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Macroprudential capital requirements, monetary policy, and financial crises[☆]

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ABSTRACT

How should bank capital requirements be designed in order to reduce the frequency and severity of financial crises? What is the role of monetary policy in this context? To answer these questions, we develop a New-Keynesian dynamic stochastic general equilibrium (DSGE) model in which the economy endogenously switches between normal times and financially turbulent times. Banks do not internalize that lower leverage contributes to the stability of the entire financial system. This creates a role for bank capital regulation. The proposed model replicates many of the dynamics observed during US financial crises. Basel-III-style capital buffers reduce the probability and length of financial crises while also reducing the size of the financial and non-financial sectors. Monetary policies that are more accommodative during financial crises can moderate economic downturns, thereby lowering the durations of financial distress. A combination of a small countercyclical capital buffer accompanied by a relief measure and an accommodative monetary policy during crises increases welfare.

1. Introduction

The Great Financial Crisis of 2007–2009 and the subsequent Great Recession reminded us starkly of the prominent role of financial factors for the real economy. It is commonly agreed that the preceding buildup of financial risk in the financial intermediation sector has been one of the main causes of the severity of the financial and economic downturn. This has brought the role of macroprudential policy, and, in particular, macroprudential capital requirements to the forefront of policy discussions worldwide. Macroprudential policies aim to prevent large disruptions to the financial system as a whole with potentially serious consequences for the real economy (e.g., ESRB, 2014). At the same time, the role of monetary policy for systemic risk and its potential interactions with macroprudential policy are widely discussed as monetary policy directly affects banks' balance sheets through interest rates and asset prices.

Missing from this discussion is a macroeconomic model that captures infrequent large disruptions to the financial sector while allowing for the joint analysis of macroprudential capital buffers and monetary policy. Our paper fills this gap. We develop a quantitative model that replicates many of the dynamics observed around US financial crises without resorting to exogenous disturbances of extraordinary size. Instead, the time-varying risk of large financial disruptions is endogenously determined by the degree of imbalances building up in the banking system. We employ perturbation techniques to facilitate the inclusion of nominal rigidities, allowing us to consider the role of monetary policy. This model is then used to examine the effects of

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capital requirements and monetary policy on the frequency and severity of financial crises and on overall economic activity.

Our New Keynesian dynamic stochastic general equilibrium (DSGE) model features leverage-constrained financial intermediaries along the lines of Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). In contrast to the original framework, we allow certain parameters to vary over time. In particular, we calibrate the key parameters that determine financial conditions to distinguish between *normal* and *financial distress* periods, as identified in US data. The probability of a regime switch is determined endogenously by assuming that higher banking-sector leverage is associated with a higher risk of entering or remaining in a period of financial distress. We further amend the model by allowing banks to issue equity, which provides them with an instrument to affect the strength of their balance sheet and, hence, their intermediation capacity (e.g., Holden et al., 2019; Akinci and Queralto, 2022). As individual banks are assumed to take aggregate conditions as given, they do not internalize their contribution to overall financial stability when choosing how much equity to issue. Therefore, in general, too little equity is issued compared to the social optimum. This creates a role for macroprudential regulation, which we introduce in the form of different Basel-III-style bank capital requirements. Specifically, we consider constant and countercyclical capital buffers,[1] which are potentially accompanied by capital relief measures. Such relief measures allow banks to free up bank capital when they incur large losses. We also consider the role of monetary policy for financial stability. In particular, we analyze the implications of regime-specific monetary policy rules. Because common solution methods are unsuitable for analyzing regime-switching DSGE models, we solve the model using the RISE toolkit, which relies on perturbation methods (Binning and Maih, 2017; Maih, 2015).

We find that all capital buffers reduce the time spent in the high-friction regime and, thereby, financial and macroeconomic volatility. This is achieved by increasing equity issuance and, hence, reducing leverage. However, doing so comes at the cost of reducing economic activity, which has negative consequences for welfare. Countercyclical capital buffers shift equity issuance from turbulent to normal times. Thereby, they are more effective in reducing the probability and length of financial crises than constant capital buffers. As such, the positive welfare effects arising from reduced volatility can outweigh the negative consequences of reduced economic activity, but only for a tiny countercyclical buffer accompanied by a relief measure. Furthermore, we find that monetary policies that are more accommodative during financially turbulent times, can moderate economic downturns and reduce the time spent in periods of financial distress. This suggests that monetary authorities should be responsive to financial cycles. Interestingly, there is recent evidence by Maih et al. (2021) that such a policy has been pursued by the US Federal Reserve Bank (Fed) during the last two decades. Considering possible interactions between macroprudential and monetary policy, we find that, in most cases, the two policies are complementary.

Our paper relates to several strands in the literature. As mentioned above, our model can replicate many of the stylized facts related to US financial crises without resorting to exogenous disturbances of extraordinary size as, e.g., Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) do. The latter two feature financial intermediation sectors similar to ours, but analyze the model's behavior around a single steady state in which the same constraint always binds (i.e., *constant-parameter* DSGE models). Our model, on the other hand, features two steady states which are characterized by different degrees of financial frictions. When the buildup of banking sector leverage drives the economy from the low-friction to the high-friction state-of-the-world, the model endogenously produces realistic crises dynamics.[2] Employing a model with an endogenous crisis probability enables us to assess the efficacy of different policies with respect to reducing systemic risk, which is the main aim of macroprudential policy. This distinguishes our analyses from a large body of literature analyzing macroprudential capital requirements and, partly, also monetary policy, in constant-parameter financial DSGE models, e.g., Christensen et al. (2011), Kannan et al. (2012), Angelini et al. (2014), Quint and Rabanal (2014), Bailliu et al. (2015), Gelain and Ilbas (2017), De Paoli and Paustian (2017), Liu and Molise (2019), de Blas and Malmierca (2020), Pozo (2023), Lubello and Rouabah (2024). As none of these models features endogenous financial crises, the reference studies are constrained to examining the efficacy of policies with respect to stabilizing business cycles. Our study is more closely related to those of Gertler et al. (2020), Elenev et al. (2021) and Akinci and Queralto (2022). These analyses share with ours the following features: They produce realistic crises dynamics endogenously, via the banking sector; banks do not internalize the effects of equity issuance on financial stability; and they consider macroprudential policies which address this externality by requiring banks to reduce leverage.[3] Hence, they all share the ability to examine the efficacy of macroprudential capital requirements with respect to reducing systemic risk. An important difference between the study by Akinci and Queralto (2022) and ours is that instead of considering equity subsidies, we model macroprudential policy more realistically as a Basel-III-style capital buffer. Modeling macroprudential policy as an equity subsidy is a common shortcut in the literature (see also Gertler et al., 2012). However, this approach tends to overstate the positive effects of capital requirements, as it essentially lowers the equity issuance costs for banks. Furthermore, we distinguish ourselves from all three of these studies by solving our model with perturbation techniques instead of relying on global solution methods. Doing so facilitates the inclusion of nominal rigidities and, hence, allows us to analyze the systemic risk implications of monetary policy and its potential interaction with macroprudential policy. Note that, Žáček (2020) and Boissay et al. (2023) analyze the implications of monetary policy on financial stability in economies with endogenous financial crises, but they do not consider regime-dependent monetary policies or macroprudential capital requirements. In summary, the novelty of our approach lies in our joint analysis of the systemic risk implications of macroprudential capital requirements and monetary policies using a single framework that endogenously produces realistic financial crisis dynamics.

In the next section we review classifications of US financial crises to identify and quantify periods of financial turmoil in US data. Section 3 provides an overview of our theoretical model. The solution technique and the calibration of standard and regime-specific parameters are outlined in Section 4. The results are then discussed in Sections 5–7. Finally, Section 8 concludes this article.

2. Chronology of periods of financial distress in the US

Various financial crisis classifications have been proposed, and the most prominent Reinhart and Rogoff (2009) defines a crisis as a rare event that results in bank failure and the provision of government relief

[1] We model countercyclical capital buffers as capital buffers that are only in place during normal times.

[2] There are further macroeconomic models endogenously producing realistic crises dynamics via a financial sector, e.g., Boissay et al. (2016), He and Krishnamurthy (2019). However, as they do not analyze the systemic risk implications of macroprudential or monetary policies they are not further discussed here.

[3] There are further important accounts of macroprudential capital requirements in economies with endogenous crisis dynamics, which, however, build upon quite different financial intermediation sectors or focus on different externalities addressed by macroprudential policy, e.g., Lorenzoni (2008), Collard et al. (2017), Bianchi and Mendoza (2018). Therefore, they are not further discussed here.

Table 1
Chronology of US financial crises.

Crisis	Period	LSN	RR	LV	BB
Commercial Bank Capital Squeeze	1973–1975	✓	–	–	✓
Less Developed Countries Debt Threat	1982–1984	✓	–	–	✓[a]
Savings and Loans Crisis	1988–1991	✓	✓[a]	✓[a]	✓[a]
Asian Crisis and NASDAQ Bubble	1997–2002	–	–	–	✓
Great Recession and aftermath	2007–2009	✓	✓	✓[a]	✓[a]

Notes: LSN: Lopez-Salido and Nelson (2010); RR: Reinhart and Rogoff (2009); LV: Laeven and Valencia (2018); BB: Brave and Butters (2012). Timeframe: 1968Q1–2019Q4.

[a] Different timing.

to financial institutions. Reinhart and Rogoff (2009) focused on the postwar US economy and found only two significant crises: the Savings and Loans Crisis of the mid-1980s and the Great Recession of 2007–2009. Other authors have revisited this crisis chronology by exploring the crisis narrative in more detail (e.g., revising journal articles and public speeches of leading policy makers from periods of financial turmoil) or by counting the number of failed institutions or distress mergers. Table 1 presents a selection of alternative classifications of periods of financial distress. Contrasting the work of Reinhart and Rogoff (2009), Lopez-Salido and Nelson (2010) identify the periods of 1973–1975 and 1982–1984 as two additional crises by focusing on strains on bank capital and bank failures. By interpreting a financial crisis even more broadly, as any form of heightened stress to the US financial system, Brave and Butters (2012)[4] also include the Asian Crisis. Documenting systemic banking crises, Laeven and Valencia (2018) identify the Savings and Loans Crisis in 1988. In the current work, we use the dating method of Lopez-Salido and Nelson (2010) because it views a financial crisis as an episode of financial turmoil that leads to bank closures and consolidations based on the elevated pressure applied to banks' balance sheets. However, an "episode of financial turmoil" does not necessarily indicate an extreme event (Laeven and Valencia, 2018), nor does it describe every brief episode of distress (Brave and Butters, 2012).

Fig. 1 plots the dynamics of certain real and financial variables in the US around the onset of a financial crisis regime, as classified by Lopez-Salido and Nelson (2010). Prior to the beginning of a crisis the economy grows. In these boom times, financial vulnerabilities start to build up. Banks enlarge their balance sheets and increase their leverage. About one to two quarters before the onset of the crisis, gross domestic product (GDP), investment and bank assets begin to drop, banks start to deleverage and credit spreads soar.[5] By definition of the crisis, with its onset, bank equity experiences a large drop. Within a short time after the onset of the crisis, financial variables begin to recover. However, after one year, GDP and investment still continue to fall. In Section 5, we compare the dynamics around financial crises produced by our theoretical model to the dynamics shown in Fig. 1.

3. Model

3.1. Overview

We set up a New Keynesian DSGE model of a closed economy with a financial intermediation sector along the lines of Gertler and Kiyotaki (2010) and Gertler and Karadi (2011). In this model, intermediate goods firms require funding from banks to finance their expenses. Banks are subject to a financial friction that requires them to have some "skin in the game", giving rise to a time-varying external finance premium and an acceleration of exogenous disturbances in the financial sector. Contrasting the original setup of the banking sector, we allow banks to optimally adjust the amount of equity during each period (see also Holden et al., 2019; Akinci and Queralto, 2022).

We assume that the economy endogenously shifts between two regimes, $r_t \in (l, h)$, which are characterized by different degrees of financial friction: **l**ow and **h**igh. These are calibrated to represent normal and financial turmoil periods, respectively. The switching probability depends on the degree of leverage of the aggregated banking system. Apart from financial intermediaries, there are households, a consumption goods producing sector, an intermediate goods producing sector, a capital goods producing sector and a monetary authority. In Section 6, we introduce the macroprudential regulator; the model features capital adjustment costs and price rigidities.

In the following subsections we will describe the model in more detail and present our equilibrium equations.

3.2. Households

There are two member types within any given household: workers and bankers. The former supplies work, L_t, to intermediate goods firms and deposits, D_t, to banks, and the latter manages a financial intermediary and transfers retained earnings back to her household when the lifetime of the bank ends. Within each household there is perfect consumption risk sharing, which allows to maintain the representative-agent framework. The fraction of household members who are workers is denoted by $1-f$, whereas the remaining household members, f, are assumed to be bankers. Between periods, there is a random turnover between these groups: with probability $\theta(r_r)$ a banker will stay a banker and with probability $1-\theta(r_t)$ the lifetime of the bank ends and the banker becomes a worker.[6] Simultaneously, a fraction of former workers becomes bankers so that the relative proportion remains fixed. New bankers are assumed to be provided startup funds from their respective households.

The lifetime utility of a representative worker, who draws utility from consumption C_t and disutility from labor L_t, is given by

$$E_t \sum_{k=0}^{\infty} \beta \frac{\left(C_{t+k} - \psi_L \frac{L_{t+k}^{1+\phi_L}}{1+\phi_L}\right)^{1-\sigma} - 1}{1-\sigma}.$$

The functional form of utility follows Greenwood et al. (1988), which implies non-separability between consumption and leisure. As can be directly seen from first-order condition (2), under this assumption, the marginal rate of substitution between consumption and labor is independent of consumption. This eliminates the wealth effect on labor supply such that labor supply remains independent of consumption dynamics.

[4] Brave and Butters (2012) use weekly dating of financial crises. All the other authors use yearly dating.

[5] The graphs display a short period of economic and financial turbulence about six quarters before the onset of the crisis. It is conjectured that this dip is the result of a relatively short time span (12 quarters) between the two crises in the eighties. If we restrict our attention to episodes where the tranquil episode had lasted at least 20 quarters before the economy entered financially turbulent times, hence, excluding the second crisis of the eighties, the dip disappears.

[6] The supplement (r_t) marks this parameter as regime-specific.

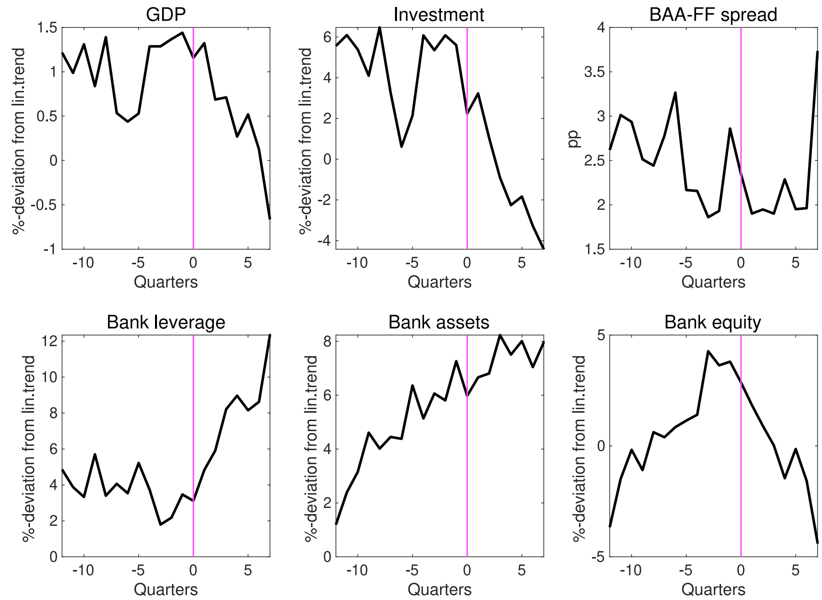

Fig. 1. Average dynamics around US financial crises.
Notes: US data (1968Q1:2019Q4) from Board of Governors of the Federal Reserve System, authors' calculations. BAA-FF spread refers to Moody's Seasoned Baa Corporate Bond Minus Federal Funds Rate. The data is reported in logs and linearly detrended, apart from the credit spread, which is expressed in percentage points (pp). (Book) Leverage is calculated as the ratio of bank assets and bank (book) equity. Definition of crises according to Lopez-Salido and Nelson (2010).

The household's period-by-period budget constraint is given by

$$C_t + D_t = R_{t-1} D_{t-1} + w_t L_t + NP_t + T_t,$$

where NP_t denotes net profits from the ownership of firms (financial and non-financial), T_t are lump-sum taxes or transfers, w_t denotes the real wage rate and R_{t-1} is the gross real risk-free rate of return from deposit holdings between $t-1$ and t.

Hence, the consumption Euler equation and the household labor supply condition take the following forms

$$\lambda_t = \beta E_t R_t \lambda_{t+1}, \tag{1}$$

$$w_t = \psi_L L_t^{\phi_L}, \tag{2}$$

where $\lambda_t = \left(C_t - \psi_L \frac{L_t^{1+\phi_L}}{1+\phi_L} \right)^{-\sigma}$ denotes the marginal utility of consumption.

3.3. Banks

Each bank channels household deposits, d_t, intra-period non-contingent debt, $s_{W,t}$, and internal funds, n_t, to non-financial firms.[7] Intra-period non-state-contingent debt is only used to finance intra-period working capital (WC) loans, which firms use to pay their wage bill in advance, i.e., $s_{W,t} = w_t L_t$.[8] The gross rate of return on WC loans is given by $R_{L,t}$. Profits from the extension of intra-period loans, $(R_{L,t} - R_{t-1}) s_{W,t}$, can be used to finance risky inter-period capital loans provided during the same period. Therefore, a bank's balance sheet is given by

$$Q_t s_t = d_t + n_t + \Delta_{L,t} s_{W,t},$$

where Q_t denotes the price of a unit of capital, s_t denotes state-contingent claims on a unit of capital used in intermediate goods production and $\Delta_{L,t} \equiv R_{L,t} - R_{t-1}$ is the working capital loan spread.[9]

Net wealth evolves according to

$$n_t = R_{k,t} Q_t s_t + e_{t-1} - R_{t-1} d_{t-1},$$

where $R_{k,t}$ is the state-contingent gross real rate of return on capital assets and e_t is new equity provided to the bank by its respective household at the end of period t.

We assume that each period a fraction 1-$\theta(r_t)$ of bankers exit the business with i.i.d. probability and pay out accumulated earnings to their respective households.[10] Note that parameter $\theta(r_t)$ is regime-specific, i.e., it is calibrated to adopt different values in the two different regimes.

To motivate the requirement to build up net wealth, we assume that the continuation value of the bank, V_t, must always be larger than a fraction λ of total asset holdings, i.e.,

$$V_t \geq \lambda (Q_t s_t + (1 - \Delta_{L,t}) s_{W,t}).$$

Gertler and Kiyotaki (2010) motivate this incentive constraint with the possibility that the banker could divert fraction λ of assets and would in turn be forced into bankruptcy. Hence, depositors will only provide funds to the bank as long as the incentive constraint holds. A different motivation for this constraint is to consider λ to be a management buffer which is decided upon by the banker, for example, to minimize the risk of breaching certain regulatory capital buffers or to ensure a favorable external credit rating. In any case, λ can be interpreted as the minimum capital ratio required by bank stakeholders, i.e.,

$$\lambda \leq \frac{V_t}{Q_t s_t + (1 - \Delta_{L,t}) s_{W,t}}. \tag{3}$$

[7] The variables of individual banks are denoted by lowercase letters.

[8] With respect to working capital loans, we follow (Akinci and Queralto, 2022) who, in turn, apply the timing assumptions proposed by Neumeyer and Perri (2005). Hence, for a more detailed description of the modeling of intra-period working capital loans, the reader is referred to Online Appendix C of Akinci and Queralto (2022) or the original work by Neumeyer and Perri (2005).

[9] Note that in Akinci and Queralto (2022), WC loans are introduced to boost the financial accelerator mechanism. Alternatively, our nominal model introduces WC loans to ensure that the change in inflation related to regime changes is constrained to realistic values.

[10] This arrangement precludes bankers from aggregating so much net wealth that their incentive constraint becomes irrelevant for them.

To solve the banker's maximization problem, define the objective of the bank recursively as

$$V_t = \max \quad E_t \Lambda_{t,t+1}[(1-\theta(r_t))(R_{k,t+1}Q_t s_t - R_t d_t) + \theta(r_t)[V_{t+1}(n_{t+1}) - e_t - C(e_t, n_t)]],$$

with $\Lambda_{t,t+1} \equiv \beta \frac{\lambda_{t+1}}{\lambda_t}$ denoting the real stochastic discount factor of a household. If the banker exits, it pays out assets minus liabilities at the beginning of the next period, before further equity is issued. If it stays in business, it has the opportunity to issue more equity. In that case, it maximizes expected future payouts net of equity issuance and associated costs. The latter are agency costs arising from informational frictions, commitment problems etc. As in Holden et al. (2019) and Akinci and Queralto (2022), we assume that equity issuance costs increase in total equity issued, which is in line with empirical evidence by Altinkiliç and Hansen (2000). Following Akinci and Queralto (2022), equity issuance costs are assumed to take a quadratic form, $C(e_t, n_t) = \frac{\kappa(r_t)}{2} x_t^2 n_t$, where $x_t \equiv \frac{e_t}{n_t}$. Parameter $\kappa(r_t)$ drives the cost of raising equity and is also assumed to be regime-specific.

Following the derivations by Akinci and Queralto (2022), we guess that the value function depends on net wealth in the following form, $V_t(n_t) = \gamma_t n_t$, where γ_t captures the value of an extra unit of net wealth. Define

$$\mu_t \equiv E_t \Lambda_{t,t+1}(1-\theta(r_t)+\theta(r_t)\gamma_{t+1})(R_{k,t+1}-R_t), \tag{4}$$

$$\upsilon_t \equiv E_t \Lambda_{t,t+1}(1-\theta(r_t)+\theta(r_t)\gamma_{t+1})R_t, \tag{5}$$

$$\nu_{e,t} \equiv E_t \Lambda_{t,t+1}(\gamma_{t+1}-1), \tag{6}$$

where μ_t is the marginal gain from expanding bank assets, υ_t is the marginal gain of an additional unit of net wealth, and $\nu_{e,t}$ the marginal gain of an additional unit of equity. Hence, the problem of the bank simplifies to

$$\gamma_t n_t = \max_{s_t, s_{W,t}, e_t} \mu_t Q_t s_t + \upsilon_t \Delta_{L,t} s_{W,t} + \theta(r_t)(\nu_{e,t} e_t - C(e_t, n_t))$$

subject to the incentive constraint

$$\mu_t Q_t s_t + \upsilon_t \Delta_{L,t} s_{W,t} + \upsilon_t n_t + \theta(r_t)(\nu_{e,t} e_t - C(e_t, n_t)) \le \lambda(Q_t s_t + (1-\Delta_{L,t}) s_{W,t}).$$

Letting ζ_t denote the Lagrange multiplier on the incentive constraint, the solution to the maximization problem of the bank is given by

$$\nu_{e,t} = \kappa(r_t) x_t \tag{7}$$

and

$$(1+\zeta_t)\mu_t = \zeta_t \lambda \text{ and}$$
$$(1+\zeta_t)\upsilon_t \Delta_{L,t} = \xi_t \lambda (1-\Delta_{L,t}),$$

which can be combined into

$$\Delta_{L,t} = \frac{\mu_t}{\mu_t + \upsilon_t}. \tag{8}$$

Note that the coefficients of the value functions depend exclusively on aggregate variables; hence, the same first-order conditions apply to the entire banking sector, which makes aggregation trivial. Assuming that the incentive constraint binds,[11] it can be expressed in terms of the coefficients of the value function,

$$Q_t S_t + (1-\Delta_{L,t}) S_{W,t} = \frac{\upsilon_t + \theta(r_t)\frac{\kappa(r_t)}{2} x_t^2}{\lambda - \mu_t} N_t \equiv \phi_t N_t, \tag{9}$$

where the capital letters refer to the aggregated values of the respective variables, i.e., $Q_t S_t + (1-\Delta_{L,t}) S_{W,t}$ denote the total assets of the banking system, and N_t is the aggregate net wealth. ϕ_t is the ratio of intermediated assets to net wealth, which can be referred to as the leverage ratio. Note that it is determined endogenously in this model. Combining Eq. (9) and the binding incentive constraint, we obtain $\gamma_t = \phi_t \lambda$ and, hence, the guess can be verified.

Finally, the evolution of aggregate bank net wealth is given by

$$N_t = (N_{n,t} + N_{e,t}) e_{t,N}, \text{ with} \tag{10}$$

$$N_{e,t} = \theta(r_t)\big[(R_{k,t} - R_{t-1}) Q_{t-1} S_{t-1} + R_{t-1} N_{t-1} + R_{t-1} \Delta_{L,t} S_{W,t-1} + E_{t-1}\big], \tag{11}$$

$$N_{n,t} = \omega(r_t) Q_t S_{t-1}, \tag{12}$$

where $N_{e,t}$ denotes existing bankers' net wealth, $N_{n,t}$ denotes new bankers' net wealth, E_t denotes aggregate equity, and regime-specific $\omega(r_t)$ is the fraction of the assets given to new bankers by their respective households. Variable $e_{t,N}$ denotes an exogenous disturbance to the net wealth of bankers.

3.4. Intermediate goods firms

Competitive intermediate goods producing firms sell their products to final goods producers at price $P_{m,t}$.

The Cobb–Douglas production function of the representative intermediate goods firm is given by

$$Y_{m,t} = A_t K_{t-1}^{\alpha} L_t^{1-\alpha}, \tag{13}$$

where $Y_{m,t}$ denotes the intermediate output and A_t technology. Parameter α denotes the output elasticity of capital. Capital stock K_{t-1} was bought from capital goods producers in the previous period at price Q_{t-1}. To finance capital purchases, the firm issues state-contingent securities to financial intermediaries at the same amount and price as capital, i.e.,

$$Q_t K_t = Q_t S_t. \tag{14}$$

After being used in production, the depreciated capital stock $(1-\delta)K_{t-1}$ is sold back to the capital goods producers.

Hence, the firm chooses its labor demand optimally as follows,

$$w_t = \frac{(1-\alpha) P_{m,t} Y_{m,t}}{L_t R_{L,t}}. \tag{15}$$

The optimal choice of capital implies that the ex-post real return of capital is given by

$$R_{k,t} = \frac{\frac{\alpha P_{m,t} Y_{m,t}}{K_{t-1}} + (1-\delta) Q_t}{Q_{t-1}}. \tag{16}$$

3.5. Capital goods firms

Competitive capital goods firms produce new capital and refurbish depreciated capital using the final output as input. The law of motion for capital is given by

$$K_t = (1-\delta) K_{t-1} + I_t, \tag{17}$$

where I_t denotes investment. Capital goods producers choose I_t to maximize lifetime profits given by

$$E_t \sum_{k=0}^{\infty} \Lambda_{t,t+k} \left\{ Q_{t+k} I_{t+k} - \left(1 + f\left(\frac{I_{t+k+1}}{I_{t+k}}\right)\right) I_{t+k} \right\},$$

where $f(\cdot)$ denotes investment adjustment costs (in consumption units). Their functional form is given by

$$f\left(\frac{I_t}{I_{t-1}}\right) = \frac{\eta_I}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2,$$

[11] Parameters and steady-state values are chosen such that the incentive constraint binds in each of the regime-specific deterministic steady states. Holding the variance of shocks small enough and calibrating the regime switches accordingly guarantees that the incentive constraint also binds in the stochastic environment.

where $\eta_I > 0$ denotes the inverse elasticity of investment with respect to the price of capital.

By solving the optimization problem of the capital goods firm, the real price of one unit of capital is obtained as

$$Q_t = 1+f\left(\frac{I_t}{I_{t-1}}\right)+\frac{I_t}{I_{t-1}}f'\left(\frac{I_t}{I_{t-1}}\right)-E_t\left\{\Lambda_{t,t+1}f'\left(\frac{I_{t+1}}{I_t}\right)\frac{{I_{t+1}}^2}{{I_t}^2}\right\}. \quad (18)$$

3.6. Final goods firms

The final output, Y_t, is assumed to be a CES composite of mass unity of differentiated final products,

$$Y_t = \left(\int_0^1 Y_t(f)^{\frac{\epsilon-1}{\epsilon}}df\right)^{\frac{\epsilon}{\epsilon-1}},$$

with $\epsilon > 0$. $Y_t(f)$ denotes the output of retailer f. The corresponding price index is given by

$$P_t = \left(\int_0^1 P_t(f)^{1-\epsilon}df.\right)^{\frac{1}{1-\epsilon}},$$

where $P_t(f)$ denotes the price of variety f.

Given that consumers allocate consumption expenditures optimally among varieties, final goods firm f faces the following demand from consumers

$$Y_t(f) = \left(\frac{P_t(f)}{P_t}\right)^{-\epsilon} Y_t,$$

i.e., its share in total final goods production, Y_t, depends on its relative price.

It is assumed that each unit of final output is assembled without cost from one unit of intermediate output. Real marginal cost is therefore given by the real intermediate output price $P_{m,t}$. It is further assumed that each period a firm faces a positive probability σ that it is not able to reset its price (i.e., Calvo-style pricing). If not able to reset its price, a firm can partly index its price to the lagged rate of inflation. Hence, the price chosen by an optimizing final goods firm is given by

$$\tilde{P}_t = \frac{\epsilon}{\epsilon-1}\frac{E_t\sum_{k=0}^{\infty}\sigma^k\beta^k\lambda_{t+k}\Pi_{t,t+k}^{\epsilon}\Pi_{t-1,t+k-1}^{-\epsilon\sigma_\pi}Y_{t+k}P_{m,t+k}}{E_t\sum_{k=0}^{\infty}\sigma^k\beta^k\lambda_{t+k}\Pi_{t,t+k}^{\epsilon-1}\Pi_{t-1,t+k-1}^{(1-\epsilon)\sigma_\pi}Y_{t+k}}P_t, \quad (19)$$

where $\Pi_t \equiv \frac{P_t}{P_{t-1}}$ denotes inflation between $t-1$ and t and σ_π denotes the degree of price indexation. The dynamics of the price index are given by

$$P_t = \left(\sigma\Pi_{t-1}^{\sigma_\pi(1-\epsilon)}P_{t-1}^{1-\epsilon}+(1-\sigma)\tilde{P}_t^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}}. \quad (20)$$

3.7. Further equilibrium equations

Price stickiness in the final goods sector implies a wedge between aggregate final and aggregate intermediate goods production, i.e.,

$$Y_{m,t} = Y_t\Delta_{p,t}, \quad (21)$$

where $\Delta_{p,t} \equiv \int_0^1\left(\frac{P_t(f)}{P_t}\right)^{-\epsilon}df$.

The aggregate resource constraint holds, i.e.,

$$Y_t = C_t + \left(1+f\left(\frac{I_t}{I_{t-1}}\right)\right)I_t + \theta(r_t)\frac{\kappa(r_t)}{2}x_t^2N_t. \quad (22)$$

In the benchmark version of the model, the central bank adjusts the nominal interest rate according to the following Taylor rule

$$\frac{R_t^n}{R^n} = \left(\frac{R_{t-1}^n}{R^n}\right)^{\rho_r}\left(\frac{\Pi_t}{\Pi}\right)^{\kappa_\pi(1-\rho_r)}\left(\frac{Y_t}{Y_t^*}\right)^{\kappa_y(1-\rho_r)}e_{t,R}, \quad (23)$$

where Y_t^* is the natural, i.e., flexible price equilibrium, level of output,[12] $e_{t,R}$ constitutes a monetary policy shock and parameter $0 < \rho_r < 1$ determines the degree of interest rate smoothing. Parameters κ_π and κ_y denote the central bank's responsiveness to inflation and the output gap, respectively.

The well-known Fisher equation links the nominal rate to the real rate and inflation,

$$R_t = \frac{R_t^n}{E_t\Pi_{t+1}}. \quad (24)$$

The technology shock follows an autoregressive process given by

$$\ln A_t = \rho_a \ln A_{t-1} + e_{t,A}, \quad (25)$$

where $\rho_A \in (0,1)$ and $e_{t,A} \sim iid(0,\sigma_A^2)$.

Eqs. (1)–(25) – apart from Eq. (3) – and the switching functions (27) and (28) (introduced in Section 4.3) are the equilibrium equations of our model.

4. Solution and calibration

4.1. Solution method

We solve the model using perturbation techniques. A commonly used perturbation technique in the context of regime-switching models is to linearize the model, assuming all parameters were constant, and then add switching to certain parameters. In this case, the solution and estimation of larger models is straightforward, however, this linear technique ignores that agents know about the possibility of regime switches and take this knowledge into account when forming their expectations.

Therefore, we resort to a non-linear perturbation technique, which allows for the consideration of higher-order terms and endogenous regime-switching. The method was developed by Maih and Waggoner (2018).[13,14] The technique is briefly described next, but for a more detailed description, please refer to Chang et al. (2021).

The system of equilibrium equations to be solved, including the switching functions, can be cast into the following form

$$\mathbb{E}_t\left[\sum_{r_{t+1}=1}^{h} p_{r_t r_{t+1}}(\mathcal{I}_t)f_{r_t}(x_{t+1}(r_{t+1}),x_t(r_t),x_{t-1},\theta_{r_t},\theta_{r_{t+1}},\epsilon_t)\right] = 0, \quad (26)$$

where x_t is a vector of model variables, r_t represents the switching process with h different states, θ_{r_t} is the vector of parameters in state r_t and $p_{r_t r_{t+1}}(\mathcal{I}_t)$ is the transition probability for going from state r_t to state r_{t+1} which depends on $\mathcal{I}_t$, the information at time t. The aim is to find a regime-specific policy function which expresses the variables of the model as a function of the states, z_t.

$$x_t = \mathcal{T}_{r_t}(z_t).$$

A key property of $\mathcal{T}_{r_t}$ is, that it is a function of the solution in other regimes, i.e.,

$$\mathcal{T}_{r_t} = \tau_{r_t}(\mathcal{T}_1,\mathcal{T}_2,\ldots,\mathcal{T}_{r_t},\ldots,\mathcal{T}_h).$$

As there is no analytical solution to the above system of equations, Maih and Waggoner (2018) propose the following perturbation solution method,

$$x_t(r_t) \approx x(r_t) + \mathcal{T}_{r_t,z}(z_t - z(r_t)) + \frac{1}{2!}\mathcal{T}_{r_t,zz}(z_t - z(r_t))^{\otimes}2 + \cdots,$$

where $z_t \equiv [x_{t-1}', \sigma, \epsilon_t']$ is the vector of state variables, wich is augmented by an auxiliary argument, the perturbation parameter σ. Note that if $\sigma = 1$, the system of equations to be solved becomes the original one, i.e., (26). On the other hand, if $\sigma = 0$, it reduces to a

[12] We approximate the ratio between actual and natural output, i.e., the output gap, by the inverse of the markup gap, given by $\frac{1}{P_{m,t}}\frac{\epsilon-1}{\epsilon}$.

[13] It is embedded in the MATLAB toolbox RISE, developed by Junior Maih. The toolbox is freely available under https://github.com/jmaih/RISE_toolbox.

[14] The perturbation approach proposed by Barthélemy and Marx (2017) also allows to solve models with endogenous regime-switching.

Table 2
Regime-invariant parameters.

Parameter	Description	Value	Source
Households			
β	subjective discount factor	0.99	Gertler and Karadi (2011)
ϕ_L	inverse of Frisch elasticity	0.276	Gertler and Karadi (2011)
σ	risk aversion	2	Akinci and Queralto (2022)
ψ_L	relative utility weight of labor	1.76	det. st. st. of labor (l) $\approx$ 0.33
Capital producing firms			
η_I	inverse elasticity of investment with respect to price of capital	1.728	Gertler and Karadi (2011)
Intermediate goods firms			
α	output elasticity of capital	0.33	standard value
δ	capital depreciation rate	0.025	standard value
Final goods firms			
θ^p	probability of keeping prices fixed	0.779	Gertler and Karadi (2011)
ϵ	elasticity of substitution between varieties	4.167	Gertler and Karadi (2011)
Financial intermediaries			
λ	fraction of divertible assets	0.35	Gertler and Karadi (2011)
Monetary policy			
κ_y	reaction coefficient on output gap	0.125	Gertler and Karadi (2011)
κ_π	reaction coefficient on inflation	1.500	Gertler and Karadi (2011)
ρ_r	interest rate smoothing coefficient	0.800	Gertler and Karadi (2011)
Exogenous processes			
ρ_A	persistence of technology shock	0.97	Gertler and Karadi (2011)
σ_N	std. dev. of net wealth shock	0.001	Gertler and Karadi (2011)
σ_A	std. dev. of technology shock	0.00246	Akinci and Queralto (2022)
σ_R	std. dev. of monetary policy shock	0.0014	Akinci and Queralto (2022)

tractable system from which any stochastic disturbances are eliminated — including the randomness resulting from possible regime changes. The system of equations is perturbed around the points where $\sigma = 0$, i.e., around regime-specific steady states.[15]

To solve the quadratic matrix equations, RISE relies on efficient functional iterations and Newton algorithms, which can handle relatively large models (see, e.g., Maih, 2015).

4.2. Calibration of regime-invariant parameters

Table 2 lists the invariant model parameters and their corresponding values, most of which were taken from (Gertler and Karadi, 2011) and Akinci and Queralto (2022), who calibrate their models to match important regularities of US business and financial cycles. Parameter ψ_L, the relative weight of labor in the utility function, was chosen to obtain a deterministic steady state (det. st. st.) value of labor in the low-friction regime of approximately 0.33.

4.3. Calibration of regime-dependent parameters and switching functions

As discussed, we assume that there are two regimes between which the economy switches, denoted by $r_t \in (l, h)$, where l refers to the low-friction and h to the high-friction regime. Three of the parameters defining the size of the financial friction, $\omega(r_t)$, $\theta(r_t)$ and $\kappa(r_t)$, are calibrated to distinguish the regimes. The probabilities of switching from the low-friction regime (i.e., normal times) to the high-friction regime (i.e., times of financial turmoil) in period t and vice versa are denoted as $p_{lh,t}$ and $p_{hl,t}$, respectively. They are assumed to depend on the deviation of bank leverage from its steady state value in the following form,[16]

$$p_{lh,t} = \frac{\alpha_{lh}}{\alpha_{lh} + exp(-\psi_{lh}(\phi_t - \bar{\phi}_l))} \tag{27}$$

$$p_{hl,t} = \frac{\alpha_{hl}}{\alpha_{hl} + exp(\psi_{hl}(\phi_t - \bar{\phi}_h))} \tag{28}$$

where $\bar{\phi}_l$ and $\bar{\phi}_h$ denote the regime-specific steady state values of the leverage ratio. Parameters ψ_{lh}, ψ_{hl}, α_{lh} and α_{hl} govern the form of the switching function.

We calibrate the three regime-specific parameters $\omega(r_t)$, $\theta(r_t)$ and $\kappa(r_t)$ jointly with the switching function parameters to hit the following targets: the ratio of the BAA-AAA spread[17] of tranquil-to-turbulent times at approximately 60%,[18] the proportion of the time spent in financially turbulent times at approximately 25%, and the mean duration of financially turbulent times at about five years.[19]

Table 3 provides an overview of the chosen regime-specific parameters and those of the switching functions. The high-friction regime is characterized by a combination of a shorter lifetime horizon of the banker, $\theta(h) < \theta(l)$, more start-up funds, $\omega(h) > \omega(l)$, and a higher cost of equity issuance, $\kappa(h) > \kappa(l)$. A banker's shorter lifetime horizon tightens its incentive constraint as it has less time to accumulate net wealth. Assuming a higher equity issuance cost parameter in the high-friction regime also increases the financial friction. It can be rationalized with increased informational frictions and commitment problems during times of financial distress (see, e.g., Hanson et al., 2011; Baron, 2020). Higher start-up funds, on the other hand, loosen

[15] Regime-specific steady states can be interpreted as resting points at which the economy would stay in the absence of shocks and of regime switches, if it happened to start at one of these points.

[16] We also considered alternative regime-switching indicators such as the deviation of the spread from its steady state values or of net wealth from its steady state value. However, these alternative indicators generated either too much or too little volatility of the economy, making it difficult to match data on the frequency of financial crises.

[17] BAA-AAA spread refers to Moody's Seasoned Baa Corporate Bond Yield minus Moody's Seasoned Aaa Corporate Bond Yield.

[18] Considering the entire post-war episode in the U.S. (1946Q1-2019Q4) this spread takes on a value of 62.5%.

[19] Five years is the average duration of financial crises in advanced economies reported by Laeven and Valencia (2013).

Table 3
Regime-specific parameters.

	"Normal times" (l-regime)	"Financially turbulent Times" (h-regime)
quart. survival prob. of banker, $\theta(r_t)$	0.97	0.955
start-up funds for new bankers, $\omega(r_t)$	0.001	0.005
equity issuance cost parameter, $\kappa(r_t)$	28	30
position of switching function, α_{lh}	0.01	–
position of switching function, α_{hl}	–	0.06
steepness of switching function, ψ_{lh}	10	–
steepness of switching function, ψ_{hl}	–	20

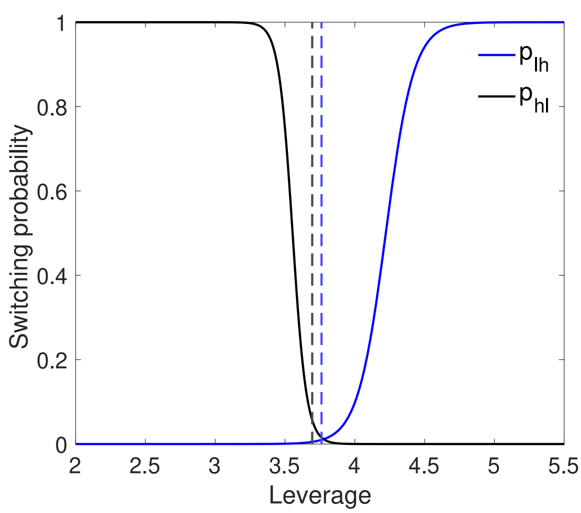

Fig. 2. Switching functions.
Notes: The *y*-axis relays the probability of a regime switch, and the *x*-axis shows banking sector leverage (ϕ_t). Regime-specific steady states are represented by dashed lines.

the financial constraint. However, we found it necessary to assume $\omega(h) > \omega(l)$ to render the model stable. We conjecture that it is necessary to increase the fraction of the assets $Q_t S_{t-1}$ provided to new bankers in the high-friction regime, due to the massive drop in Q_t.

Fig. 2 shows how the switching functions behave for the given choice of parameter values. The solid lines reflect the switching probability as a function of leverage, whereas the dashed lines reflect the regime-specific steady state values of leverage. The likelihood of switching from the low- to the high-friction regime (blue graph) increases when banks start leveraging up. The switching probability is quite low (around 1%) when leverage is at its steady state value of 3.7, but starts to increase exponentially after passing a value of four. The likelihood of switching from the high- to the low-friction regime (black graph) increases when banks reduce their leverage. It is around 6% when leverage is at its regime-specific deterministic steady state value of 3.6.

5. Analysis of the benchmark model

5.1. Model moments

Table 4 provides the moments of several model variables. The first column contains the regime-specific mean values obtained from simulating the model, approximated at first-order, for 100,000 periods. The second column shows the respective standard deviations, and the third column gives the regime-specific deterministic steady state values.

The assumption of endogenous regime-switching introduces non-linearities even in a first-order approximation of the model. This is because that, with endogenous regime switches, the model economy reacts differently to positive and negative shocks. Such non-linearities can

Table 4
Model moments.

	Mean	Std. dev. (∗ 100)	Det. st. st.
Spread (ann., in pp) (l)	0.572	82.477	0.634
Spread (ann., in pp) (h)	1.145	118.641	1.002
Leverage (l)	3.710	15.290	3.761
Leverage (h)	3.857	18.153	3.695
Output (l)	0.846	5.818	0.853
Output (h)	0.836	5.844	0.803
Consumption (l)	0.698	4.573	0.704
Consumption (h)	0.694	4.629	0.667
Labor (l)	0.329	1.879	0.331
Labor (h)	0.325	1.904	0.315
Inflation (ann., in %) (l)	0.596	101.931	0.000
Inflation (ann., in %) (h)	−1.585	110.400	0.000
Time in h-regime (in %)	25.471	–	14.888
Duration l-regime (in quarters)	68.627	–	101.000
Duration h-regime (in quarters)	23.454	–	17.667
Probability l to h (in %)	1.426	–	0.990
Probability h to l (in %)	3.069	–	5.660

Notes: Mean and standard deviation (std. dev.) stem from a simulation of the model, approximated at the first order, over 100,000 periods. The last column shows the deterministic steady state (det. st. st.) values of the model.

be observed when comparing the simulation means to the deterministic steady-state values. The non-linearities are particularly large with respect to the financial variables. In the deterministic steady state, the spread of the low-friction regime takes a value of 63 bps and the spread of the high-friction regime amounts to 100 bps. In the regime-switching model, they change to 57 bps and 115 bps, respectively, indicating that the difference between the two regimes grows much larger. Regarding leverage, the non-linearities are even more pronounced. While in the deterministic steady state of the low-friction regime, leverage is larger than that of the deterministic steady state of the high-friction regime, the opposite holds true for the stochastic case. The intuition behind this is that, in general, leverage increases considerably when financial conditions worsen, which is the case when moving from the low-friction to the high-friction regime. Furthermore, greater leverage itself increases the probability of switching from the low-friction to the high-friction regime followed by remaining high. Hence, generally, when the economy enters financially turbulent times, leverage is already higher than its average value.

When comparing the two regimes, we can see that the means (and the deterministic steady-state values) of the key variables of the real economy (i.e., output, consumption and labor) are higher in the low-friction regime (normal times). Regarding the standard deviations of the variables, the economy is much more volatile in the high-friction regime (crisis times). The reason is that in the low-friction regime, the established trust in the banking sector allows banks to adjust their balance sheets more readily in response to shocks, which reduces the volatility of the entire economy. Moreover, the high-friction regime is dominated by the dynamics of the regime change, which display very high volatility. The regime switch to the high-friction regime is discussed in more detail in the next section.

5.2. Average dynamics around a switch to the financially turbulent regime

Fig. 3 shows the average dynamics during a switch from tranquil to financially turbulent times in the model economy. Period zero marks the first period of the high-friction regime. All variables, except for the switching probability, the spread, the inflation rate and the shocks, are reported in %-deviations from their simulation means. To obtain the dynamics, the model was solved at first-order and simulated for 1,000,000 quarters, discarding a burn-in period of 100,000 quarters. Only crisis episodes were considered in which the tranquil regime lasted at least 20 quarters prior to the regime change, and where the subsequent turbulent regime lasted for at least eight quarters. As such,

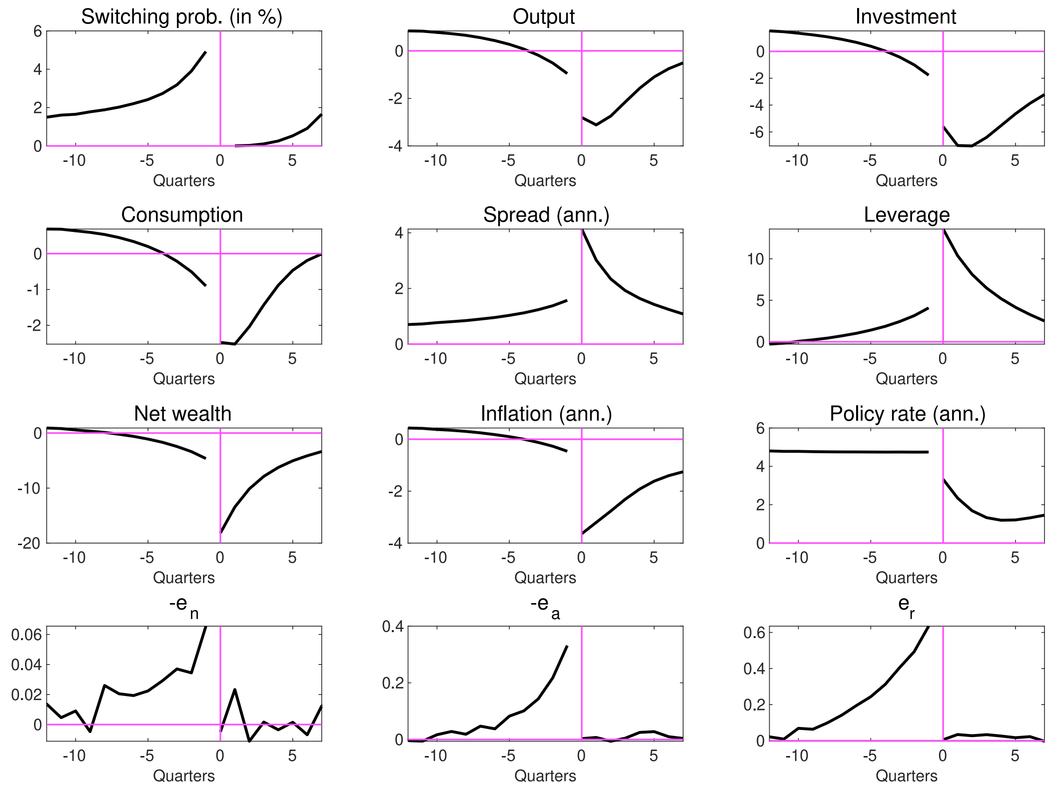

Fig. 3. Average dynamics around financial crises in the model.
Notes: The switch to the high-friction regime takes place between periods −1 and 0 in the plots. Figures are reported in %-deviation from simulation mean, apart from the switching probability, spread, and inflation rate, which are reported in %. Shocks are reported in standard deviations. The model economy was simulated over 1,000,000 quarters with a burn-in period of 100,000 quarters. Only episodes were considered, where the tranquil regime had lasted at least 20 quarters before the regime switch, and where the subsequent turbulent regime lasted for at least eight quarters.

our objective was to exclude the effects of previous crises on the tranquil regime and restrict our attention to financially turbulent episodes whose durations were comparable to the financial crises identified in the data (cf. Boissay et al., 2023).

It can be seen that up to approximately one year prior to the start of the crisis, the real economy finds itself well above its mean. Very similar to the dynamics depicted in Fig. 1, around five quarters before the regime switch, economic conditions start to worsen. This slowdown can also be observed in the financial sector, where leverage and spread increase and net wealth drops. The drop in net wealth reflects a decrease in capital returns. The switching probability, which is a function of leverage, increases rapidly, indicating a buildup of risk in the banking sector. The onset of a crisis is ultimately triggered by a sequence of adverse net wealth and technology shocks and a sequence of contractionary monetary policy shocks. Note, however, that the realizations of the shocks triggering the crisis are not abnormally large, they are well below one standard deviation of the shock. The average switch to the crisis regime is characterized by a soaring credit spread (+300 bps on impact), a drastic fall in bank net wealth (−15 pp on impact) and – due to the latter – a dramatic rise in leverage (+10 pp on impact). To meet balance sheet constraints, banks are forced to deleverage quickly by selling off assets, i.e., cutting credit, as reflected by a large drop in investment (−4 pp on impact). The crisis in the banking sector and the induced decline in credit have large effects on output, which declines by about 2.5 pp in the first crisis quarters. Approximately one year after the crisis began, the leverage ratio and net wealth are back to their pre-crisis levels. Hence, the probability of returning to the normal regime begins to increase considerably. However, about 1.5 years after the beginning of the crisis, investment is still lower than before the regime switch. Very similar dynamics can also be observed in the average financial turmoil seen in the US, as depicted in Fig. 1. However, it should be noted, that the reduction in GDP observed in the data is much more persistent than in the model economy, where output and consumption return to their pre-crisis levels about 1.5 years after the onset of the crisis.

Table 5
Episodes of financial turmoil — model versus data.

	US data (LSN dating)	Model
Dynamics around regime switch		
GDP	−1.2pp	−2.3pp
Investment	−8.3pp	−5.7pp
Leverage	+7.2pp	+6.8pp
Net wealth	−5.7pp	−9.4pp
Assets	−1.3pp	−2.5pp
Spread	+100bps +177bps	+153bps
Crisis times		
Time in crisis (in %)	25.0	25.5
Mean duration l-regime (quarters)	31.2	68.6
Mean Duration h-regime (quarters)	13.0	23.5

Notes: Reported numbers of the dynamics around regime changes for the model are calculated as the difference between the mean value of the year before and the year after the regime switch, using the data from Fig. 3. Reported numbers for the US in the first column are calculated as the largest drop/increase within one year of the regime switch, using the data from Fig. 1. The BAA-FF spread exhibits two large jumps around the regime switch (see Fig. 1), which we both report.

The upper part of Table 5 summarizes the changes in GDP, investment, leverage, net wealth, credit and the spread around the regime switch, as displayed in Fig. 3. These dynamics are contrasted with the corresponding dynamics of the average US crisis described in Section 2 and displayed in Fig. 1. The model indicators are calculated as the difference between the mean value of the year before and the year after the regime change. The dynamics of the US variables are calculated as the largest drop or increase within a year of the regime switch. The BAA-FF spread exhibits two large jumps in close proximity to the regime switch (see Fig. 1), which we both report.

Comparing the first and second columns in the upper part of the table, we can see that the model does well in matching the average dynamics around the onset of a financial crisis in the US – with respect to real and financial variables. Our model only considerably overpredicts the drop in net wealth and assets. However, the net wealth and assets considered in the data are book values, while net wealth and assets in the model are heavily impacted by asset prices. For market net wealth of US banks, much larger drops have been reported as well.[20]

In the lower part of the table, we compare further indicators of crisis times between the model and the data. While the total time the model economy spends in the crisis regime corresponds to US data, both regimes in our model are much more persistent than those in the data — according to the classification by Lopez-Salido and Nelson (2010).

6. Macroprudential policy

6.1. Objectives and implementation of macroprudential policy

Equity issuance provides bankers with an additional instrument to control the strength of their balance sheet. By increasing equity, bankers can increase their net wealth and, hence, enable more intermediation currently and in the future. With more solid balance sheets in the aggregate, the economy enters less frequently into crises, and those that occur are less powerful. However, because equity issuance is costly, and banks do not internalize the positive effects of equity issuance on aggregate financial stability, too little equity is issued, compared with the social optimum. Additionally, because the net present value of an equity transfer from the household to the bank, $v_{e,t}$, increases when financial conditions worsen, banks tend to issue more equity during financially turbulent times, i.e., when equity issuance is relatively more costly (see Table A.1 in the appendix), further raising financial intermediation costs for society.[21] Therefore, the key objectives of the macroprudential authority in our model are addressing the externality stemming from costly equity issuance, and incentivizing banks to strengthen their balance sheets when it is less costly (during normal times), while allowing them to make use of their capital buffers during turbulent times to attenuate drops in credit and the adverse consequences for the real economy.

In practice, Basel III applies two capital buffers for all banks, capital conservation and countercyclical capital buffer (CCyB). The former is set at 2.5% of total risk-weighted assets and applies at all times. Whenever the buffer falls below the given value, constraints on capital distribution are imposed automatically until the buffer is replenished. The latter varies between 0 and 2.5% of the total risk-weighted assets. It is activated and increased by national authorities when an elevated risk of above-normal future losses is observed, such as when credit growth is excessive. Subsequently, during downturns, the CCyB should be decreased or turned off to help ensure the continued function of financial intermediation, even when losses are incurred (BIS, 2019).

During the COVID-19 pandemic, we observed that many countries resorted to capital and leverage relief measures in order to help banks absorb losses and, hence, to maintain the flow of credit to the real economy. Some authorities reduced capital conservation buffers (e.g., European Central Bank), whereas others lowered capital surcharges and systemic risk buffers to free up bank capital in support of the domestic economies (e.g., Canada, The Netherlands). The US Fed announced technical changes to the total loss-absorbing capacity (TLAC) requirement, which applies an additional capital cushion for banks (Fed, 2020).[22]

Several other studies have analyzed macroprudential policies targeting the strength of banks' balance sheets in models similar to ours. For the sake of tractability, many studies have implemented such policies in the form of taxes or subsidies (e.g., Gertler et al., 2012; Tavman, 2015; Gelain and Ilbas, 2017; Akinci and Queralto, 2022),[23] while we implement capital requirements in the form of inequality constraints, which resemble regulatory Basel-III-style capital buffers and relief measures quite closely (e.g., Elenev et al., 2021; Pozo, 2023).[24]

In particular, we assume that the macroprudential authority implements a potentially regime-dependent capital requirement, $\lambda^{\text{reg}}(r_t)$, which directly affects the incentive constraint of banks,

$$\lambda + \lambda^{\text{reg}}(r_t) \leq \frac{V_t}{Q_t s_t + (1 - (R_{L,t} - R_{t-1}))s_{W,t}}. \tag{3'}$$

We analyze different capital requirement designs, in particular,

1. a constant capital buffer that tightens the constraint at all times: $\lambda^{\text{reg}}(l) = \lambda^{\text{reg}}(h) > 0$,
2. a regime-dependent capital buffer that tightens the constraint only during tranquil times: $\lambda^{\text{reg}}(l) > 0$,
3. a regime-dependent capital requirement that tightens the constraint during tranquil times and loosens it during financially turbulent times: $\lambda^{\text{reg}}(l) > 0$, $\lambda^{\text{reg}}(h) < 0$,
4. and a regime-dependent capital relief measure that loosens the constraint during financially turbulent times: $\lambda^{\text{reg}}(h) < 0$.

Note that the fourth measure is not designed to prevent the occurrence of financial crises but rather to alleviate the real effects of financial disturbances when they occur. Therefore, it does not constitute a macroprudential policy in the strict sense. Nevertheless, as capital and leverage relief measures are also an important part of the toolbox of macroprudential regulators, such as during COVID-19, we consider these measures. In the following section, we describe how the design and strength of the given macroprudential policies affect the overall time spent in the high-friction regime, the average duration of financial crises, the volatility of the economy, and the mean of certain important financial and macroeconomic variables. We consider capital requirements that increase or decrease the benchmark capital ratio λ by 0 to 1.5 pp (i.e. $0 \leq \lambda^{\text{reg}}(r_t) \leq 0.015$). This aligns with actual economies.[25]

6.2. Effects of capital requirements

Fig. 4 shows how the introduction of the four different capital requirements introduced in the previous section affects various financial stability indicators. All policies shorten the duration of the crisis

[20] Using a historical sample of advanced and emerging countries, Baron et al. (2021) find that an average market-based bank equity decline around the onset of a financial crisis amounts to more than 40%.

[21] Countercyclical equity issuance by banks can also be observed in the data (see, e.g., Holden et al., 2019; Gertler et al., 2020).

[22] The Yale Program on Financial Stability (YPFS) outlines the measures taken by various countries to ease capital buffers and support financial intermediation during the COVID-19 pandemic under https://som.yale.edu/blog/countries-ease-bank-capital-buffers.

[23] There are further examples of analyses modeling macroprudential policy in the form of a debt tax and/or equity or net wealth subsidy. Those cited here employ a very similar financial intermediation sector as ours.

[24] There are further examples of analyses implementing macroprudential policies taking the form of inequality constraints; however, they usually focus on different objectives, such as controlling boom–bust cycles (Lorenzoni, 2008), reducing overborrowing in a small open economy (Bianchi, 2011), or counteracting risk-shifting (Nguyen, 2015).

[25] Basel III foresees a CCyB up to 2.5%. However, raising λ by more than 1.5 pp in the model renders it unsolvable for many parameter combinations.

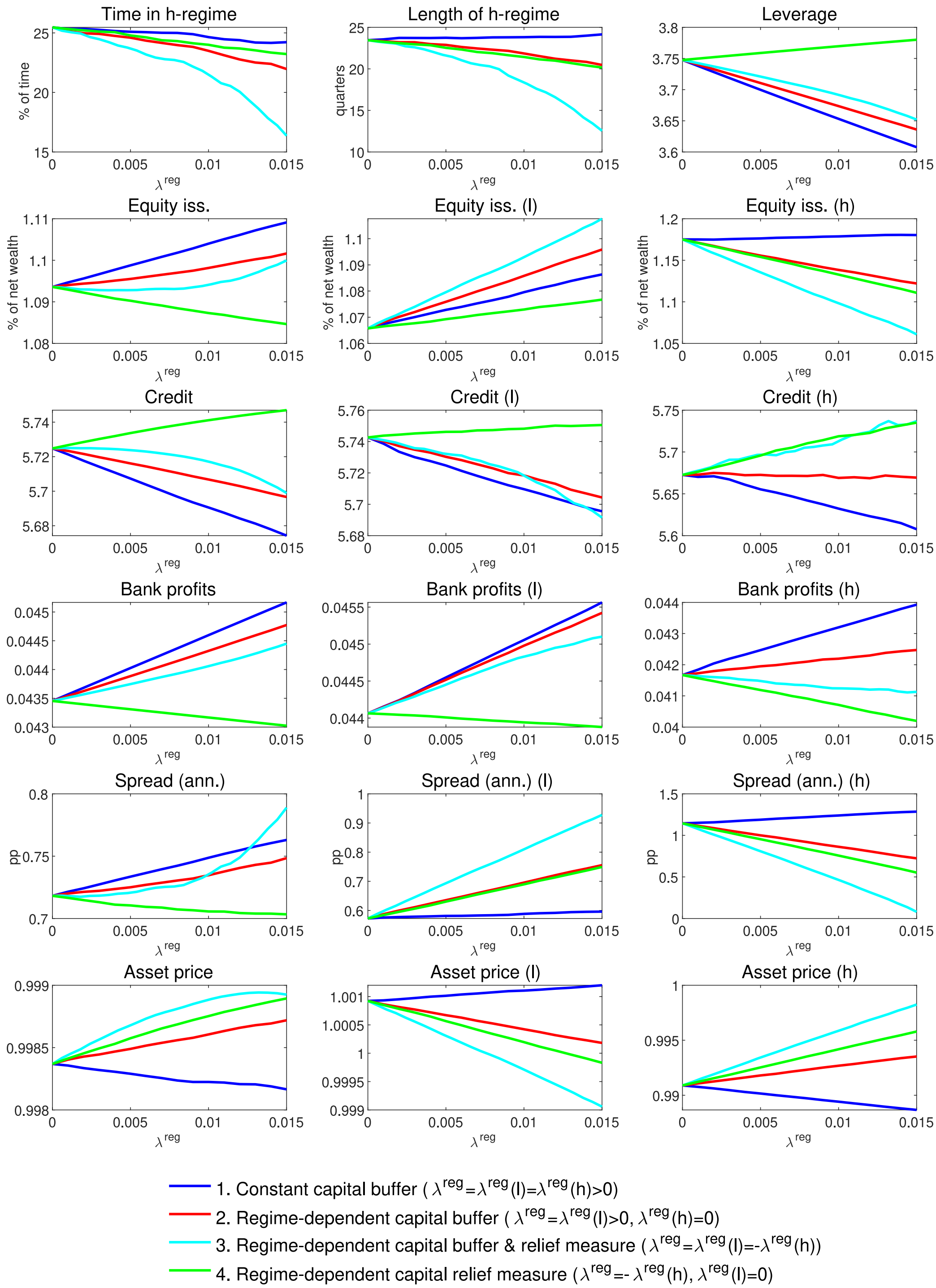

Fig. 4. Effects of capital requirements on financial stability.

regime, but to very different extents. While a constant capital buffer (i.e., blue line) of 1.5 pp reduces the time in the high-friction regime by only about 1 pp, a capital buffer of 1.5pp that is only active during normal times and combined with relief measures of the same size during turbulent times (i.e., light blue line) reduces the time in the high-friction regime by almost 10 pp. Furthermore, all measures, apart from the constant capital buffer, enable the banking sector to return to normal times faster. That is, the duration of the high-friction regime is reduced. For the capital buffers (policies 1–3), the reason for the reduced time spent in the crisis regime is, by construction, the reduction in leverage directly implied by the capital requirement. Furthermore, when capital buffers are eliminated or further lowered during turbulent times (policies 2 and 3), the freed-up bank capital enables banks to make up for some of the losses that occur during the onset of the crisis. Hence, these policies allow for a quicker balance-sheet recovery and reduced high-friction regime durations. On the other hand, the constant capital buffer, which also forces banks to hold more capital during crisis times, slightly increases the length of the high-friction regime.

All policies requiring banks to hold a higher capital ratio at some point (policies 1–3) lead to higher equity issuance on average. That is,

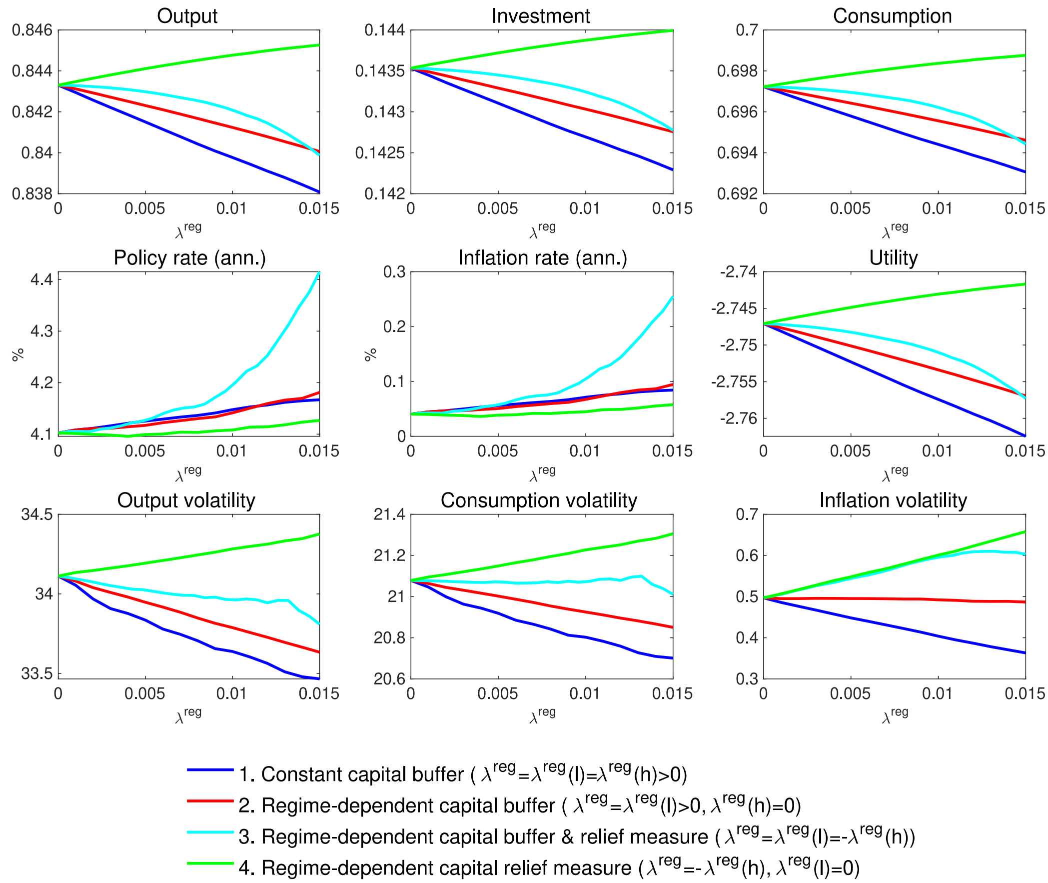

Fig. 5. Effects of capital requirements on macroeconomic variables.

the externality associated with private equity issuance costs is reduced. The capital relief measure, on the other hand, reduces equity issuance on average. When considering equity issuance in each regime separately, we can observe that banks issue more equity in the low-friction regime and, in most cases, less equity in the high-friction regime. Hence, all measures, apart from the constant capital buffer, are effective in shifting equity issuance from financially turbulent to normal times, thereby reducing the cost of equity issuance.

Policies associated with higher capital requirements (policies 1–3) essentially tighten banks' constraints, as implied by the observed increase in the spread. Considering again the differences between regimes, Fig. 4 shows that for all policies, the spread increases in the normal regime. However, for all policies, apart from the constant buffer, it decreases during episodes of financial turmoil. It is noteworthy that policy 2 (i.e., the regime-dependent capital buffer, red line) does not provide actual relief during crisis times; it merely frees up the capital buffer. Nevertheless, it is almost as effective in loosening the constraint and reducing equity issuance in the high-friction regime as the pure relief measure (i.e., policy 4, green line).

Tighter constraints, on average, effectively force banks to scale down intermediation activities as reflected in a significant drop in credit (policies 1–3). This drop is especially pronounced in the low-friction regime, when the buffers force banks to hold larger capital ratios. Considering the credit extended in the high-friction regime, only policies 3 and 4, which are associated with relief measures can attenuate the drop in credit. As Fig. 5 shows, this drop in credit adversely affects the real economy. Output, investment, and consumption decrease, and inflation increases with an increasing buffer as more funds are tied up in the banking system. The latter can be explained by higher production costs in the firm sector caused by elevated external finance premia. While macroeconomic activity is reduced by capital buffers, macroeconomic volatility decreases considerably. To better understand the effects of capital buffers and relief measures on volatility, Fig. A.1 in the appendix shows how the dynamics around a regime switch from normal to turbulent times are affected by macroprudential policies. With capital requirements in place, output, investment and consumption return to their means much earlier. Fig. 5 also displays mean utility, which is a good approximation to welfare, as it takes into account the effects of consumption and labor fluctuations. As the decrease in utility shows, the decrease in consumption and labor volatility[26] cannot make up for the decrease in the level of consumption. For the pure relief measure, on the other hand, the negative effects stemming from the increase in volatility do not outweigh the positive effects from the increase in the level of consumption. Therefore, an increase in the relief measure has positive effects on utility.

In summary, we find that all measures reduce the time spent in the high-friction regime. The capital buffers (policies 1–3) achieve this by increasing equity issuance and, hence, reducing leverage. The pure relief measure (policy 4) actually decreases equity and increases leverage; however, by actively supporting credit issuance in turbulent times, it helps the economy to recover faster. Capital buffers which are in place during normal times but eliminated during times of financial distress (policies 2 and 3) shift equity issuance from the high-friction to the low-friction regime and are more effective in reducing the probability and duration of financial crises than constant capital buffers (policy 1). However, the benefits of reducing financial and macroeconomic volatility are only achieved at the cost of reducing the size of the real and financial sectors. In our model, all buffers

[26] Note that labor volatility is not reported, but it is proportional to the volatility of output.

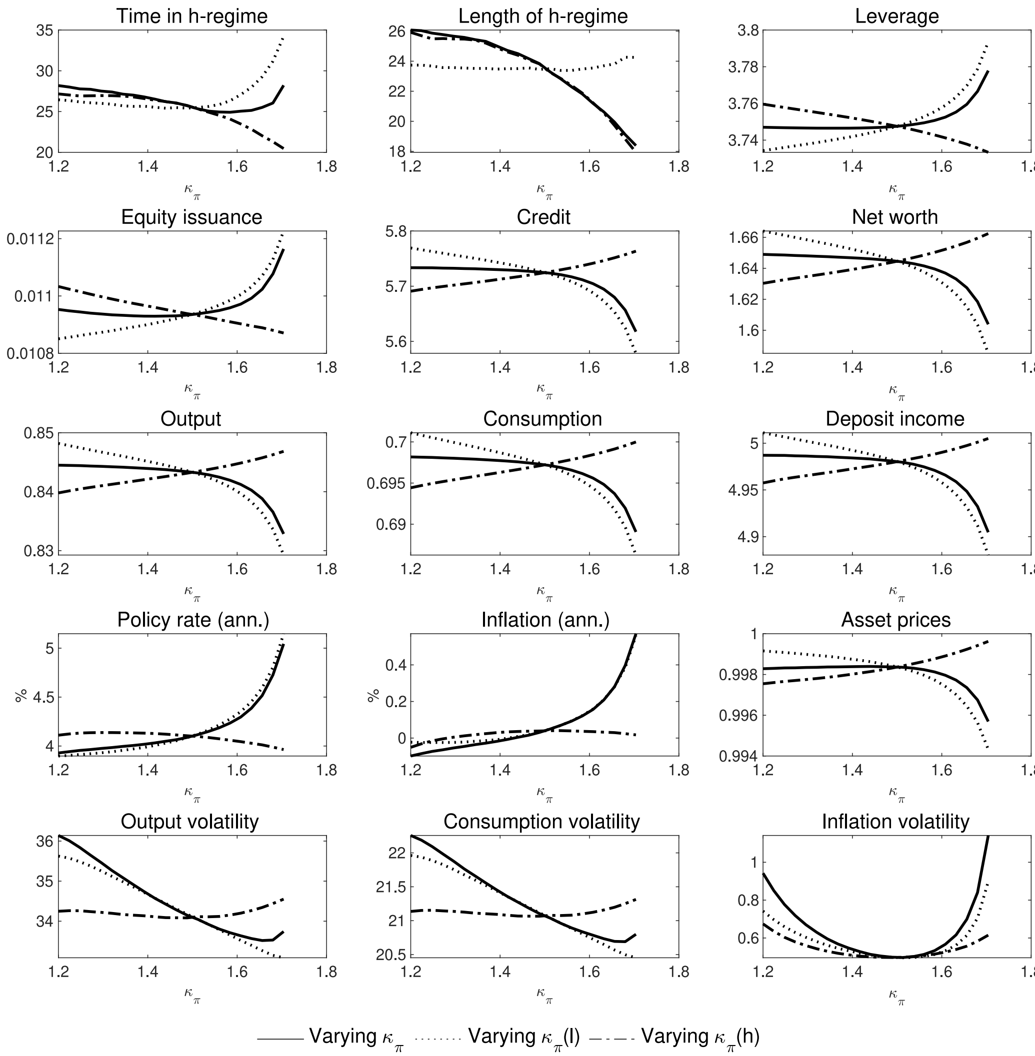

Fig. 6. Effects of varying the responsiveness to inflation.
Notes: When varying κ_π in only one of the two regimes, it is kept at its benchmark value of 1.5 in the other regime. Parameter κ_y is kept at its benchmark value of 0.125.

decrease welfare, and only the pure relief measure has positive effects on welfare. This result has been shown by other authors who model macroprudential policies as Basel-III-style capital requirements (e.g., Elenev et al., 2021).[27] Conversely, studies that model macroprudential policy as equity subsidy (e.g., Gertler et al., 2012; Akinci and Queralto, 2022), mainly for tractability reasons, often come to the conclusion that macroprudential policies have large positive welfare effects. This is unsurprising, as the equity subsidy essentially lowers the equity issuance cost for banks.

7. Monetary policy and financial stability

7.1. Design of the monetary policy rule and financial stability

By affecting interest rates and asset prices, monetary policy can impact financial stability. Fig. 3 shows that restrictive monetary policy shocks can drive the economy closer to the financially turbulent regime. In this section, we study the implications of monetary policy design for financial stability. In particular, we consider monetary policy rules with varying reaction coefficients and monetary policy rules that differ between the two financial regimes.

Fig. 6 shows how varying the reaction coefficient on inflation, κ_π, affects financial stability and the mean and variance of some important variables. The solid line shows the implications of a regime-independent Taylor rule, the dotted line shows the implications of varying κ_π in the low-friction regime and the dashed–dotted line shows the implications of varying κ_π in the high-friction regime. When varying κ_π in only one of the two regimes, it is kept at its benchmark value of 1.5 in the other regime. Therefore, all graphs intersect at 1.5. Parameter κ_y is also kept at its benchmark value of 0.125.

Starting from the left end of the plot, increasing κ_π independently of the regime (solid line) at first reduces the overall time spent in the high-friction regime; however, raising it above 1.6 actually increases it. The positive effect for $\kappa_\pi < 1.6$ is mostly driven by a reduction in the time spent in the high-friction regime, where higher reaction coefficients imply more policy accommodation. In the low-friction regime, on the other hand, a higher reaction coefficient has a negative impact on asset prices and thereby reduces net wealth, which leads to higher leverage. As such, a higher switching probability prevails despite higher equity issuance. A higher financial friction implies higher financing costs for firms, eventually increasing inflation. The regime-specific effects on these variables can be seen in Fig. A.2 in the appendix. Higher financing costs for firms also imply less investment and, hence, less real activity.

[27] Notably, Durdu et al. (2022) provide an overview of various macroeconomic models that assess the impact of Basel III.

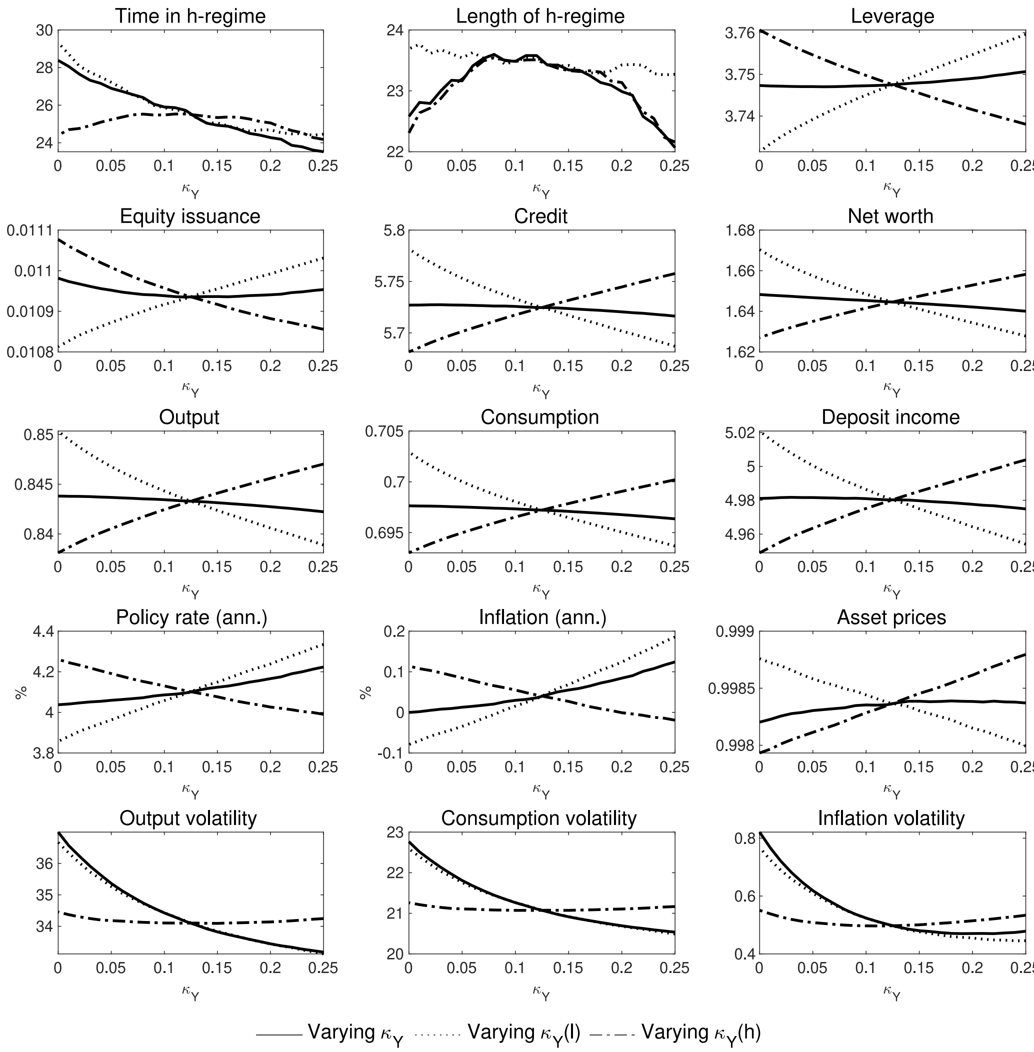

Fig. 7. Effects of varying the responsiveness to output.
Notes: When varying κ_y in only one of the two regimes, it is kept at its benchmark value of 0.125 in the other regime. Parameter κ_π is kept at its benchmark value of 1.5.

The effects described are aggravated if only $\kappa_\pi(l)$ is increased (dashed line), i.e., if the central bank is more responsive to inflation only in the low-friction regime.

If, on the other hand, the central bank is increasingly more reactive in the high-friction regime (dashed–dotted line), i.e., accommodates the economy increasingly more during crises ($\kappa_\pi(h)$ increasing), the total time spent in the high-friction regime is reduced. The reason for this is the shorter average duration of episodes of financial distress, and the decreasing leverage in both regimes which lowers the probability of switching from normal times to turbulent times. It should be noted that the decrease in leverage is not brought about by an increase in equity issuance, but rather by a more profitable banking sector which intermediates more and profits from higher asset prices. Therefore, increasing net wealth is seen. Although the central bank is more accommodating only during financially turbulent times, the effects of this policy carry over to normal times.

Fig. 7 shows how varying the reaction coefficient on the output gap, κ_y, affects financial stability and the mean and variance of some important variables. The solid line shows the implications of a regime-independent Taylor rule, the dotted line shows the implications of varying κ_y in the low-friction regime and the dashed–dotted line shows the implications of varying κ_y in the high-friction regime. When varying κ_y in only one of the two regimes, it is kept at its benchmark value of 0.125 in the other regime. Therefore, all graphs intersect at 0.125. Parameter κ_π is also kept at its benchmark value of 1.5. Empty spaces exist in the graphs as the model cannot be solved for those parameter constellations.

Starting from the left end of the plot, increasing κ_y independently of the regime (solid line) or only in normal times (dotted line) continuously reduces the time spent in the high-friction regime.

Similar to the experiments conducted with κ_π, increasing the policy coefficient on the output gap at all times (solid line) or only in normal times (dotted line), has a negative impact on asset prices and thereby reduces net wealth during normal times. This tightens the incentive constraint for banks. A higher financial friction implies higher financing costs for firms and increases inflation. Regime-specific effects on these variables can be seen in Fig. A.3 in the appendix. Higher financing costs for firms imply less investment and less real activity.

If, on the other hand, the central bank is increasingly more reactive only in the high-friction regime (dashed–dotted line) and accommodates the economy increasingly during crises ($\kappa_y(h) > 0.125$), the total time spent in the high-friction regime is reduced. The reason for this is the quicker return to normal times (shorter length of h-regime) and the decreasing leverage, which lowers the probability of switching from normal times to turbulent times. Regarding the effects shown in Fig. 6, the decrease in leverage is not brought about by an increase in equity issuance, but rather by a more profitable banking sector which intermediates more and profits from higher asset prices.

Table 6
Model moments under different monetary policy rules.

	$\kappa_y = 0.125$ $\kappa_\pi = 1.50$	$\kappa_y(h) = 0.250$, $\kappa_\pi(h) = 1.60$	$\kappa_y = 0.250$ $\kappa_\pi = 1.60$
Conditional welfare loss (in %)	14.136	14.044	14.215
Time in h-regime (in %)	25.471	19.963	26.300
Duration l-regime (in quarters)	68.627	68.291	48.743
Duration h-regime (in quarters)	23.454	17.033	17.383
Spread (ann., in pp)	0.718	0.543	1.042
Leverage	3.748	3.728	3.773
Output (mean)	0.843	0.852	0.832
Output (volatility)	34.112	34.611	33.725
Consumption (mean)	0.697	0.704	0.688
Consumption (volatility)	21.078	21.360	20.881
Labor (mean)	0.328	0.331	0.324
Labor (volatility)	3.594	3.693	3.628

Notes: Conditional welfare is the discounted sum of utility when starting from the same point (deterministic steady state of the low-friction regime) in all simulations. It is calculated as the mean of 2,000 simulations with the same stochastic processes over 800 periods. The welfare loss measures the fraction of the consumption stream a household would be willing to give up to stay in the deterministic steady state of the low-friction regime forever, instead of living in the stochastic world under the given monetary policy regime.

Therefore, increasing net wealth is seen. Although the central bank is more accommodating only during financially turbulent times, the effects of this policy carry over to normal times.

In summary, we find that a monetary policy that is more reactive, i.e., more accommodative, during times of financial distress than during normal times, supports the recovery of the financial sector and thereby also of the real economy. The time spent in turbulent episodes is significantly reduced, and the positive effects of this policy during crisis times even carry over to normal times. Additionally, as consumption and output volatility are only slightly affected by this policy and due to increased consumption, we may conclude that it is welfare-improving when the central bank is more reactive to inflation and/or the output gap during financially turbulent episodes.

By estimating a Markov-switching DSGE model for the USA and the euro area, Maih et al. (2021) find that during the two most recent decades, the US Fed reacted more strongly to deteriorating macroeconomic conditions during times of financial distress. Our previous analysis suggests that such a policy can improve financial stability and welfare. Therefore, we may now refine our approach to analyzing the effects of such a policy in our model. Table 6 shows the results, where the first column represents the model moments of the benchmark case in which κ_y and κ_π are regime-independent and at their benchmark values. The second column shows the same model moments for a scenario in which κ_y and κ_π are higher in the low-friction regime, and the last column reflects a scenario in which κ_y and κ_π are higher at all times. A policy resembling that of the Fed, as found by Maih et al. (2021) (column 2), significantly reduces the time spent in the high friction regime (from 25.5 to 20.0%) while increasing real economic activity and welfare.[28]

7.2. Monetary-macroprudential policy interactions

In the previous section, it is shown that in our model, the coefficients of the Taylor rule are important determinants of the proportion of time an economy spends in financially turbulent times. In particular, a more accommodative policy in the high-friction regime reduces the severity of a crisis and allows the economy to return to normal times faster. In this section, we analyze whether such an accommodative monetary policy has implications for the efficacy of macroprudential policy.

Figs. A.4–A.7 in the appendix show the effects of varying the size of the four capital requirements introduced in Section 6.1 for the different accommodative monetary policy rules which were shown to be effective in enhancing financial stability while improving real performance (higher $\kappa_\pi(h)$ and/or higher $\kappa_y(h)$). In each graph, the solid line shows the benchmark economy corresponding to the solid line of the same color in Fig. 4. The dashed line reflects an economy in which the monetary authority reacts more strongly to the output gap in financially turbulent times. The dotted line reflects an economy in which the monetary authority reacts more strongly to deflation in financially turbulent times, and the dashed–dotted line reflects an economy in which the monetary authority reacts strongly to both the output gap and deflation during financially turbulent times.

We are mainly interested in the questions whether capital requirements become more or less effective in reducing the time spent in the high-friction regime (i.e., the graph becomes steeper or flatter), when accompanied by regime-specific monetary policy, and whether a regime-specific monetary policy can alleviate the adverse effects of capital buffers on the real economy.

Two interesting findings emerge. First, as shown in Fig. A.4 in the appendix, under any regime-specific monetary policy, the constant capital buffer becomes ineffective in reducing the time spent in the high-friction regime. Under a policy with higher $\kappa_\pi(h)$ *and* higher $\kappa_y(h)$ (dashed–dotted line), it even increases the time spent in financial turbulences. Second, Fig. A.6 in the appendix, where the capital buffer is combined with a relief measure of equal size, shows that if the central bank reacts more strongly to the output gap in the high-friction regime (dashed line and dashed–dotted line), a very low value of λ^{reg} (0.001–0.002) raises the output. The reason seems to be that under these two monetary policies, credit is higher while inflation is very low for smaller capital requirements. Under the monetary policy regime reflected by the dashed line (i.e., the central bank reacts more strongly to output only), a small capital buffer (0.001) is found to be welfare-enhancing (see the utility plot) as it increases consumption volatility less than the monetary policy which additionally reacts more strongly to inflation.

Apart from these two peculiarities, the efficacy of macroprudential policy with respect to reducing the frequency of financial crises and its effects on the real economy are not altered very much by regime-dependent monetary policies. In most cases, monetary and macroprudential policies are complementary.

8. Conclusion

We build a macroeconomic model with a state-of-the-art financial intermediation sector featuring endogenous transitions between a low-friction and a high-friction regime, calibrated to capture normal and financial distress times identified in US data. The model is solved using perturbation techniques that allow for the inclusion of medium-scale model features and, hence, the possibility of analyzing the implications of monetary policy on systemic risk.

Our model replicates scenarios in which, entering an episode of financial turmoil, volatility increases strongly, spreads surge, and the production economy suffers from larger repercussions than during tranquil times. Notably, these dynamics are found without resorting to exogenous disturbances of extraordinary size. Therefore, our model provides a laboratory well suited to analyze the effects of policies aimed at reducing the frequency and magnitude of financial crises.

Our analysis of macroprudential policy shows that a policy that promotes equity issuance, modeled through a minimum capital requirement, can be used as a tool to reduce the frequency and magnitude of

[28] The welfare losses we obtain are quite high compared to those obtained by other studies measuring the costs of economic fluctuations. The reason is that we employ a regime-switching model and measure the fraction of the consumption stream a household would be willing to give up to stay in the deterministic steady state of the low-friction regime forever, instead of entering the stochastic world. Hence, our measure takes into account the potential welfare losses from the very large fluctuations around regime changes.

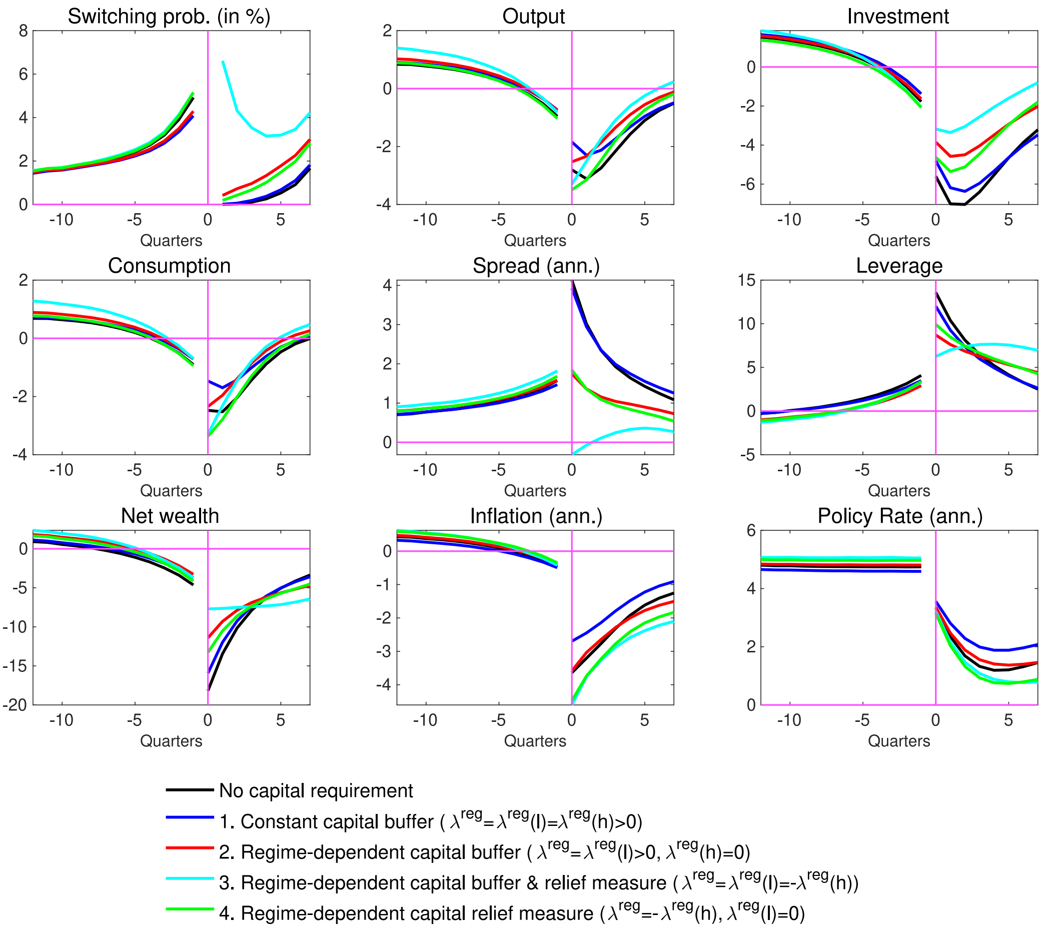

Fig. A.1. Average dynamics around financial crises in the model with capital requirements.

financial crisis. Thereby, it can reduce the volatility of the entire economy. Minimum capital requirements that are not always in place, but are used only preemptively during the low-friction regime, turn out to be much more effective than constant capital requirements in lowering the frequency and magnitude of financial turmoil. However, all capital requirements considered decrease the size of the economy and have negative welfare consequences under the benchmark monetary policy rule. This suggests that although Basel-III-style capital requirements are very effective in promoting financial and macroeconomic stability, the macroprudential authority must remain well-aware of their potentially negative consequences pertaining to capital accumulation and economic growth.

With respect to monetary policy, we find that policies that are more accommodative during financially turbulent times, can moderate the economic downturn and reduce the time spent in periods of financial distress. Such a policy was recently documented for the US by Maih et al. (2021). Regarding possible interactions, we find that macroprudential and monetary policies have mostly complementary effects on financial and macroeconomic stability. A combination of a small countercyclical capital buffer accompanied by a relief measure and accommodative monetary policy during crises increases welfare.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Available at Mendeley

Replication files for "Macroprudential capital requirements, monetary policy, and financial crises" (Original data) (Mendeley Data)

Appendix

See Table A.1 and Figs. A.1–A.7.

Table A.1
Moments of x_t (share of equity in net wealth).

Mean (l) (in %)	1.066
Mean (h) (in %)	1.175
Std. Dev. *100 (l)	0.147
Std. Dev. *100 (h)	0.198
Correlation with multiplier	0.965
Correlation with N	−0.535
Correlation with Y	−0.120
Correlation with C	−0.098

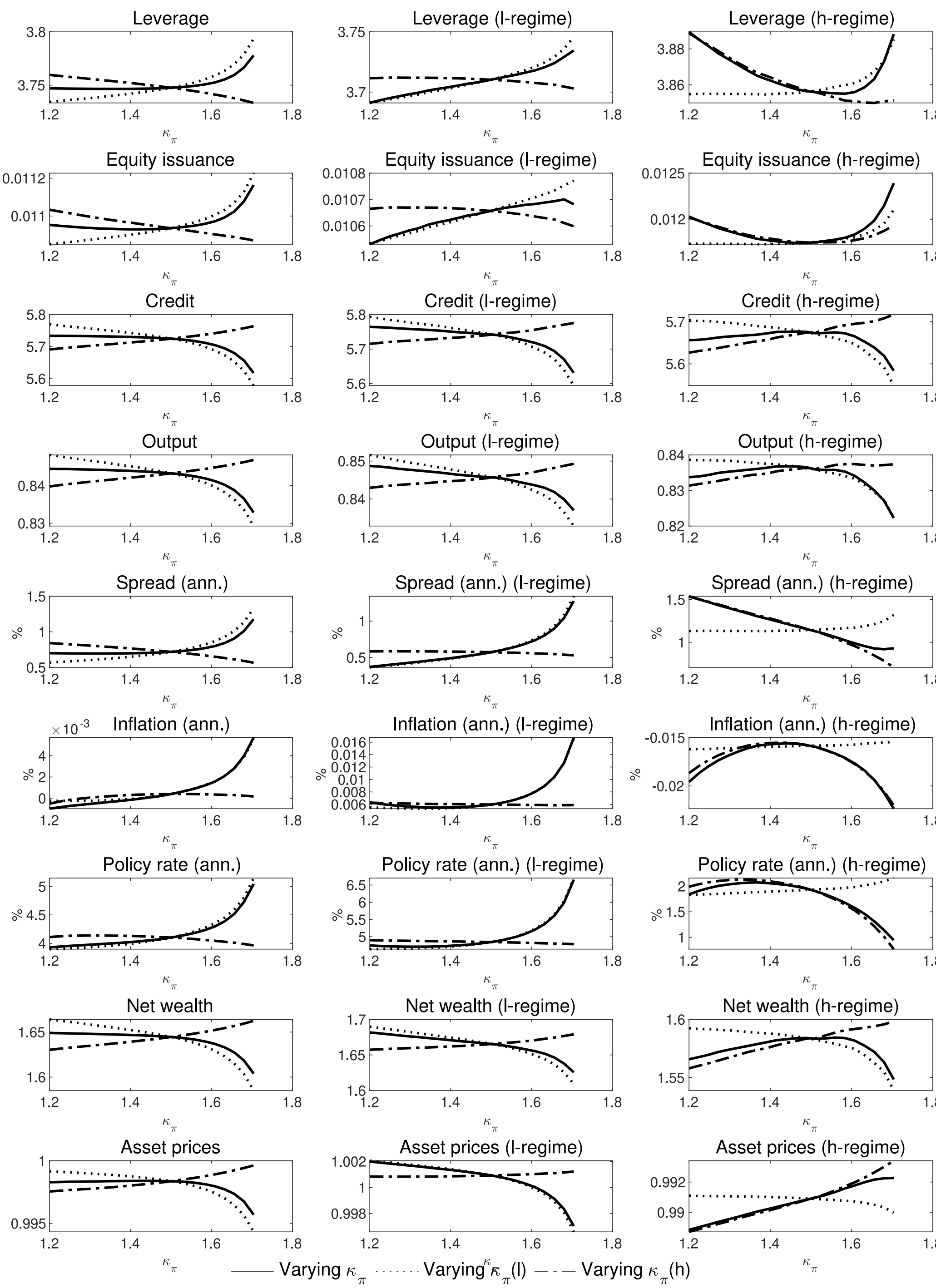

Fig. A.2. Regime-specific effects of varying the responsiveness to inflation.

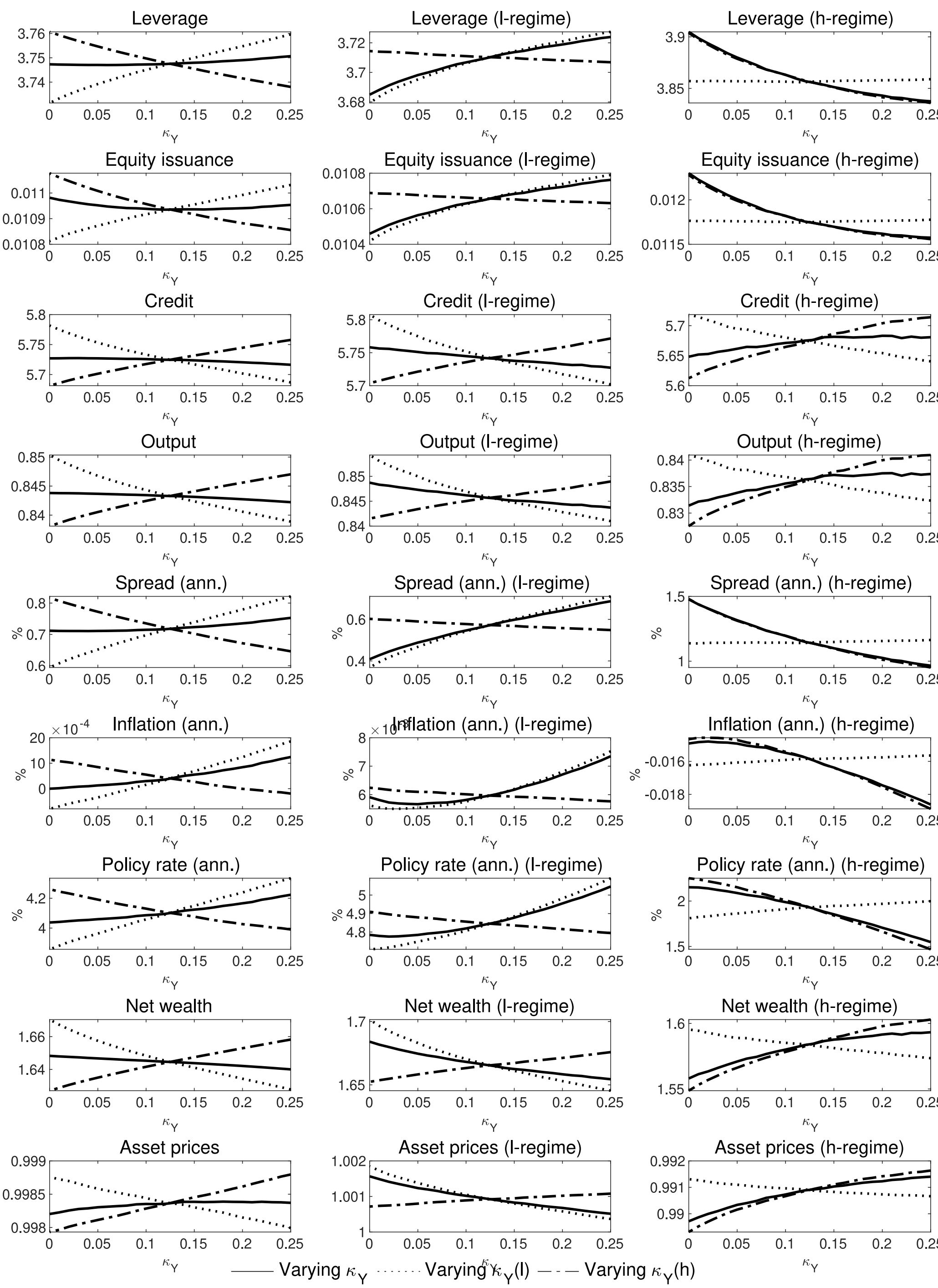

Fig. A.3. Regime-specific effects of varying the responsiveness to output.

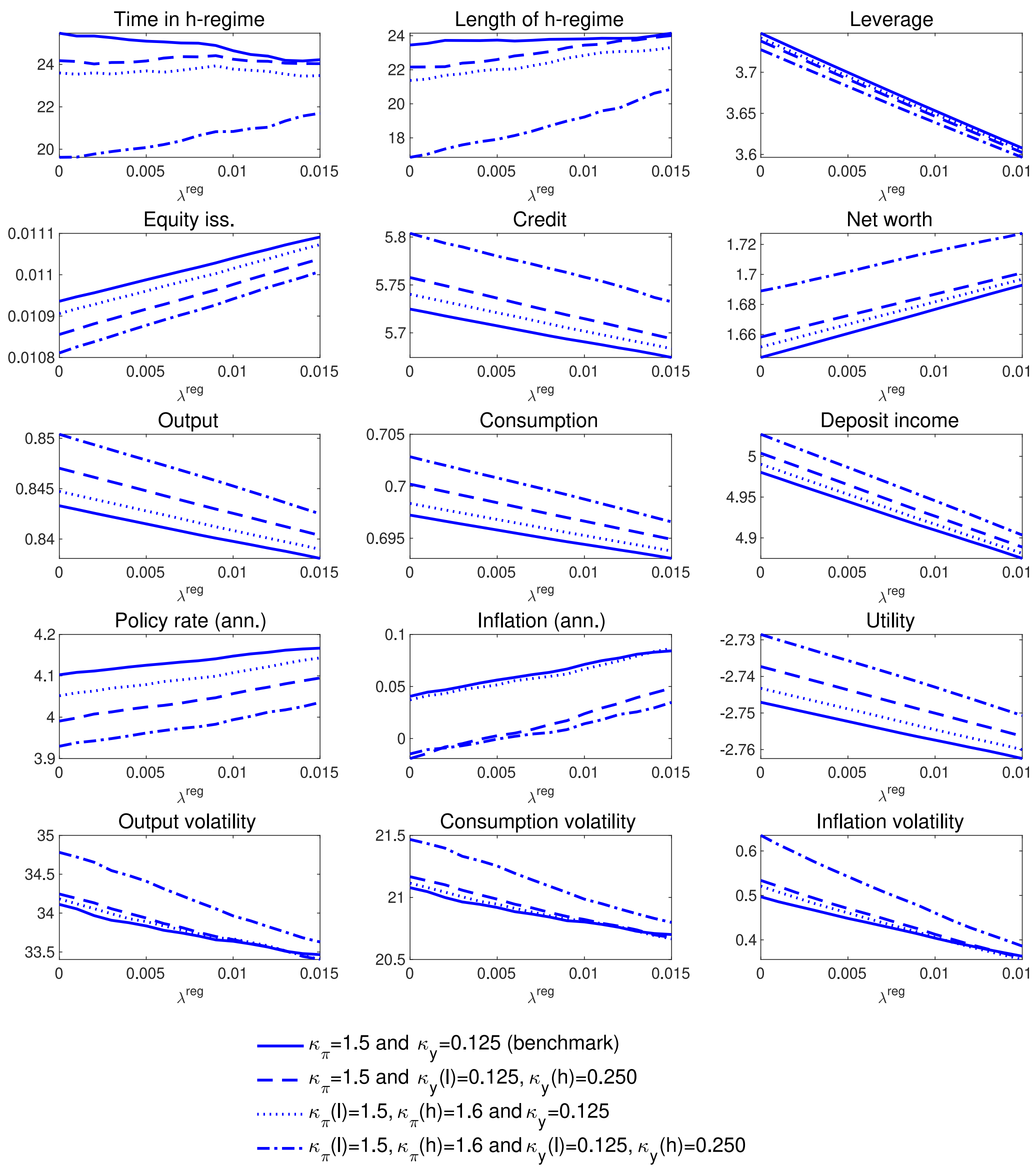

Fig. A.4. Constant capital buffer and different monetary policies.

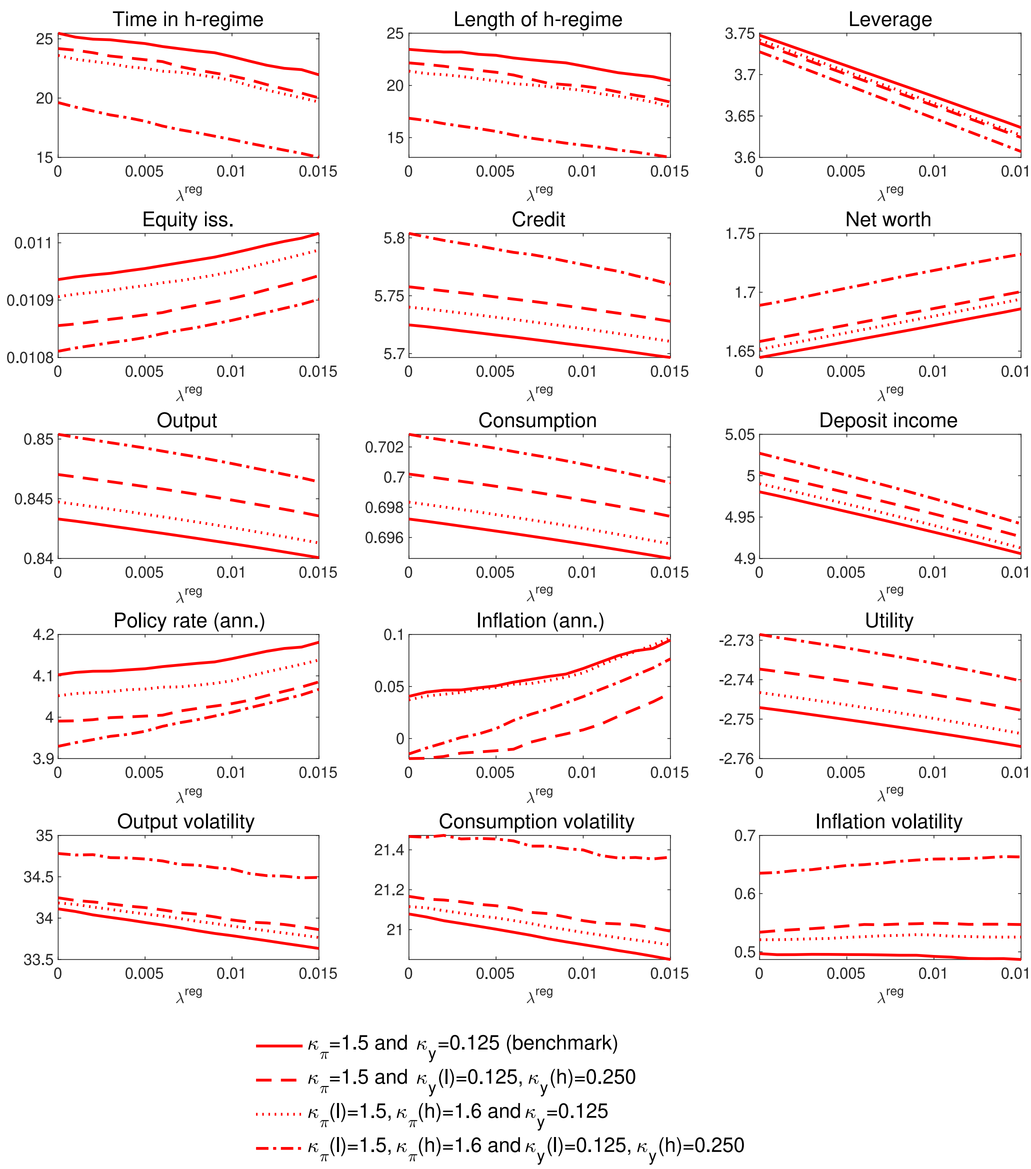

Fig. A.5. Regime-dependent capital buffer (in normal times) and different monetary policies.

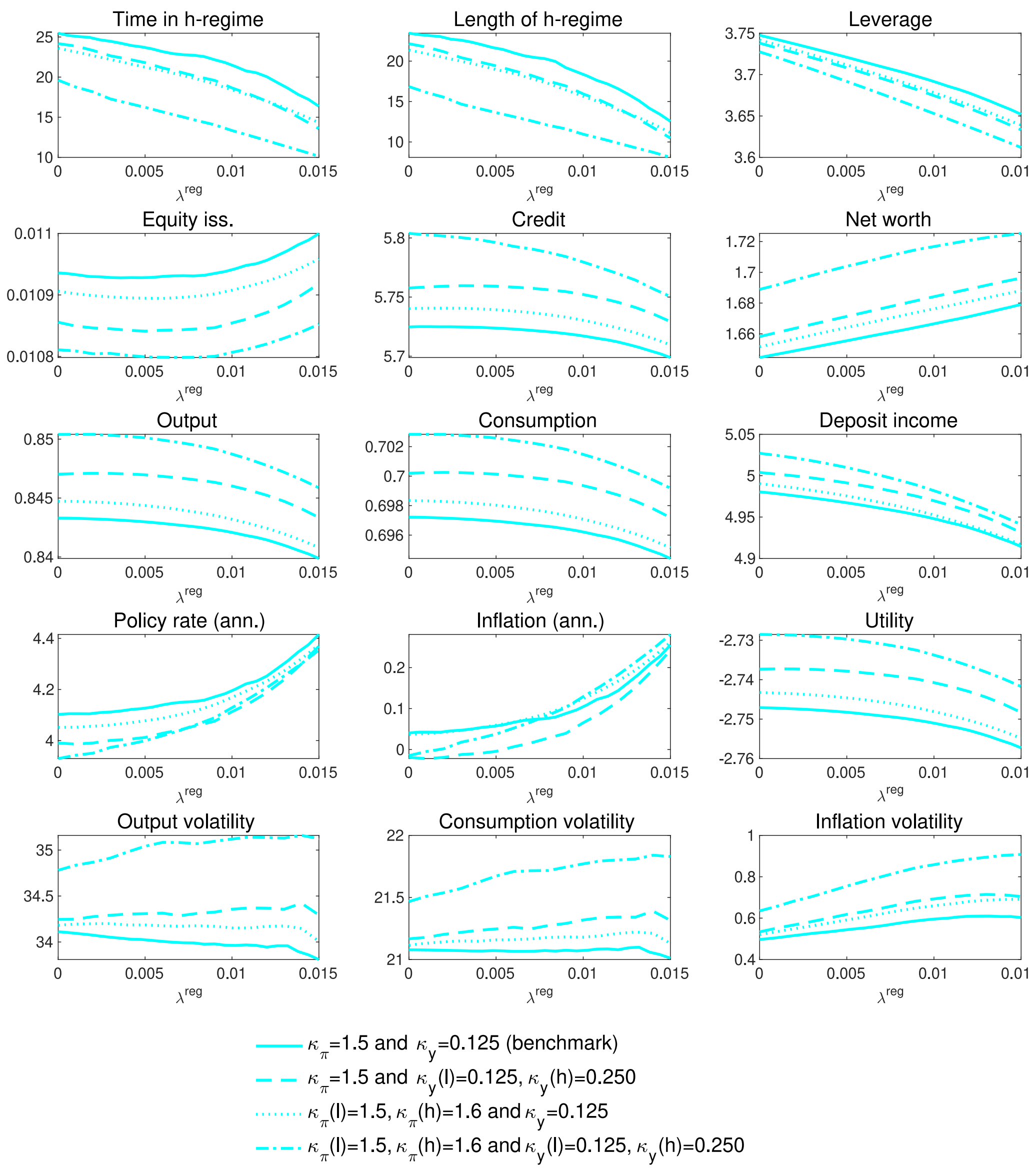

Fig. A.6. Regime-dependent capital buffer (in normal times) and relief measure (in crisis times) and different monetary policies.

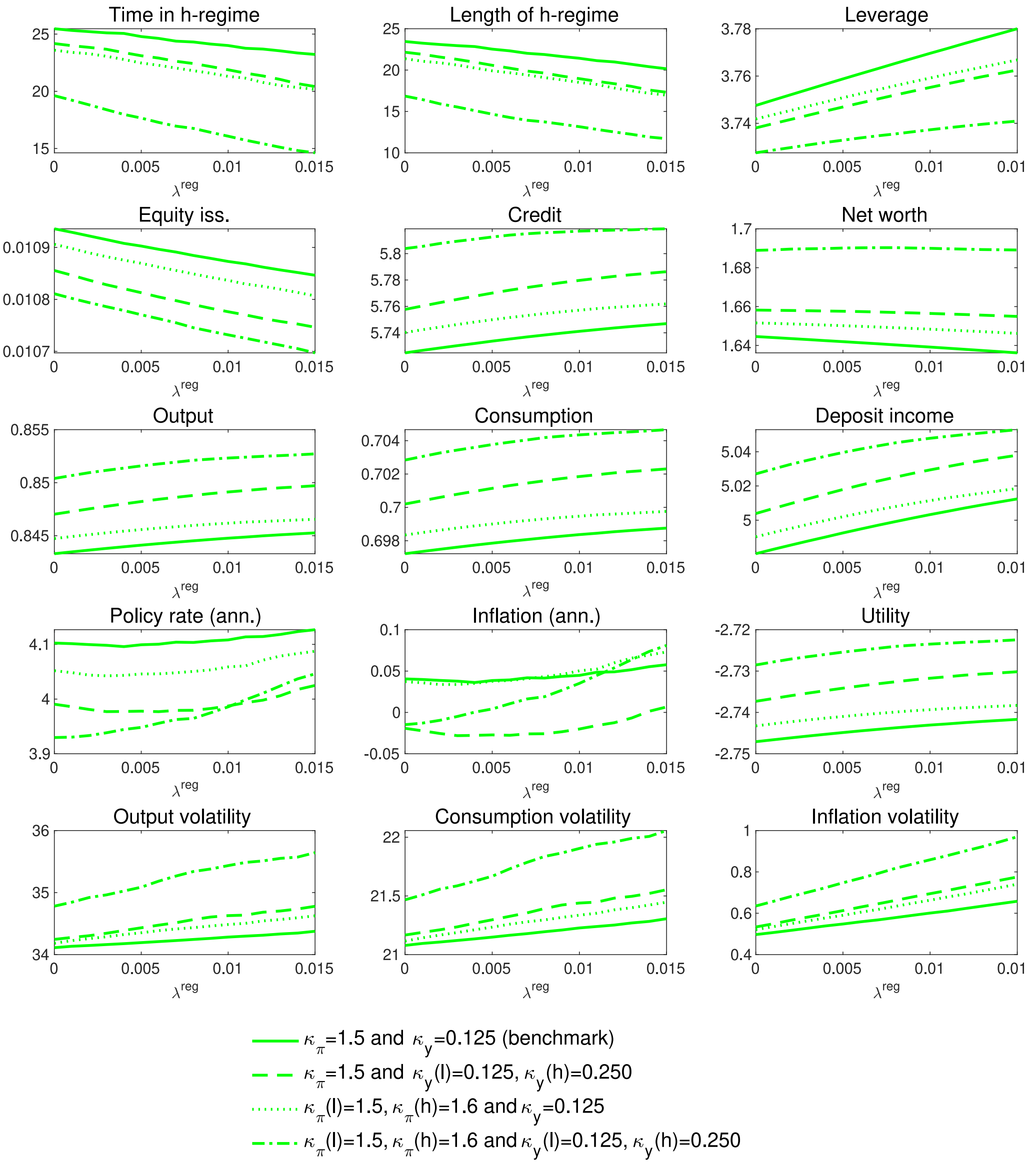

Fig. A.7. Regime-dependent capital relief measure (in crisis times) and different monetary policies.

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