_t &= \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\theta} dj, \\ &= (1-\xi)\left(\frac{\tilde{P}_t}{P_t}\right)^{-\theta} + (1-\xi)\,\xi\left(\frac{\tilde{P}_{t-1}\pi_{t-1}^{\gamma}}{P_t}\right)^{-\theta} + (1-\xi)\,\xi^2\left(\frac{\tilde{P}_{t-2}\pi_{t-1}^{\gamma}\pi_{t-2}^{\gamma}}{P_t}\right)^{-\theta} + ..., \\ &= (1-\xi)\tilde{\pi}_t^{-\theta} + \xi\left(\frac{P_{t-1}\pi_{t-1}^{\gamma}}{P_t}\right)^{-\theta}\left[(1-\xi)\left(\frac{\tilde{P}_{t-1}}{P_{t-1}}\right)^{-\theta} + (1-\xi)\,\xi\left(\frac{\tilde{P}_{t-2}\pi_{t-2}^{\gamma}}{P_{t-1}}\right)^{-\theta} + ...\right], \\ &= (1-\xi)\tilde{\pi}_t^{-\theta} + \xi\left(\frac{\pi_{t-1}^{\gamma}}{\pi_t}\right)^{-\theta} s_{t-1}. \end{aligned} \tag{58}$$

Defining $H_t \equiv \int_0^1 H_t(j)dj$ and $K_t^d \equiv \int_0^1 K_t^d(j)dj$ allows us to rewrite total profits of the intermediary goods producing firms as the value of the total output minus the compensation for labor and capital:

$$\Pi_t^I = Y_t - w_t H_t - r_t^K K_t^d. \tag{59}$$

Substituting the excess profits of the intermediary goods producing firm, the final goods producing firm, and the bank (using Π_t^B, while setting $\Pi_t^G = 0$) into the household budget constraint yields:

$$C_t + I_t = Y_t, \tag{60}$$

which verifies that aggregate demand is equal to aggregate supply.

Appendix B: Model summary

The model is summarized by the following expressions:

The household

$$C_t + D_t + E_t = w_t H_t + \frac{R_{t-1}^D}{\pi_t} D_{t-1} + \frac{R_{t-1}^E}{\pi_t} E_{t-1} + \Pi_t, \tag{61}$$

$$\Pi_t = \Pi_t^I + \Pi_t^F + \Pi_t^B, \tag{62}$$

$$\left(C_t - \frac{\chi {H_t}^{1+\varphi}}{1+\varphi}\right)^{-\sigma} = \lambda_t, \tag{63}$$

$$\chi {H_t}^{\varphi} = w_t, \tag{64}$$

$$\beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{R_t^D}{\pi_{t+1}}\right) = 1, \tag{65}$$

$$\beta\, \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{R_t^E}{\pi_{t+1}}\right) = 1. \tag{66}$$

The bank

$$\Pi_t^B \equiv \frac{R_{t-1}^L}{\pi_t} L_{t-1} - \frac{R_{t-1}^D}{\pi_t} D_{t-1} - \frac{R_{t-1}^E}{\pi_t} E_{t-1} + \Pi_t^K, \tag{67}$$

$$L_t \equiv D_t + E_t, \tag{68}$$

$$E_t \equiv \kappa L_t, \tag{69}$$

$$R_t^L = \frac{(1-\kappa) R_t^D + \kappa R_t^E}{1 + F\left(\bar{\omega}_{t+1} + \hat{\omega}_{t+1}\right) \Gamma\left(\bar{\omega}_t\right) + \Gamma\left(\hat{\omega}_t\right)} \tag{70}$$

$$\Gamma(\bar{\omega}_t) = \bar{\omega}_t - 1 - \sigma_\omega \frac{f\left(0\right) - f\left(\bar{\omega}_t\right)}{F\left(\bar{\omega}_t\right) - F\left(0\right)}, \tag{71}$$

$$\Gamma(\hat{\omega}_t) = \bar{\omega}_t - 1 - \sigma_\omega \frac{f\left(0\right) - f\left(\bar{\omega}_t + \hat{\omega}_t\right)}{F\left(\bar{\omega}_t + \hat{\omega}_t\right) - F\left(0\right)} - \Gamma(\bar{\omega}_t), \tag{72}$$

$$\bar{\omega}_t \equiv (1-\kappa)\frac{R_t^D}{R_t^L} \tag{73}$$

$$\hat{\omega}_t \equiv (S_t/L_t)\,\frac{R_t^D}{R_t^L} \tag{74}$$

$$S_t \equiv \max\left(0; \bar{\omega}_{t-1} - \omega_t\right)\frac{R_{t-1}^L}{\pi_t}L_{t-1}, \tag{75}$$

$$\omega_t \equiv \frac{R_t^K - \delta}{\mathbb{E}_{t-1}\left(R_t^K\right) - \delta} \tag{76}$$

The capital goods producing firm

$$\Pi_t^K \equiv (1+r_t^K)K_{t-1} - \delta K_{t-1} - \frac{R_{t-1}^L}{\pi_t}L_{t-1}, \tag{77}$$

$$K_t \equiv L_t, \tag{78}$$

$$I_t \equiv K_t - (1-\delta)K_{t-1}, \tag{79}$$

$$\frac{R_t^L}{\mathbb{E}_t(\pi_{t+1})} = \mathbb{E}_t\left(R_{t+1}^K\right) - \delta. \tag{80}$$

$$R_t^K = 1 + r_t^K, \tag{81}$$

The intermediary goods producing firms

$$Y_t^I = Z_t {H_t}^{1-\alpha} {K_t^d}^{\alpha}, \tag{82}$$

$$K_t^d = K_{t-1}, \tag{83}$$

$$\log(Z_t) = \rho^Z \log(Z_{t-1}) + \varepsilon_t^Z, \tag{84}$$

$$mc_t = \frac{1}{Z_t}\left(\frac{w_t}{1-\alpha}\right)^{1-\alpha}\left(\frac{r_t^K}{\alpha}\right)^{\alpha}, \tag{85}$$

$$\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{H_t}{K_{t-1}}\right) = \frac{r_t^K}{w_t}, \tag{86}$$

$$\Pi_t^I = Y_t - w_t H_t - r_t^K K_t^d, \tag{87}$$

$$F_t^1 = \tilde{\pi}_t^{1-\theta} Y_t + \mathbb{E}_t\left[\beta\xi\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{\pi_t^{\gamma}}{\tilde{\pi}_{t+1}}\right)^{1-\theta} F_{t+1}^1\right], \tag{88}$$

$$F_t^2 = \tilde{\pi}_t^{-\theta} mc_t Y_t + \mathbb{E}_t\left[\beta\xi\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{\pi_t^{\gamma}}{\tilde{\pi}_{t+1}}\right)^{-\theta} F_{t+1}^2\right], \tag{89}$$

$$F_t^1 = \frac{\theta}{\theta-1} F_t^2, \tag{90}$$

$$1 = (1-\xi)\tilde{\pi}_t^{1-\theta} + \xi\left(\frac{\pi_{t-1}^{\gamma}}{\pi_t}\right)^{1-\theta}. \tag{91}$$

The final goods producing firm

$$\Pi_t^F = 0. \tag{92}$$

The government and central bank

$$\Pi_t^G = 0, \tag{93}$$

$$\frac{R_t^D}{R^{D^*}} = \left(\frac{R_{t-1}^D}{R^{D^*}}\right)^{\phi^R}\left(\left(\frac{\pi_t}{\pi^*}\right)^{\phi^P}\right)^{1-\phi^R}. \tag{94}$$

Market clearing

$$Y_t^I = s_t Y_t, \tag{95}$$

$$s_t = (1-\xi)\tilde{\pi}_t^{-\theta} + \xi \left(\frac{\pi_{t-1}^{\gamma}}{\pi_t}\right)^{-\theta} s_{t-1}. \tag{96}$$

Appendix C: Steady state

In the steady state, the expressions in Appendix B simplify to:

The household

$$C = wH + \left(R^D - 1\right) D + \left(R^E - 1\right) E + \Pi, \tag{97}$$

$$\Pi = \Pi^I + \Pi^F + \Pi^B, \tag{98}$$

$$\left(C - \frac{\chi H^{1+\varphi}}{1+\varphi}\right)^{-\sigma} = \lambda, \tag{99}$$

$$\chi H^{\varphi} = w, \tag{100}$$

$$R^D = \frac{1}{\beta}, \tag{101}$$

$$R^E = \frac{1}{\beta}. \tag{102}$$

The bank

$$\Pi^B = R^L L - R^D D - R^E E + \Pi^K, \tag{103}$$

$$L = D + E, \tag{104}$$

$$E = \kappa L, \tag{105}$$

$$R^L = \frac{(1-\kappa)R^D + \kappa R^E}{1 + F\left(\bar{\omega} + \hat{\omega}\right)\Gamma\left(\bar{\omega}\right) + \Gamma\left(\hat{\omega}\right)} \tag{106}$$

$$\Gamma(\bar{\omega}) = \bar{\omega} - 1 - \sigma_\omega \frac{f\left(0\right) - f\left(\bar{\omega}\right)}{F\left(\bar{\omega}\right) - F\left(0\right)}, \tag{107}$$

$$\Gamma(\hat{\omega}) = \bar{\omega} - 1 - \sigma_\omega \frac{f\left(0\right) - f\left(\bar{\omega} + \hat{\omega}\right)}{F\left(\bar{\omega} + \hat{\omega}\right) - F\left(0\right)} - \Gamma(\bar{\omega}), \tag{108}$$

$$\bar{\omega} = (1-\kappa)\frac{R^D}{R^L} \tag{109}$$

$$\hat{\omega} = \left(S/L\right)\frac{R^D}{R^L} \tag{110}$$

$$S = \max\left(0; \bar{\omega} - \omega\right) R^L L, \tag{111}$$

$$\omega = 1 \tag{112}$$

The capital goods producing firm

$$\Pi^K = (1 + r^K - \delta)K - R^L L, \tag{113}$$

$$K = L, \tag{114}$$

$$I = \delta K, \tag{115}$$

$$R^L = R^K - \delta. \tag{116}$$

$$R^K = 1 + r^K \tag{117}$$

The intermediary goods producing firms

$$Y^I = ZH^{1-\alpha}K^{d\alpha}, \tag{118}$$

$$K^d = K, \tag{119}$$

$$Z = 1, \tag{120}$$

$$mc = \frac{1}{Z}\left(\frac{w}{1-\alpha}\right)^{1-\alpha}\left(\frac{r^K}{\alpha}\right)^{\alpha}, \tag{121}$$

$$\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{H}{K}\right) = \frac{r^K}{w}, \tag{122}$$

$$\Pi^I = Y - wH - r^K K^d, \tag{123}$$

$$F^1 = \frac{Y}{1-\beta\xi}, \tag{124}$$

$$F^2 = \frac{mcY}{1-\beta\xi}, \tag{125}$$

$$F^1 = \frac{\theta}{\theta-1}F^2, \tag{126}$$

$$1 = 1. \tag{127}$$

The final goods producing firm

$$\Pi^F = 0. \tag{128}$$

The government and central bank

$$\Pi^G = 0, \tag{129}$$

$$1 = 1, \tag{130}$$

Market clearing

$$Y^I = sY, \tag{131}$$

$$s = 1. \tag{132}$$

Solving the steady state

Given that:

$$R^E = R^D = \frac{1}{\beta}, \tag{133}$$

we can write:

$$\bar{\omega} \equiv \frac{1-\kappa}{\beta R^L}, \tag{134}$$

and:

$$\hat{\omega} \equiv \frac{S/L}{\beta R^L}. \tag{135}$$

When we focus on a steady state without a shortfall it follows that $S/L = 0$, while otherwise we calibrate $S/L = 0.01$. Using these ingredients, the bank lending rate equals:

$$R^L = \frac{1/\beta}{1 + F\left(\bar{\omega} + \hat{\omega}\right)\Gamma\left(\bar{\omega}\right) + \Gamma\left(\hat{\omega}\right)} \tag{136}$$

which we solve for R^L numerically. Given this value for R^L we obtain $1 + r^K = R^K = R^L$. Noting that $mc = (\theta - 1)/\theta$, we use the value for r^K in:

$$\left(\frac{w}{1-\alpha}\right)^{1-\alpha}\left(\frac{r^K}{\alpha}\right)^{\alpha} = \frac{\theta - 1}{\theta}, \tag{137}$$

to obtain the value of w. Together with the calibrated value $H = \bar{H}$ we then use:

$$\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{H}{K}\right) = \frac{r^K}{w}, \tag{138}$$

to obtain the value of K. The rest of the model can be solved recursively.

Appendix D: Auxiliary derivations for the banking sector

The result in expression (7) is derived as:

$$\begin{aligned} S_{t+1} &\equiv \max\left(0; \frac{R_t^D}{\pi_{t+1}} D_t - \frac{R_t^L}{\pi_{t+1}} L_t - \Pi_{t+1}^K\right), \\ &= \max\left(0; (1-\kappa)\frac{R_t^D}{R_t^L} - 1 - \frac{\Pi_{t+1}^K / L_t}{R_t^L / \pi_{t+1}}\right) \frac{R_t^L}{\pi_{t+1}} L_t, \\ &= \max\left(0; (1-\kappa)\frac{R_t^D}{R_t^L} - \frac{R_{t+1}^K - \delta}{R_t^L / \pi_{t+1}}\right) \frac{R_t^L}{\pi_{t+1}} L_t, \\ &= \max\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t, \end{aligned} \tag{139}$$

where we get from the first line to the second line by using the balance sheet identity in (3) and the equity requirement in (4), while factoring out $\frac{R_t^L}{\pi_{t+1}} L_t$. The third line follows from the description of the capital producing firm in Appendix A, which shows that $\Pi_t^K \equiv R_t^K K_{t-1} - \delta K_{t-1} - \frac{R_{t-1}^L}{\pi_t} L_{t-1}$ and $K_t = L_t$. The last line follows from defining $\bar{\omega}_t \equiv (1-\kappa)\frac{R_t^D}{R_t^L}$ and $\omega_{t+1} \equiv \frac{R_{t+1}^K - \delta}{R_t^L / \pi_{t+1}} = \frac{R_{t+1}^K - \delta}{\mathbb{E}_t\left(R_{t+1}^K\right) - \delta}$.

The result in expression (10) is derived as:

$$\begin{aligned} \Gamma(\bar{\omega}_t) &\equiv \int_0^{\bar{\omega}_t} (\bar{\omega}_t - \omega_{t+1}) f(\omega_{t+1}) d\omega_{t+1}, \\ &= \mathbb{E}_t\left(\bar{\omega}_t - \omega_{t+1} | 0 < \omega_{t+1} < \bar{\omega}_t\right), \\ &= \bar{\omega}_t - \mathbb{E}_t\left(\omega_{t+1} | 0 < \omega_{t+1} < \bar{\omega}_t\right), \\ &= \bar{\omega}_t - \mathbb{E}_t\left(\omega_{t+1}\right) - \sigma_\omega \frac{f(0) - f(\bar{\omega}_t)}{F(\bar{\omega}_t) - F(0)}, \\ &= \bar{\omega}_t - 1 - \sigma_\omega \frac{f(0) - f(\bar{\omega}_t)}{F(\bar{\omega}_t) - F(0)}, \end{aligned} \tag{140}$$

where the fourth line uses the fact that $\mathbb{E}_t\left(\omega_{t+1} | 0 < \omega_{t+1} < \bar{\omega}_t\right)$ is the expectation of a truncated normal distribution $\mathcal{N}(1, \sigma_\omega)$ that is bounded from below by 0 and bounded from above by $\bar{\omega}_t$.

The result in expression (11) follows from:

$$
\begin{aligned}
& \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t - \max\left(0; \Pi_{t+1}^K + \frac{R_t^L}{\pi_{t+1}} L_t - \frac{R_t^D}{\pi_{t+1}} D_t\right)\right) \\
= \quad & \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t - \max\left(0; \omega_{t+1} - \bar{\omega}_t\right) \frac{R_t^L}{\pi_{t+1}} L_t\right), \\
= \quad & \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t + \min\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t\right) + S_{t+1} - S_{t+1}, \\
= \quad & \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t + \min\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t\right) + \max\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t - S_{t+1}, \\
= \quad & \max\left(\max\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t, \frac{R_t^D}{\pi_{t+1}} S_t + \left(\bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t\right) - S_{t+1}, \\
= \quad & \max\left(0, \frac{R_t^D}{\pi_{t+1}} S_t + \left(\bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t\right) - S_{t+1}, \\
= \quad & \max\left(0, \bar{\omega}_t + \hat{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t - S_{t+1}, \qquad (141)
\end{aligned}
$$

where the second line follows from using the negative of the definition of the shortfall in (7). The third line uses $-\max\left(0; \omega_{t+1} - \bar{\omega}_t\right) = \min\left(0; \bar{\omega}_t - \omega_{t+1}\right)$, and adds and subtracts the shortfall S_{t+1}. The fourth line uses the definition of the shortfall in (7). The expression in the fifth line is obtained by factoring $\max\left(0; \bar{\omega}_t - \omega_{t+1}\right) \frac{R_t^L}{\pi_{t+1}} L_t$ in the first maximization operator and noting that $\max(0, \bar{\omega}_t - \omega_{t+1}) + \min(0, \bar{\omega}_t - \omega_{t+1}) = \bar{\omega}_t - \omega_{t+1}$. The sixth line follows from evaluating the fifth line for $S_t = 0$ and also for $S_t > 0$, and observing that the result in both cases can be written as the sixth line. The last line defines $\hat{\omega}_t \equiv \mathbb{E}_t\left(\frac{R_t^D}{\pi_{t+1}} S_t / \frac{R_t^L}{\pi_{t+1}} L_t\right) = \left(S_t / L_t\right) \frac{R_t^D}{R_t^L}$.

The result in expression (13) follows from first observing that:

$$
\begin{aligned}
& \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi_{t+1+\tau}^B - S_{t+1+\tau}\right) + \\
& \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\int_0^{\bar{\omega}_{t+\tau} + \hat{\omega}_{t+\tau}} \left(\left(\bar{\omega}_{t+\tau} + \hat{\omega}_{t+\tau} - \omega_{t+1+\tau}\right) \frac{R_{t+\tau}^L}{\pi_{t+1+\tau}} L_{t+\tau}\right) f(\omega_{t+1+\tau}) d\omega_{t+1+\tau}\right), \\
= \quad & \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\Pi_{t+1+\tau}^B - S_{t+1+\tau}\right) + \\
& \mathbb{E}_t \sum_{\tau=0}^{\infty} \Lambda_{t+1+\tau} \left(\int_0^{\bar{\omega}_{t+\tau} + \hat{\omega}_{t+\tau}} \left(\left(\bar{\omega}_{t+\tau} - \omega_{t+1+\tau}\right) \frac{R_{t+\tau}^L}{\pi_{t+1+\tau}} L_{t+\tau} + \frac{R_{t+\tau}^D}{\pi_{t+1+\tau}} S_{t+\tau}\right) f(\omega_{t+1+\tau}) d\omega_{t+1+\tau}\right), \qquad (142)
\end{aligned}
$$

and then taking the derivative with respect to L_t using Leibniz's integral rule. This derivative equals:

$$
\begin{aligned}
&\Lambda_{t+1}\frac{\partial \Pi^B_{t+1}}{\partial L_t} - \Lambda_{t+1}\frac{\partial S_{t+1}}{\partial L_t} + \Lambda_{t+1}\int_0^{\bar{\omega}_t+\hat{\omega}_t}(\bar{\omega}_t-\omega_{t+1})\frac{R^L_t}{\pi_{t+1}}f(\omega_{t+1})d\omega_{t+1}\\
&+\Lambda_{t+1}\left[(\bar{\omega}_t-\bar{\omega}_t-\hat{\omega}_t)\frac{R^L_t}{\pi_{t+1}}L_t+\frac{R^D_t}{\pi_{t+1}}S_t\right]f(\bar{\omega}_t+\hat{\omega}_t)\frac{\partial(\bar{\omega}_t+\hat{\omega}_t)}{\partial L_t}\\
&+\Lambda_{t+2}\int_0^{\bar{\omega}_{t+1}+\hat{\omega}_{t+1}}\left(\frac{R^D_{t+1}}{\pi_{t+2}}\frac{\partial S_{t+1}}{\partial L_t}\right)f(\omega_{t+2})d\omega_{t+2}\\
&+\Lambda_{t+2}\left[(\bar{\omega}_{t+1}-\bar{\omega}_{t+1}-\hat{\omega}_{t+1})\frac{R^L_{t+1}}{\pi_{t+2}}L_{t+1}+\frac{R^D_{t+1}}{\pi_{t+2}}S_{t+1}\right]\times f(\bar{\omega}_{t+1}+\hat{\omega}_{t+1})\frac{\partial(\bar{\omega}_{t+1}+\hat{\omega}_{t+1})}{\partial L_t},
\end{aligned}
\tag{143}
$$

where the expressions in the second and fourth line are equal to zero as the terms between square brackets are zero. Noticing that $\frac{\partial S_{t+1}}{\partial L_t} = \Gamma(\bar{\omega}_t)\frac{R^L_t}{\pi_{t+1}}$ and using $\Lambda_{t+2}\frac{R^D_{t+1}}{\pi_{t+2}} = \Lambda_{t+1}$ gives:

$$
\begin{aligned}
&\Lambda_{t+1}\frac{\partial \Pi^B_{t+1}}{\partial L_t} - \Lambda_{t+1}\Gamma(\bar{\omega}_t)\frac{R^L_t}{\pi_{t+1}} + \Lambda_{t+1}\int_0^{\bar{\omega}_t+\hat{\omega}_t}(\bar{\omega}_t-\omega_{t+1})\frac{R^L_t}{\pi_{t+1}}f(\omega_{t+1})d\omega_{t+1}\\
&+\Lambda_{t+1}\int_0^{\bar{\omega}_{t+1}+\hat{\omega}_{t+1}}\Gamma(\bar{\omega}_t)\frac{R^L_t}{\pi_{t+1}}f(\omega_{t+2})d\omega_{t+2},
\end{aligned}
\tag{144}
$$

which can be simplified as:

$$
\begin{aligned}
&\Lambda_{t+1}\frac{\partial \Pi^B_{t+1}}{\partial L_t} + \Lambda_{t+1}\left(\int_0^{\bar{\omega}_t+\hat{\omega}_t}(\bar{\omega}_t-\omega_{t+1})f(\omega_{t+1})d\omega_{t+1}-\Gamma(\bar{\omega}_t)\right)\frac{R^L_t}{\pi_{t+1}}\\
&+\Lambda_{t+1}F(\bar{\omega}_{t+1}+\hat{\omega}_{t+1})\Gamma(\bar{\omega}_t)\frac{R^L_t}{\pi_{t+1}},
\end{aligned}
\tag{145}
$$

where in the second line we used $\int_0^{\bar{\omega}_{t+1}+\hat{\omega}_{t+1}} f(\omega_{t+2})d\omega_{t+2} = \int_0^{\bar{\omega}_{t+1}+\hat{\omega}_{t+1}} f(\omega_{t+1})d\omega_{t+1} = F(\bar{\omega}_{t+1}+\hat{\omega}_{t+1})$. Defining $\Gamma(\hat{\omega}_t) \equiv \int_{\bar{\omega}_t}^{\bar{\omega}_t+\hat{\omega}_t}(\bar{\omega}_t-\omega_{t+1})f(\omega_{t+1})d\omega_{t+1} = \int_0^{\bar{\omega}_t+\hat{\omega}_t}(\bar{\omega}_t-\omega_{t+1})f(\omega_{t+1})d\omega_{t+1}-\Gamma(\bar{\omega}_t)$, solving $\frac{\partial \Pi^B_{t+1}}{\partial L_t}$, setting the resulting expression equal to zero and rearranging then gives:

$$
R^L_t = \frac{(1-\kappa)R^D_t+\kappa R^E_t}{1+F(\bar{\omega}_{t+1}+\hat{\omega}_{t+1})\Gamma(\bar{\omega}_t)+\Gamma(\hat{\omega}_t)}. \tag{146}
$$