Bank of Finland Research Discussion Papers
9 • 2024

Dominik Hecker – Hun Jang – Margarita Rubio – Fabio Verona

Robust design of countercyclical capital buffer rules

Bank of Finland
Research

Bank of Finland Research Discussion Papers
Editor-in-Chief Esa Jokivuolle

Bank of Finland Research Discussion Papers 9/2024
25 October 2024

Dominik Hecker – Hun Jang – Margarita Rubio – Fabio Verona:
Robust design of countercyclical capital buffer rules

ISSN 1456-6184, online

Bank of Finland
Research Unit

PO Box 160
FIN-00101 Helsinki

Phone: +358 9 1831

Email: research@bof.fi
Website: www.suomenpankki.fi/en/research/research-unit/

Robust design of countercyclical capital buffer rules*

Dominik Hecker† Hun Jang‡

Margarita Rubio§ Fabio Verona¶

Abstract

In this paper, we design countercyclical capital buffer rules that perform robustly across a wide range of Dynamic Stochastic General Equilibrium (DSGE) models. These rules offer valuable guidance for policymakers uncertain about the most appropriate model(s) for decision-making. Our results show that robust rules call for a relatively restrained response from macroprudential authorities. The cost of insuring against model uncertainty is moderate, emphasizing the practicality of following these robust countercyclical capital buffer rules in uncertain economic environments.

Keywords: countercyclical capital buffers, macroprudential policy, model comparison, structural models, model uncertainty, robust rule

JEL classification: E32, E44, E47, E60, G20, G28

* The views expressed are those of the authors and do not necessarily reflect those of the Bank of Korea, the Bank of Finland, the Deutsche Bundesbank, or the Eurosystem. We thank the editor (Thorsten Beck), an anonymous referee, Iftekhar Hasan, and Aino Silvo for useful comments. Any errors are the sole responsibility of the authors. We also thank everyone who shared their codes with us or made them available online.

† Deutsche Bundesbank and University of Kiel (hecker@economics.uni-kiel.de)

‡ Economic Research Institute, Bank of Korea (janghun@bok.or.kr)

§ University of Nottingham (margarita.rubio@nottingham.ac.uk)

¶ Bank of Finland – Monetary Policy and Research Department, and University of Porto – *Cef.up* (fabio.verona@bof.fi)

1 Introduction

The global financial crisis opened a debate on the appropriate policy for avoiding excessive credit growth and promoting financial stability. In both academic and policy circles, the focus centered on macroprudential policy. While the macroprudential toolkit available to policymakers is ample, the Basel accords propose the addition of a new instrument – the countercyclical capital buffer (CCyB) – that goes beyond the traditional setting of static mandatory capital requirements for banks by providing a dynamic buffer for countering procyclicality in the financial system.

Evaluating this policy instrument is empirically difficult due to limited real-world data.[1] From a theoretical perspective, it is also challenging to compare outcomes from simulations across structural models due to the lack of any widely agreed-upon theoretical framework for the study of macroprudential policies, especially in situations where the macroprudential authority is uncertain as to application of the available tools.[2] In spite of this uncertainty, the macroprudential authority must strive to act in the best interests of the economy.

The theoretical literature on the effectiveness of CCyB policies highlights these challenges. For instance, output and credit (and housing prices to a lesser extent) are the variables commonly used in setting the CCyB and modeling the mandate of the macroprudential authority. These variables, however, are represented as growth rates, ratios, or deviations from steady-state levels. This produces a multiplicity of mandates and policy rules from which the macroprudential authority must then choose. Ultimately, these modeling choices affect the conclusions that might be drawn about the effectiveness of a particular CCyB policy and thereby the policy recommendations.

Likewise, the source of shocks hitting the economy is crucial in understanding the consequences of dynamic macroprudential policies and their optimal use (see e.g. Angelini, Neri and Panetta, 2014 and Lozej, Onorante and Rannenberg, 2022). In general, the policy reaction depends on the calibration of

[1] See Gulan, Jokivuolle and Verona (2022) for a discussion on the empirical estimates of optimal bank capital requirements surveyed in the literature.

[2] It seems uncontroversial to argue that the state of knowledge is far less advanced in macroprudential policy than in monetary policy. In fact, when analyzing optimal conventional monetary policy, there is a general consensus among policymakers and academics on the core framework (i.e. the New Keynesian model with sticky prices), on the objectives of the central bank (i.e. stabilizing inflation and output / unemployment), and on the tools to achieve them (i.e. Taylor-type interest rate rules).

the shock processes and the origin of the shocks.[3] The effectiveness of CCyB regulation following non-financial shocks, for example, is far from clear. Finally, as shown by Agenor and Jackson (2022) and Malmierca (2023), among others, the effectiveness of CCyB policies also depends on the monetary and fiscal policy stance and how well these policies are coordinated.

Given the rich constellation of structural models, shocks, macroprudential policy mandates, and macroprudential policy rules used in the literature, comparison of results across theoretical studies is a non-trivial task. Not surprisingly, as noted by Gulan et al. (2022), researchers offer a spectrum of conclusions about the economic impact of countercyclical capital regulation that ranges from helpful (e.g. Rubio and Carrasco-Gallego, 2016) to damaging (e.g. Canzoneri, Diba, Guerrieri and Mishin, 2023).

The immediate research and policy question is thus whether the policymaker should use a dynamic capital buffer to augment the static capital requirement, and if so, how. In this paper, we use theoretical models to provide insight into this question. However, as mentioned, there is still no consensus on an appropriate macroprudential policy framework to use to answer this question. Therefore, the starting point is finding a way to unify the existing frameworks and conclusions so as to provide policymakers with well-informed recommendations.

To offer robust insight into the effectiveness of countercyclical capital regulation, in this paper we run comparable simulations (i.e. consider the same macroprudential policy rules and macroprudential loss functions) across a wide range of structural macroeconomic models in which bank capital plays a key role. All models share the same methodological core, but each one features different frictions, shocks, and transmission channels. In line with the existing literature, we find that some models prescribe no dynamic reaction from the macroprudential authority, while others call for an aggressive response. This result is hardly helpful to policymakers seeking clarity. To overcome this problem, we identify CCyB rules that perform well across all the considered models. The optimized CCyB rules, which are robust to model uncertainty, prescribe a fairly muted response by the macroprudential authority. We show that the overall cost of insurance against model uncertainty is moderate and that there is a positive relationship between the level of model uncertainty and the cautiousness of policy responses: as the number of models

[3] This is akin to monetary policymaker's problem of reacting to supply versus demand shocks.

increases, model uncertainty rises, leading to more restrained actions by policymakers. Thus, the clear policy recommendation of this paper is that policymakers facing model uncertainty need to exercise caution in the use of the countercyclical capital buffer.

The paper is organized as follows. Section 2 briefly reviews the two literatures on which our work builds, the work on dynamic capital regulation in macro models and the work on model uncertainty and robust policy rules. In Section 3 we present the modeling of the macroprudential authority mandate and policy rule, and the Dynamic Stochastic General Equilibrium (DSGE) models with bank capital we use, with a particular attention to the modeling of the banking sector. In Section 4 we compute the optimized model-specific and model-robust CCyB rules. Section 5 concludes.

2 Literature review

Our paper touches on two strands of literature, one on the theoretical literature on dynamic capital regulation and one on model uncertainty and robust policy rules. We start our analysis with a brief overview of these two areas of research.

2.1 Dynamic bank capital regulation in structural models

Simulations using DSGE models suggest that countercyclical capital regulation is, at least to some extent, helpful in smoothing business cycle fluctuations, increasing welfare, or both.[4] Simulation results, nonetheless, are conditional on such assumptions as the source of business cycle fluctuations (technology, financial, etc.), the state of the economy, the macroeconomic or financial variables used in the macroprudential rule and the macroprudential authority's loss function, the stance of monetary and fiscal policy and coordination with them, as well as the method used to solve the model (global solution vs. local approximation). Therefore, comparing policy prescriptions across studies with different models and assumptions is challenging. Our aim is to reduce the result uncertainty to provide more definitive policy

[4] See Gulan et al. (2022) for an extensive literature review on the effectiveness of CCyB regulation in DSGE models.

recommendations.

First, the cyclical nature of CCyB regulation heightens the need to understand and disentangle the underlying shocks driving business and financial cycles in real time. Identifying shocks in real time is, unfortunately, not possible. Our approach uses a wide set of models, each of them calibrated or estimated for different countries or regions and with different set of stochastic shocks, so that we can give policy recommendations that are not shock specific (as usually done in the literature) but are overall solid.

There is, second, uncertainty about which variables the macroprudential authority should consider in their responses. Authorities can emphasize any variable that seems reasonable to them in assessing the sustainability of credit and the level of systemic risk. Common indicators used in the literature include asset prices, output, and credit variables. For instance, asset and housing price growth is used by Darracq Paries, Kok Sorensen and Rodriguez-Palenzuela (2011), credit growth by Gelain and Ilbas (2017), output by Hollander (2017), credit and asset price gaps by Liu and Molise (2019) and Lozej et al. (2022), and the growth rate of the credit gap by Gebauer and Mazelis (2023). Here, we follow the preponderance of the literature and consider the credit gap (defined as the deviation of the credit-to-output ratio from its steady-state level) as our main indicator. We also include output as an objective for the macroprudential authority as a proxy for macroeconomic stability. Most importantly, we simulate all models using the same CCyB rule and consider the same objective function for the macroprudential policymaker.

Finally, national macroprudential authorities in the Euro area face an additional challenge – coordination with their domestic fiscal policy and area-wide monetary policy. Cross-country asymmetries and country-specific shocks are significant issues in the design and implementation of domestic macroprudential policy in a monetary union framework (Bosca, Ferri and Rubio, 2024). In this paper we take monetary and fiscal policy as given and mainly focus on macroprudential policy.[5]

[5] A small group of papers attempt to quantify the *optimal* range of the CCyB. For instance, Malherbe (2020) finds that the risk-weighted capital requirement should rise from 8 to 9.12 % after an expansionary technology shock. Davydiuk (2019) finds that optimal Ramsey policies keep the total capital requirement between 5 and 7 %. Similarly, Elenev, Landvoigt and Nieuwerburgh (2021) find that a capital requirement oscillating between 5 and 9 % outperforms a fixed capital requirement of 7 %, implying a ± 2 % range for the CCyB around the fixed capital requirement.

2.2 Model uncertainty and the need for robust policy rule

DSGE models are widely used in policy analysis.[6] While several models incorporating a banking sector into a New Keynesian framework are currently available, none provides the true model of the economy and none can be considered a benchmark model for macroprudential analysis (as in the case of the three-equation New Keynesian model of Clarida, Gali and Gertler, 1999 for monetary policy). Furthermore, a policy rule that is optimal in one model can perform poorly in another. Thus, the choice of model(s) and rules matters.

Model uncertainty is therefore an important source of uncertainty facing policymakers. In the monetary policy literature, several studies have identified monetary policy rules that perform well across a variety of structural models (see e.g. Levin and Williams, 2003, Levin, Wieland and Williams, 2003, Kuester and Wieland, 2010, Taylor and Wieland, 2012, and Dück and Verona, 2023). These rules are defined to be robust to model uncertainty.

Given the lack of consensus on the benchmark model to use for macroprudential policy analysis and following the above mentioned monetary policy literature, we adopt a robust approach that takes a holistic view of models. To our knowledge, the closest paper to ours is Binder, Lieberknecht, Quintana and Wieland (2018), who use three DSGE models (also included here in our analysis) and mainly focus on the interaction between macroprudential and monetary policy.[7] Our main interest in this paper is in the design of CCyB rules that are robust to model uncertainty. Hence, we take monetary policy as given and use a larger set of 12 models to more thoroughly account for model uncertainty.[8]

[6] For instance, the QUEST model (Ratto, Roeger and in't Veld, 2009) is used by the European Commission, the del Negro, Giannoni and Schorfheide (2015) model is in use at the New York Fed, and the Aino models (Kilponen, Orjasniemi, Ripatti and Verona, 2016 and Silvo and Verona, 2020) at the Bank of Finland, just to name a few.

[7] Angelini, Clerc, Curdia, Gambacorta, Gerali, Locarno, Motto, Roeger, den Heuvel and Vlcek (2015) also analyze the effects of CCyB using three DSGE models.

[8] Incomplete information and uncertainty are also discussed in the macroprudential policy literature. With respect to macroprudential rules, Rubio and Unsal (2020) find that when there is incomplete information, fighting aggressively against deviations of credit from it steady state may worsen the problem. This finding is related to a general result in the monetary policy literature that shows that the optimized coefficient on the output gap in the Taylor rule declines in the presence of errors in measuring the output gap (see e.g. Aoki, 2003 and Orphanides, 2003).

3 The setup

3.1 The macroprudential authority's objectives

The literature on optimal macroprudential policy obtains normative conclusions either by maximizing welfare by taking a second-order approximation of the households' utility function or by minimizing a loss function. The latter approach explicitly considers those variables of greatest concern to the macroprudential authority (i.e. variables related to financial or macroeconomic stability or the smoothness of the policy instrument).

Here, we follow the second approach and search for the optimal countercyclical policy response by minimizing a loss function. As a reasonable and widely used specification, we follow Angelini et al. (2014) and assume that the macroprudential authority cares about the variability of the credit gap (as a proxy for financial stability), the volatility of output (as a proxy for macroeconomic stability), and the variability of the macroprudential policy instrument (to keep changes and the size of the CCyB moderate).[9]

In the literature on optimal monetary policy, it is well established that including the variance of the policy instrument, typically the short-term interest rate, in the central bank's loss function should be considered. This approach has both analytical and computational justifications. Analytically, a positive weight on the interest rate's variance is derived from second-order approximations of the households' loss function (Woodford, 2003). Computationally, negligible weights on the interest rate's variance can lead to unreasonably large elasticities in optimized policy rules with respect to the output gap and inflation's deviation from the target.

In contrast, including the variance of the policy instrument in the macroprudential policy literature is less clear due to ambiguity surrounding the policy instrument itself. However, there are still good reasons for incorporating this concept into an ad-hoc loss function. Firstly, neglecting the variance of the capital buffer could lead to unreasonable values in optimized macroprudential rules (Angelini et al., 2014). Secondly, a policymaker who frequently changes the capital buffer may cause uncertainty in the economy.

[9] Ferrero, Harrison and Nelson (2024) analytically derive a loss function which is consistent with the ad-hoc functions that are widely used in the literature, like the one in this paper.

Hence, banks and policymakers themselves might have an interest in smoothing the capital buffer to avoid such uncertainties.

Analytically, we assume that the macroprudential authority's mandate consists of minimizing a weighted average of the variances of the credit-to-output ratio (B/Y), output (Y), and the change of the macroprudential policy instrument (Δcr):

$$\sigma^2_{B/Y} + \kappa_1 \sigma^2_Y + \kappa_2 \sigma^2_{\Delta cr} \ , \tag{1}$$

where $\sigma^2_{B/Y}$, σ^2_Y, and $\sigma^2_{\Delta cr}$ are variances of credit-to-output, output, and the change in the capital requirement, respectively. κ_1 and κ_2 are the relative weight that the macroprudential authority assigns to these targets. For completeness, we consider the following five loss functions: $\kappa_1 = 0$ and $\kappa_2 = 0.1$, $\kappa_1 = \kappa_2 = 0.1$, $\kappa_1 = 0.1$ and $\kappa_2 = 0.5$, $\kappa_1 = \kappa_2 = 0.5$, and $\kappa_1 = \kappa_2 = 1$. First and foremost, the macroprudential authority aims at stabilizing the volatility of the credit-to-output ratio. Additionally, the policymaker always attaches some weight to the volatility of the policy instrument, that is key to generate a trade-off in the models. The last case considers equal weights in the loss function.[10]

3.2 The countercyclical capital requirements rule

To achieve its target, we assume that the macroprudential regulator sets the capital requirement cr_t using the following rule:

$$cr_t = cr \left(\frac{B_t/Y_t}{B/Y} \right)^{\phi_{ccyb}} \ , \tag{2}$$

where cr is the steady-state value of the capital-to-asset ratio requirement, B and Y are the steady-state values of credit and output, respectively, and $\phi_{ccyb} \geq 0$ is the degree of the countercyclical capital requirement. For $\phi_{ccyb} = 0$ the rule implies a static capital buffer as prescribed by Basel I, while $\phi_{ccyb} > 0$ represents the leaning-against-the-wind policy of the Basel III countercyclical capital regulation – promoting the buildup of capital buffers in good times, which can then be released in bad times.

[10] Interestingly, Rubio and Carrasco-Gallego (2017) show that the macroprudential regulator should give more weight to output and housing prices than to credit growth as the former indicators anticipate credit growth (by the time the regulator observes credit growth, it is probably too late to avoid it).

Some of the models we use do not specify a CCyB rule (i.e. they only consider static capital requirements) or use alternative specifications of the CCyB rule. We use our specified rule consistently across models.[11]

3.3 The suite of DSGE models with bank capital

While still in its infancy, the theoretical literature on modeling bank capital requirements in DSGE models is growing fast and several models are nowadays available. In this paper we solve the models with the traditional log-linear approximation around the steady state, so for comparability of the results we exclude the models solved with different solution methods. For instance, the models in Faria-e-Castro (2021) and Canzoneri et al. (2023) involve occasionally binding constraints, hence they are solved with global or non-linear solution methods. Furthermore, we exclude some models because they are too sensitive to the parameterization of the countercyclical capital requirements rule (e.g. Hollander, 2017 and Liu and Molise, 2019).

Ultimately, we focus on 12 quantitative monetary DSGE models in which banking capital plays a key role. The list of the models with summaries of their key features is reported in table 1. The models include financial frictions on the supply side of financial intermediation and are representative of the latest generation of models putting financial intermediaries and their balance sheets at the center of business cycle fluctuations.

All models except one (Clerc, Derviz, Mendicino, Moyen, Nikolov, Stracca, Suarez and Vardoulakis, 2015) feature a common New Keynesian DSGE core with nominal rigidities à la Smets and Wouters (2003) with nowadays standard bells and whistles (e.g. habits in consumption, adjustment costs in investment, and variable capital utilization). While we include mainly closed economy models, we also use two models of small open economies and two two-country models for countries within the European Monetary Union (EMU). Inclusion of these models is a first step in addressing the issue of parameter uncertainty as they were estimated or calibrated for countries or regions other than the United States or

[11] We note that simulations conducted with DSGE models are different from real-world implementation of a CCyB (e.g. in terms of defining excessive credit growth, time lags between announcement and implementation, or asymmetric speed of implementation between building the buffer and its release). See Angelini et al. (2015, Section 2) for further discussion.

the Euro area. In particular, rather than coordinating for the same structural parameters across different models, the parameter calibration of each model is based on the values provided by the author(s) so that it reflects the parameterization best suited to the model's specific features.

Some of these models also include financial frictions stemming from the demand side of financial intermediation. They usually introduce heterogeneity in the household sector using the impatient borrowers / patient savers setup of Iacoviello (2005), in which borrowers are financially constrained and subject to collateral requirements in the form of loan-to-value ratios.

Three main approaches have been used to introduce banking frictions related to capital requirements: monopolistic banking competition, asymmetric information and costly state verification, and moral hazard. In the following sub-section we describe these banking frictions in more details, with particular attention to the modeling of the (countercyclical) capital requirement, and refer the reader to the online appendix for a more comprehensive description of each model.

3.4 The source of banking frictions in our suite of DSGE models

3.4.1 Monopolistic banking competition and quadratic penalty costs

This approach is based on Gerali, Neri, Sessa and Signoretti (2010) and has been used by Angelini et al. (2014) (M_1), Darracq Paries et al. (2011) (M_3), Poutineau and Vermandel (2017) (M_8), and in the commercial banking sector in Gebauer and Mazelis (2023) (M_12).

In this modeling framework, the banking sector is assumed to be monopolistically competitive, allowing banks to have price-setting power. Banks incur a quadratic cost if their capital-to-asset ratio deviates from the level set by the macroprudential authority (cr_t). Solving banks' profit maximization problem yields the following credit spread equation:

$$R_t^b = R_t^d - \kappa_{K^b} \left(\frac{K_t^b}{B_t} - cr_t \right) \left(\frac{K_t^b}{B_t} \right)^2 , \tag{3}$$

where R^b denotes the interest rate on loans (B_t), R^d denotes the interest rate on deposits (D_t), K_t^b represents the level of bank capital (which can be accumulated by using retained earnings), and κ_{K^b} measures the intensity of the penalty costs. While the regulatory capital requirement (cr) is constant in Gerali et al. (2010), the modeling framework can be easily modified to allow for time-varying and countercyclical cr_t, as done in M_1. In this framework, when the credit gap deviates positively from its steady state, more bank capital needs to be raised (recall equation 2). As a result, banks increase lending rates through equation (3), which, in turn, reduces the demand for credit and negatively affects investment and consumption.

Regarding the variables used in the CCyB rule, our preferred variable is the credit gap. In M_1 and M_3, there are two types of borrowers (impatient households and entrepreneurs), and we define credit in these models as the sum of loans to households and entrepreneurs. In M_8, which is a two-country model of the Euro area economy, two measures of credit are available: loan supply or loan demand. Furthermore, loans can be split into national or union-wide loans. In our simulation, we consider credit supply and domestic loan only (i.e., we consider the response of the macroprudential authority in country 1 in that model). In M_12, there is one borrower and, potentially, two lenders: commercial and shadow banks. In our simulation with M_12, credit only includes commercial bank loans to entrepreneurs.

3.4.2 Asymmetric information, credit risks, and costly state verification

Malmierca (2023) (M_4), Lozej et al. (2022) (M_5), and Clerc et al. (2015) (M_10) follow the seminal contribution of Bernanke, Gertler and Gilchrist (1999) and introduce costly state verification as a form of financial friction in the banking sector.

In this framework, borrowers and banks sign a debt contract, according to which borrowers commit to making full debt repayment (say, $R_{t+1}B_t$, where R_{t+1} is the gross interest rate on the loan and B_t is the loan amount) unless they default. Borrowers' asset returns (from housing properties or capital goods) is given by $\omega_{t+1}R^k_{t+1}q_tk_{t+1}$, where R^k_{t+1} is the expected average nominal gross rate of return on capital, q_t is the price of capital, k_{t+1} is the stock of capital, and ω_{t+1} is an idiosyncratic productivity shock which follows a log-normal distribution: $\log(\omega_{t+1}) \sim N\left(-\frac{\sigma^2}{2}, \sigma^2\right)$.

Financial frictions arise from asymmetric information between entrepreneurs and banks. Entrepreneurs costlessly observe their idiosyncratic shocks, while banks must pay a monitoring cost (that represents a fraction μ, $0 < \mu < 1$, of the entrepreneur's gross return) to observe the shocks. The optimal financing mechanism is a debt contract that gives the lender the right to all liquidation proceeds of the entrepreneur defaults.

In this framework, borrowers default if their total repayment burdens exceed realized asset returns, generating a threshold point of idiosyncratic shocks (ϖ_{t+1}) that make borrowers indifferent between default and full repayment (i.e., $R_{t+1}B_t = \varpi_{t+1}R^k_{t+1}q_tk_{t+1}$). In this setup, the following condition holds in equilibrium:

$$\underbrace{\left[1-F\left(\varpi_{t+1}\right)\right]R_{t+1}B_t}_{Returns\ from\ full\ repayment}+\underbrace{\left(1-\mu\right)\int_0^{\varpi_{t+1}}\omega dF\left(\omega\right)R^k_{t+1}q_tk_{t+1}}_{Returns\ when\ default\ occurs}=\underbrace{X_t}_{Costs}, \tag{4}$$

where $F_t\left(\omega\right)$ is the cumulative distribution function of ω_{t+1}.While the specification of X_t varies across models, it is commonly assumed that X_t is positively associated with regulatory requirements, which are set to be countercyclical according to equation (2).

Specifically, in M_4, X_t is total interest payment on deposits ($R^d_tD_t$, where D_t is the stock of deposit and R^d_t the deposit interest rate) and it is assumed that the amount of deposits should be greater than that of corporate loans (B_t) such that $D_t = cr_tB_t$, $cr_t \geq 1$. Thus, as capital requirement (cr_t) increases, banks increase lending rates to compensate for the higher deposit costs for a given level of B_t, leading to lower demand for loans. In our simulations with M_4, which is a two-country model, credit is defined as domestic credit (i.e. we exclude foreign credit). M_10 takes a similar approach, where capital requirement depends on total credit, which encompasses both corporate and household loans. Differently, X_t in M_5 includes risks associated with uncertainty in lending revenues due to idiosyncratic shocks. Given this uncertainty, banks incur a penalty cost per unit of lending if they fail to meet capital requirements. As cr_t increases, the probability of facing such penalties rises, leading banks to reduce their lending activities to minimize costs when penalties materialize.

3.4.3 Moral hazard problems

Meh and Moran (2010) (M_2) and Gertler and Karadi (2011) (M_11) introduce financial frictions in the form of moral hazard.[12]

M_2 introduces a double moral hazard problem, one between borrowers (entrepreneurs) and banks, and one between banks and depositors (households). Borrowers with net worth n_t want to start a project of size i_t, so they need external funding in the amount of $i_t - n_t$. They have incentives to invest in a project that delivers the highest profit for them but has a lower probability of success. To force them to choose the project with the highest success probability, the bank should pay monitoring cost (μ) which is proportional to the size of the project. Such monitoring activities are delegated to banks by depositors who cannot monitor borrowers' behavior themselves. Thus, banks also have an incentive for imperfect monitoring, which requires them to raise a fraction of funds through their net worth (a_t) to mitigate moral hazard, thereby creating a link between i_t and a_t. Given this setup, the borrower chooses the size of the investment project under incentive-compatible constraints such that (i) borrowers choose the project with the highest success probability and (ii) banks exert their best monitoring efforts. Ultimately, the following condition holds in equilibrium:

$$i_t = \frac{a_t + n_t}{G_t} \quad , \tag{5}$$

where $1/G_t$ is the leverage achieved by the financial contract over the combined net worth of the bank and the entrepreneur, and G_t is positively correlated with the monitoring cost (μ). Equation (5) shows that the size of the project is positively related to the level of banks' net worth. Although Meh and Moran (2010) do not explicitly adopt a CCyB rule, it can be incorporated by adequately adjusting equation (5). Following Binder et al. (2018), we divide a_t in equation (5) by the regulatory capital requirement (cr_t), which in practice limits the amount of banks' net worth to be used to finance the loan granted to the entrepreneur.

M_11 incorporates a moral hazard problem between investors (households) and bankers. Banks obtain funds from investors to finance loans to entrepreneurs. The moral hazard problem arises because banks

[12] In the shadow banking sector in Gebauer and Mazelis (2023) there is also a moral hazard friction between shadow banks and investing households.

can divert a fraction λ of available funds from the project and go bankrupt. To enforce them to behave, the expected terminal wealth from banking operations should be greater than or equal to the benefit from diverting funds. Such incentive compatibility condition is given by:

$$\nu_t Q_t S_t + \eta_t N_t \geq \lambda Q_t S_t \ , \tag{6}$$

where S_t is the quantity of intermediary assets, Q_t is the relative price of such claims, N_t is the bank's wealth or net worth, ν_t is the expected marginal gain to the banker of expanding assets ($Q_t S_t$) by a unit, holding net worth constant, and η_t is the expected value of having another unit of wealth, holding S_t constant. As equation (6) holds with equality, the level of financial claim is expressed as banks' net worth, i.e., $Q_t S_t = \phi_t N_t$ where $\phi_t = \frac{\eta_t}{\lambda - \nu_t}$. To incorporate dynamic macroprudential policy, we follow Binder et al. (2018) and introduce capital requirements directly in the incentive compatibility condition such that $\nu_t Q_t S_t + \frac{\eta_t N_t}{cr_t} = \lambda Q_t S_t$, which determines the proportion of bank capital which can be used to fund investment projects.

3.4.4 Other modeling frameworks

Alpanda, Cateau and Meh (2018) (M_6), Agenor and Jackson (2022) (M_7), and Tayler and Zilberman (2016) (M_9) take different approaches. In general, such models introduce a specific type of cost that influences depositors' or financial intermediaries' decisions.

M_6 assumes that saver households incur monitoring costs which depend on the leverage position of banks and on the capital requirement ratio on banks. All else equal, stricter capital regulations due to e.g. excessive credit, as implied by equation (2), increase the monitoring costs of investors funding the banks. The funding spread faced by the bank then increases and, as a result, lending decreases. In this model, credit is defined as the sum of loans to households and entrepreneurs.

M_7 adopts a monopolistic competition framework in the banking sector similar to the one in Gerali et al. (2010) and in the models in section 3.4.1. The loan interest rate set by commercial banks thus incorporates a premium, above and beyond the marginal cost of funding. Banks are subject to capital requirements, imposed by the regulator. They must hold an amount of capital that covers a time-varying percentage of its investment loans. In this model, rather than a cost imposed whenever the capital-to-asset position of the bank deviates from the level chosen by the regulator, banks face a pecuniary cost of monitoring risky investment loans. As a result, the lending rate depends negatively on the probability of loan repayment (which in turn depends on the monitoring effort of the bank) and positively on the time-varying regulatory capital requirement.

M_9 also introduce costs associated with capital requirements. Here, the collateral is firms' (borrowers') output (Y_t), which is subject to an idiosyncratic shock and it is seized with probability χ_t in the event of default. Thus, firms default if the expected value of foreclosure ($\chi_t Y_t$) is smaller than their debt liabilities, meaning that credit (default) risk is negatively associated with the output level. In terms of cost, the authors assume that a linear cost is incurred as the bank capital level increases. The lending rate is determined from the zero profit condition as a function of the regulatory bank capital-to-loan ratio, which is negatively related to credit risk. In other words, as output increases (credit risk decreases) bank capital requirement increases, resulting in a higher lending rate that reduces the demand for corporate loans.

4 Optimized countercyclical capital buffer rules

4.1 Model-specific CCyB rules

For each model $m \in M$, we solve the following optimization problem:

$$\min_{\phi_{ccyb}} \left(\sigma^2_{B/Y}\right)_m + \kappa_1 \left(\sigma^2_Y\right)_m + \kappa_2 \left(\sigma^2_{\Delta cr}\right)_m$$
$$s.t.\ \ cr_t = cr \left(\frac{B_t/Y_t}{B/Y}\right)^{\phi_{ccyb}}$$
$$E_t \left[f_m \left(x^m_t, x^m_{t+1}, x^m_{t-1}, z^m_t, \Theta^m\right)\right] = 0$$

and there exists a unique and stable equilibrium for that model, where f_m is the set of all model-specific equations besides the policy rule, and x^m,z^m_t, and Θ^m are model-specific endogenous variables, exogenous shocks, and parameters, respectively.

We solve the optimization problem by running a grid search over the ϕ_{ccyb} parameter. The lower and upper boundaries for ϕ_{ccyb} are 0 and 10, respectively, and the step of the search is 0.1.[13]

Table 2, panel A, reports the optimized model-specific ϕ_{ccyb} coefficients ($\phi_{ccyb}^{model-specific}$). Overall, results vary greatly across models and loss functions. For two models (M_7 and M_8), the search for the optimized parameters always reaches the lower or upper bound, regardless of the weights on the loss function. For the other models, the optimized ϕ_{ccyb} parameter usually decreases when the macroprudential authority attaches more weight to the other objectives of the loss function. These heterogeneous results may be due to the characteristics of the individual models, even though they share a common New Keynesian core. We now briefly discuss how the included sectors, frictions, and their interactions may influence the optimal design of the CCyB rule.

Models incorporating cross-border trade (M_4 and M_8) are more likely to yield optimized coefficients close or at the upper bound of our optimization range. It is noteworthy that when searching for the optimized coefficients in these models, we consider a scenario where only one of the two included macroprudential authorities adjusts its behavior. This suggests that coordination between macroprudential authorities in countries with substantial trade may be beneficial. We reserve further investigation into this hypothesis for future study.

In a similar vein, M_1 and M_3 exhibit comparable banking sector modeling. Consequently, their optimized coefficients are of similar magnitude. In contrast, M_12 introduces moral hazard as an additional friction while also featuring monopolistic competition in the banking sector (like M_1 and M_3). The related optimized coefficients for M_12 are significantly smaller, hence suggesting that introducing moral hazard in the banking sector diminishes the reaction of capital buffers, prompting policymakers to assess the relevance of moral hazard when designing CCyB rules.

Finally, models M_1, M_3, and M_6, and M_10, which feature some form of household heterogeneity (patient / impatient households), are associated with a relatively subdued optimal response in the CCyB

[13] Simulations were conducted with Dynare (versions 4.5.6 and 5.3) and Matlab 2022b.

rule. Impatient households have a larger discount factor than patient households when optimizing their lifetime utility, leading patient households to transfer savings via financial flows to impatient households that, depending on the specific model, borrow against some form of collateral. It is crucial to note that whether the somewhat lower optimized coefficient in comparison to models with homogeneous households is significant depends on the quantitative importance of heterogeneity in the economy under the macroprudential authority's purview.

As mentioned in the introduction, the results on the optimal macroprudential policy response also depend on the origin of the shocks hitting the economy. For instance, we find that the strong CCyB response obtained in M_8 would be dampened if the government spending shock were the only driver of business cycle fluctuations in that model. Each of the models in our suite has been estimated or calibrated using a different set of shocks, so that our results can be used to give broad policy recommendations that are not shock contingent. From a practical standpoint, this is welcome given the fact that it is not possible to disentangle, in real time, the exact source of shocks driving business cycle fluctuations. From a theoretical standpoint, it is difficult to find and isolate a common set of shocks across the models. However, the monetary policy (interest rate) shock is consistently modeled across all models and has received special attention in the macroprudential policy literature. Hence, in section 4.5 we analyze the optimal CCyB response conditional on monetary policy being the only shock driving business cycle fluctuations.

We now investigate how sensitive loss functions are to changes in the model-specific ϕ_{ccyb} coefficients. We show the results for the loss function with $\kappa_1 = \kappa_2 = 1$ (qualitatively, the results for the other loss functions are the same).[14] In table 3 we report, for each model, a graph of the loss function (second column) as a function of the ϕ_{ccyb} coefficient, the optimized model-specific ϕ_{ccyb} coefficient (third column), and the percentage loss increase with respect to the optimized minimum loss (obtained at the optimized model-specific ϕ_{ccyb} coefficient) if we set the ϕ_{ccyb} coefficient to 0 (fourth column) or 10 (fifth column). This table shows how steep / flat the loss function is and how sensitive each model is to changes in the ϕ_{ccyb} coefficient.

[14] The variances of the credit gap, output, and changes in the policy instrument for each models are reported in figures 1 to 3 in the online appendix.

Some models (M_5 and M_11) are not too sensitive to the parameterization of the ϕ_{ccyb} coefficient and the loss functions are symmetric U-shaped. The loss functions of models M_7 and M_12 are upward sloping and become very steep at the right boundary. Indeed, the losses would be much higher (i.e. the economy would be extremely volatile) if one would set ϕ_{ccyb} to 10 in those models. The opposite result holds for models M_4 and M_8, as their loss functions become very steep at the left boundary. For the remaining models, the loss functions are U-shaped and asymmetric.

The fact that models are quite sensitive to the choice of ϕ_{ccyb} reinforces the need to look for CCyB rules that perform well across all the models, to which we turn in the next sub-section.

4.2 Model-robust CCyB rules

To identify model-robust CCyB rules, we follow Kuester and Wieland (2010) and apply model averaging. Formally, the model-robust rule is obtained by choosing the ϕ_{ccyb} parameter that solves the following optimization problem:

$$\min_{\phi_{ccyb}} \sum_{m=1}^{M} \omega_m \left[\left(\sigma^2_{B/Y}\right)_m + \kappa_1 \left(\sigma^2_Y\right)_m + \kappa_2 \left(\sigma^2_{\Delta cr}\right)_m \right]$$

$$s.t. \;\; cr_t = cr \left(\frac{B_t/Y_t}{B/Y} \right)^{\phi_{ccyb}}$$

$$E_t \left[f_m \left(x_t^m, x_{t+1}^m, x_{t-1}^m, z_t^m, \Theta^m \right) \right] = 0 \quad \forall m \in M$$

and there exists a unique and stable equilibrium $\forall m \in M$. We follow Kuester and Wieland (2010) and use equal weights ($\omega_m = 1/M$) on the considered models.

The solution to this problem depends crucially on the variance-covariance matrix of the shock processes. Hence, to avoid that model-robust policy rules are driven by a single model, we take Angelini et al. (2014) model as benchmark (which has been estimated by Gerali et al., 2010 on Euro area data) and recalibrate the variance-covariance matrix of the shocks in the other models such that the unconditional variance of the credit gap (when $\phi_{ccyb} = 0$) in the other models is the same as in Angelini et al. (2014).[15]

[15] This recalibration strategy is in line with the approach of Binder et al. (2018).

Results are reported in panel B of table 2. Regardless of the policymaker's preferences, the model-robust ϕ_{ccyb} coefficient ($\phi_{ccyb}^{model-robust}$) is rather low, thus implying a muted response by the macroprudential authority. That is, for a policymaker who is uncertain about which (is the right) model to use, this result suggests that the countercyclical capital buffer should be used with caution. This result relates to the literature on model uncertainty in monetary policy, in which a cautious response is the best response for a central bank facing model uncertainty (see e.g. Dück and Verona, 2023).

The last column in table 3 reports, for each model, the percentage loss increase with respect to the optimized minimum loss (obtained at the $\phi_{ccyb}^{model-specific}$ coefficient) if we set the ϕ_{ccyb} coefficient to the optimized model-robust value (0.1). It is evident that, except for M_8, the extreme losses are smoothed out when setting the CCyB coefficient to the optimized model-robust value.

We then look at the $\phi_{ccyb}^{model-robust}$ coefficient for different specifications of the macroprudential regulator preferences. Figure 1 plots the heat map with the values of the $\phi_{ccyb}^{model-robust}$ coefficient for different combinations of κ_1 and κ_2, with $\kappa_1, \kappa_2 \in [0,1]$. If the macroprudential authority is willing to tolerate a more volatile capital requirement ($\kappa_2 = 0$), then the robust rule would prescribe a much more aggressive reaction by the policymaker. Otherwise, the robust coefficient becomes much smaller whenever the macroprudential authority is concerned about the volatility of the policy instrument (i.e. as soon as it does not want to change it often and by large amounts). Finally, the larger the importance of output volatility, the larger the robust response by the macroprudential authority.

Finally, we note that we obtain similar results (on the optimized model-specific and model-robust coefficients) if we replace the credit gap (B_t/Y_t) in equations (1) and (2) with other measures of credit that often appear in the literature such as credit growth ($B_t - B_{t-1}$), credit in deviation from its steady state ($B_t - B$), and the European Systemic Risk Board credit gap ($B_t/(Y_t + Y_{t-1} + Y_{t-2} + Y_{t-3})$).

4.3 The choice of models matters

To compute the model-robust rules, in the baseline scenario we follow Kuester and Wieland (2010) and choose equal weights for each model. We now run two exercises to check how sensitive the model-robust results are to the choice of models' weights.

In the first exercise, we compute the model-robust coefficients using subsets of models. This is equivalent of giving zero weight to some models and equal weight to the remaining models in the subset. In particular, we start by removing one model at a time and recompute the $\phi_{ccyb}^{model-robust}$ coefficient for the remaining combinations of 11 models. We then remove two models at a time and recompute the $\phi_{ccyb}^{model-robust}$ coefficient for the remaining combinations of 10 models. We proceed in this way until we only use one model at a time. Overall, we evaluate 4095 possible combinations of models. Results for each of the five loss function specifications are plotted in figure 2. In each box, the red line displays the median across models, the boundaries of the box depict the 25 % and 75 % percentiles, and the whiskers outside of the box mark the 90 % confidence interval of the distribution. Black dots denote the results using all the 12 models. Regardless of the loss function specification, the model-robust responses become smaller when larger sets of models are used. In other words, more cautiousness is needed for a policymaker facing higher model uncertainty.

In the second experiment, we randomly draw a series of $N = 10000$ sets of $M = 12$ weights. These weights are normalized so that the sum of all M weights at every iteration i of the N random series equals unity. At each iteration i, we compute the $\phi_{ccyb}^{model-robust}$ coefficient. After N iterations, we collect the optimized CCyB parameters and visually inspect the probability density function for the distribution of these optimized parameters. Figure 3 shows the distribution of the optimized parameters for each of the five loss function specifications, and the red vertical line denotes the median value of the robust ϕ_{ccyb} parameter for that loss function. Regardless of the loss function specification, most of the probability mass is concentrated on values for the $\phi_{ccyb}^{model-robust}$ coefficient below 0.5, and only a small density is observed for values larger than 1. Using randomly drawn model weights thus confirms our central finding of a modest robust macroprudential policy reaction.

4.4 Insurance against model uncertainty

The model-robust rule is designed so that it performs well across all models. However, it is rarely the best rule for any model. In this section we provide a measure of its relative performance in a particular model m by computing the percentage increase of the loss function (ΔL_m) when using the optimized model-robust rule relative to the first-best outcome obtainable in that model (that is, the optimized model-specific rule for that model). Analytically, this value is given by

$$\Delta L_m^{model-robust} = 100 \frac{L_m\left(\phi_{ccyb}^{model-robust}\right) - L_m\left(\phi_{ccyb}^{model-specific}\right)}{L_m\left(\phi_{ccyb}^{model-specific}\right)} .$$

We also compute the aggregate $\Delta L^{model-robust}$, which is given by

$$\Delta L^{model-robust} = 100 \frac{\sum_{m=1}^{12} L_m\left(\phi_{ccyb}^{model-robust}\right) - \sum_{m=1}^{12} L_m\left(\phi_{ccyb}^{model-specific}\right)}{\sum_{m=1}^{12} L_m\left(\phi_{ccyb}^{model-specific}\right)} .$$

We follow Levin and Williams (2003) to interpret the economic significance of these metrics. They looked at historical variations in the value of ΔL and concluded that a rule generating ΔL up to 50 % might be viewed as yielding satisfactory performance, whereas a rule yielding ΔL greater than 100 % would suggest that insurance against model uncertainty is costly.

In panel A of table 4, we report the $\Delta L_m^{model-robust}$ for each loss function and for each individual model. The result that stands out is that the robust rule performs badly in models M_4 and M_8 – the two two-country models in our suite of models. This result is somehow expected, given that these models prescribe an aggressive macroprudential response and their loss functions are very steep in the proximity of the $\phi_{ccyb}^{model-robust}$ coefficient. However, in the other models, the performance of the robust rule is quite good, especially when more weight is attached to the volatilities of the policy instrument and output.

In panel B of table 4, we report the aggregate $\Delta L^{model-robust}$. Percentage losses vary between 6 % and 41 %, which are well below the Levin and Williams (2003) 50 % threshold. Overall, the insurance against model uncertainty only slightly comes at the expense of higher overall volatility, especially when policymakers are also concerned about macro stability.

4.5 The interaction between countercyclical capital requirements and monetary policy

Angelini et al. (2014), de Paoli and Paustian (2017), Gelain and Ilbas (2017), and Silvo (2019), among others, show that the optimal design of macroprudential policy depends on the conduct and interaction with monetary policy. To address this issue, we analyze the robust CCyB response following a monetary policy shock. This scenario assumes that monetary policy acts independently, and the macroprudential authority responds accordingly.[16]

For this simulation, we keep the Taylor rules and its calibrated coefficients as in the original papers. The monetary policy shock also follows the original specification: in models M_5, M_6, and M_8, the shock is modeled as an AR(1) process, while in the remaining models, the shock is independent and identically distributed (i.i.d.). We exclude model M_10, which is a model without nominal rigidities, and consider the foreign interest rate shock in model M_5 as the monetary policy shock.

The optimized model-specific and model-robust CCyB coefficients, conditional on a monetary policy shock, are reported in panels A and B in table 5, respectively. The main conclusions are qualitatively similar to the benchmark findings. If anything, the robust response by the macroprudential authority to a monetary policy shock is even more attenuated.[17]

5 Concluding remarks

For many years, researchers have developed theoretical models that policymakers later use in their decision-making (see e.g. Ciccarelli, Darracq Paries, Priftis, Angelini, Banbura, Bokan, Fagan, Gumiel,

[16] While theoretically interesting, we do not consider perfect coordination between these policies, as it is of little practical relevance given their real-life implementation.

[17] We obtain the same results if we change the shock process to an i.i.d. shock in models M_5, M_6, and M_8, as commonly done in the literature (see e.g. Christiano, Motto and Rostagno, 2014 and Furlanetto, Gelain and Taheri Sanjani, 2021).

Kornprobst, Lalik and Mo, 2024). While many structural models exist, none may be perfectly suited to address a specific policy question. To tackle this issue, the literature on monetary policy has suggested the use of robust monetary policy rules – rules that perform well across a wide range of structural models. By building on this approach, this paper contributes to the emerging macroprudential policy literature by employing the latest generation of DSGE models, in which banking capital plays a central role, to design robust CCyB rules. These robust rules provide valuable guidance for macroprudential policymakers facing uncertainty about which models to use, while also being unable to identify the sources of business cycle fluctuations in real time.

Our key conclusion is that policymakers must exercise prudence when applying countercyclical capital buffer rules, particularly in environments of uncertainty. A cautious approach ensures the policy's effectiveness while minimizing risks associated with model uncertainty. Importantly, the cost of insuring against uncertainty in model selection remains moderate, making this approach both practical and manageable for policymakers.

References

Agenor, Pierre-Richard and Timothy P. Jackson, "Monetary and macroprudential policy coordination with biased preferences," *Journal of Economic Dynamics and Control*, 2022, *144*, 104519.

Alpanda, Sami, Gino Cateau, and Cesaire Meh, "A policy model to analyze macroprudential regulations and monetary policy," *Canadian Journal of Economics*, 2018, *51* (3), 828–863.

Angelini, Paolo, Laurent Clerc, Vasco Curdia, Leonardo Gambacorta, Andrea Gerali, Alberto Locarno, Roberto Motto, Werner Roeger, Skander Van den Heuvel, and Jan Vlcek, "Basel III: Long-term Impact on Economic Performance and Fluctuations," *Manchester School*, 2015, *83* (2), 217–251.

—, Stefano Neri, and Fabio Panetta, "The Interaction between Capital Requirements and Monetary Policy," *Journal of Money, Credit and Banking*, 2014, *46* (6), 1073–1112.

Aoki, Kosuke, "On the optimal monetary policy response to noisy indicators," *Journal of Monetary Economics*, 2003, *50* (3), 501–523.

Bernanke, Ben S., Mark Gertler, and Simon Gilchrist, "The financial accelerator in a quantitative business cycle framework," in J. B. Taylor and M. Woodford, eds., *Handbook of Macroeconomics*, Vol. 1, Elsevier, 1999, chapter 21, pp. 1341–1393.

Binder, Michael, Philipp Lieberknecht, Jorge Quintana, and Volker Wieland, "Robust Macroprudential Policy Rules under Model Uncertainty," VfS Annual Conference 2018 (Freiburg, Breisgau): Digital Economy 181503, German Economic Association 2018.

Bosca, Jose E., Javier Ferri, and Margarita Rubio, "Fiscal and Macroprudential Policies in a Monetary Union," *Review of Quantitative Finance and Accounting*, 2024, *forthcoming.*

Canzoneri, Matthew, Behzad Diba, Luca Guerrieri, and Arsenii Mishin, "A Static Capital Buffer is Hard To Beat," Technical Report 2023.

Christiano, Lawrence J., Roberto Motto, and Massimo Rostagno, "Risk Shocks," *American Economic Review*, 2014, *104* (1), 27–65.

Ciccarelli, Matteo, Matthieu Darracq Paries, Romanos Priftis, Elena Angelini, Marta Banbura, Nikola Bokan, Gabriel Fagan, Jose Emilio Gumiel, Antoine Kornprobst, Magdalena Lalik, and Mo, "ECB macroeconometric models for forecasting and policy analysis," Occasional Paper Series 344, European Central Bank 2024.

Clarida, Richard, Jordi Gali, and Mark Gertler, "The Science of Monetary Policy: A New Keynesian Perspective," *Journal of Economic Literature*, 1999, *37* (4), 1661–1707.

Clerc, Laurent, Alexis Derviz, Caterina Mendicino, Stephane Moyen, Kalin Nikolov, Livio Stracca, Javier Suarez, and Alexandros P. Vardoulakis, "Capital Regulation in a Macroeconomic Model with Three Layers of Default," *International Journal of Central Banking*, 2015, *11* (3), 9–63.

Darracq Paries, Matthieu, Christoffer Kok Sorensen, and Diego Rodriguez-Palenzuela, "Macroeconomic Propagation under Different Regulatory Regimes: Evidence from an Estimated DSGE Model for the Euro Area," *International Journal of Central Banking*, 2011, *7* (4), 49–113.

Davydiuk, Tetiana, "Dynamic Bank Capital Requirements," mimeo, available at SSRN: https://ssrn.com/abstract=3110800 2019.

de Paoli, Bianca and Matthias Paustian, "Coordinating Monetary and Macroprudential Policies," *Journal of Money, Credit and Banking*, 2017, *49* (2-3), 319–349.

del Negro, Marco, Marc P. Giannoni, and Frank Schorfheide, "Inflation in the Great Recession and New Keynesian Models," *American Economic Journal: Macroeconomics*, 2015, *7* (1), 168–196.

Dück, Alexander and Fabio Verona, "Monetary policy rules: model uncertainty meets design limits," Bank of Finland Research Discussion Papers 12/2023, Bank of Finland 2023.

Elenev, Vadim, Tim Landvoigt, and Stijn Van Nieuwerburgh, "A Macroeconomic Model With Financially Constrained Producers and Intermediaries," *Econometrica*, 2021, *89* (3), 1361–1418.

Faria-e-Castro, Miguel, "A quantitative analysis of the countercyclical capital buffer," ESRB Working Paper Series 120, European Systemic Risk Board 2021.

Ferrero, Andrea, Richard Harrison, and Benjamin Nelson, "House Price Dynamics, Optimal LTV Limits and the Liquidity Trap," *Review of Economic Studies*, 2024, *91* (2), 940–971.

Furlanetto, Francesco, Paolo Gelain, and Marzie Taheri Sanjani, "Output Gap, Monetary Policy Trade-offs, and Financial Frictions," *Review of Economic Dynamics*, 2021, *41*, 52–70.

Gebauer, Stefan and Falk Mazelis, "Macroprudential regulation and leakage to the shadow banking sector," *European Economic Review*, 2023, *154*, 104404.

Gelain, Paolo and Pelin Ilbas, "Monetary and macroprudential policies in an estimated model with financial intermediation," *Journal of Economic Dynamics and Control*, 2017, *78* (C), 164–189.

Gerali, Andrea, Stefano Neri, Luca Sessa, and Federico M. Signoretti, "Credit and Banking in a DSGE Model of the Euro Area," *Journal of Money, Credit, and Banking*, 2010, *42* (6).

Gertler, Mark and Peter Karadi, "A model of unconventional monetary policy," *Journal of Monetary Economics*, 2011, *58* (1), 17–34.

Gulan, Adam, Esa Jokivuolle, and Fabio Verona, "Optimal bank capital requirements: What do the macroeconomic models say?," BoF Economics Review 2/2022, Bank of Finland 2022.

Hollander, Hylton, "Macroprudential policy with convertible debt," *Journal of Macroeconomics*, 2017, *54*, 285–305.

Iacoviello, Matteo, "House Prices, Borrowing Constraints, and Monetary Policy in the Business Cycle," *American Economic Review*, 2005, *95* (3), 739–764.

Kilponen, Juha, Seppo Orjasniemi, Antti Ripatti, and Fabio Verona, "The Aino 2.0 model," Research Discussion Papers 16/2016, Bank of Finland 2016.

Kuester, Keith and Volker Wieland, "Insurance Policies for Monetary Policy in the Euro Area," *Journal of the European Economic Association*, 2010, *8* (4), 872–912.

Levin, Andrew and John C. Williams, "Robust monetary policy with competing reference models," *Journal of Monetary Economics*, 2003, *50* (5), 945–975.

_ , Volker Wieland, and John C. Williams, "The Performance of Forecast-Based Monetary Policy Rules Under Model Uncertainty," *American Economic Review*, 2003, *93* (3), 622–645.

Liu, Guangling and Thabang Molise, "Housing and credit market shocks: Exploring the role of rule-based Basel III counter-cyclical capital requirements," *Economic Modelling*, 2019, *82* (C), 264–279.

Lozej, Matija, Luca Onorante, and Ansgar Rannenberg, "Countercyclical capital regulation in a small open economy DSGE model," *Macroeconomic Dynamics*, 2022, pp. 1–38.

Malherbe, Frederic, "Optimal Capital Requirements over the Business and Financial Cycles," *American Economic Journal: Macroeconomics*, 2020, *12* (3), 139–174.

Malmierca, Maria, "Optimal macroprudential and fiscal policy in a monetary union," *Economic Modelling*, 2023, *122*, 106238.

Meh, Cesaire A. and Kevin Moran, "The role of bank capital in the propagation of shocks," *Journal of Economic Dynamics and Control*, 2010, *34* (3), 555–576.

Orphanides, Athanasios, "Monetary policy evaluation with noisy information," *Journal of Monetary Economics*, 2003, *50* (3), 605–631.

Poutineau, Jean-Christophe and Gauthier Vermandel, "Global banking and the conduct of macroprudential policy in a monetary union," *Journal of Macroeconomics*, 2017, *54*, 306–331.

Ratto, Marco, Werner Roeger, and Jan in't Veld, "QUEST III: An estimated open-economy DSGE model of the euro area with fiscal and monetary policy," *Economic Modelling*, 2009, *26* (1), 222–233.

Rubio, Margarita and D. Filiz Unsal, "Macroprudential policy under incomplete information," *European Journal of Finance*, 2020, *26* (7-8), 616–639.

_ and Jose A. Carrasco-Gallego, "The new financial regulation in Basel III and monetary policy: A macroprudential approach," *Journal of Financial Stability*, 2016, *26* (C), 294–305.

_ and _ , "Bank Capital Requirements and Collateralised Lending Markets," *Manchester School*, 2017, *85*, 79–103.

Silvo, Aino, "The Interaction of Monetary and Macroprudential Policies," *Journal of Money, Credit and Banking*, 2019, *51* (4), 859–894.

_ and Fabio Verona, "The Aino 3.0 model," Research Discussion Papers, Bank of Finland 2020.

Smets, Frank and Raf Wouters, "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," *Journal of the European Economic Association*, 2003, *1* (5), 1123–1175.

Tayler, William J. and Roy Zilberman, "Macroprudential regulation, credit spreads and the role of monetary policy," *Journal of Financial Stability*, 2016, *26* (C), 144–158.

Taylor, John B. and Volker Wieland, "Surprising Comparative Properties of Monetary Models: Results from a New Model Database," *Review of Economics and Statistics*, 2012, *94* (3), 800–816.

Woodford, Michael, *Interest and Prices, 2ed*, Princeton University Press, 2003.

Paper	Acronym	Overview of the model		Banking sector friction	Heterogeneity
		Closed / SOE	C / E, country		
Angelini et al. (2014)	M_1	closed	E, Euro area	Monopolistic competition	P / I households
Meh and Moran (2010)	M_2	closed	C, United States	Double moral hazard	//
Darracq Paries et al. (2011)	M_3	closed	E, Euro area	Monopolistic competition	P / I households
Malmierca (2023)	M_4	two-country	C	Costly state verification	//
Lozej et al. (2022)	M_5	SOE	E, Ireland	Costly state verification	//
Alpanda et al. (2018)	M_6	SOE	C, Canada	Monitoring costs	P / I households
Agenor and Jackson (2022)	M_7	closed	C	Monopolistic competition	//
Poutineau and Vermandel (2017)	M_8	two-country	E, Euro area	Monopolistic competition	//
Tayler and Zilberman (2016)	M_9	closed	C	Borrowing cost channel	//
Clerc et al. (2015)	M_10	closed	C, Euro area	Costly state verification	P / I households
Gertler and Karadi (2011)	M_11	closed	C	Moral hazard	//
Gebauer and Mazelis (2023)	M_12	closed	E, Euro area	Monopolistic competition and moral hazard	//

Table 1: Key features of employed models

Notes. SOE: Small Open Economy model. C / E: Calibrated / Estimated model. P / I: Patient / Impatient households.

Model	Loss Function $\kappa_1 = 0$ $\kappa_2 = 0.1$	$\kappa_1 = 0.1$ $\kappa_2 = 0.1$	$\kappa_1 = 0.1$ $\kappa_2 = 0.5$	$\kappa_1 = 0.5$ $\kappa_2 = 0.5$	$\kappa_1 = 1$ $\kappa_2 = 1$
Panel A: Optimized model-specific coefficients					
M_1	6.9	6.9	3.1	3.1	2.1
M_2	1.2	1.6	0.6	1	1
M_3	9.3	9.3	4	4	2.5
M_4	10	10	10	7	3.7
M_5	10	10	7.2	7.3	5
M_6	0.9	1	0.2	0.4	0.3
M_7	0	0	0	0	0
M_8	10	10	10	10	10
M_9	0.8	1	0.2	0.4	0.3
M_10	1.3	1.2	0.9	0.8	0.6
M_11	10	10	6.1	6.1	4.2
M_12	0.6	0.6	0.1	0.1	0.1
Panel B: Optimized model-robust coefficients					
	0.3	0.4	0.1	0.2	0.1

Table 2: Optimized model-specific and model-robust ϕ_{ccyb} coefficients

Notes. Panel A (B) reports the optimized model-specific (model-robust) ϕ_{ccyb} coefficients for different loss functions of the macroprudential authority.

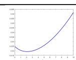
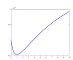
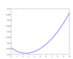
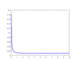
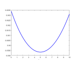
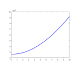
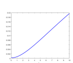
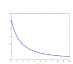
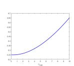
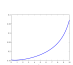
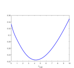
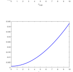
Model	Loss function $(\kappa_1 = \kappa_2 = 1)$	$\phi_{ccyb}^{model-specific}$	%-loss when $\phi_{ccyb} = 0$	$\phi_{ccyb} = 10$	$\phi_{ccyb}^{model-robust} = 0.1$
M_1		2.1	29	222	26
M_2		1	85	263	57
M_3		2.5	15	113	14
M_4		3.7	1754	3	368
M_5		5	7	6	7
M_6		0.3	0.3	247	0.1
M_7		0	0	7833	2
M_8		10	1318	0	1230
M_9		0.3	0.2	161	0.1
M_10		0.6	0.8	145	0.5
M_11		4.2	49	56	45
M_12		0.1	0.2	3572	0

Table 3: Loss functions and percentage losses for different values of the ϕ_{ccyb} coefficient

Notes. For each individual model, the second column plots the loss function (for $\kappa_1 = \kappa_2 = 1$) for $0 \leq \phi_{ccyb} \leq 10$, the third column reports the optimized model-specific ϕ_{ccyb} coefficients, and the fourth, fifth, and sixth columns report the percentage loss with respect to the optimized minimum loss (obtained at the optimized model-specific ϕ_{ccyb} coefficients) when setting the ϕ_{ccyb} coefficient to 0, to 10, or to the optimized model-robust value (0.1), respectively.

Model	Loss Function				
	$\kappa_1 = 0$ $\kappa_2 = 0.1$	$\kappa_1 = 0.1$ $\kappa_2 = 0.1$	$\kappa_1 = 0.1$ $\kappa_2 = 0.5$	$\kappa_1 = 0.5$ $\kappa_2 = 0.5$	$\kappa_1 = 1$ $\kappa_2 = 1$
Panel A: Cost of insurance (in %) in each model					
M_1	87	82	42	37	26
M_2	74	58	49	47	57
M_3	68	65	26	24	14
M_4	9457	964	3091	389	368
M_5	21	20	12	10	7
M_6	4	1	0	0	0
M_7	27	19	7	8	2
M_8	1225	1140	1359	1227	1230
M_9	1	1	0	0	0
M_10	2	1	2	0	0
M_11	186	180	76	71	45
M_12	1	1	0	0	0
Panel B: Aggregate cost of insurance (in %)					
	41	23	18	8	6

Table 4: Cost of insurance against model uncertainty

Notes. Panel A reports the percentage losses, for each loss function and for each model, when setting the ϕ_{ccyb} coefficient to the optimized model-robust values instead of using the optimized model-specific values for each model. Panel B reports the percentage losses, for each aggregate loss function, when setting the ϕ_{ccyb} coefficient to the optimized model-robust values instead of using the optimized model-specific values for each model. Values are rounded to the nearest integer.

Model	Loss Function $\kappa_1 = 0$, $\kappa_2 = 0.1$	$\kappa_1 = 0.1$, $\kappa_2 = 0.1$	$\kappa_1 = 0.1$, $\kappa_2 = 0.5$	$\kappa_1 = 0.5$, $\kappa_2 = 0.5$	$\kappa_1 = 1$, $\kappa_2 = 1$
Panel A: Optimized model-specific coefficients					
M_1	5.1	5.1	1.4	1.5	0.8
M_2	0.4	0.5	0.1	0.3	0.2
M_3	0	0	0	0	0
M_4	10	10	10	8.9	4.7
M_5	10	10	10	10	10
M_6	2.4	3.5	1.1	2.4	2.2
M_7	0	0	0	0	0
M_8	10	10	10	10	10
M_9	0.9	1.3	0.3	0.6	0.5
M_11	10	10	5.6	5.6	0
M_12	0.4	0.4	0.1	0.1	0
Panel B: Optimized model-robust coefficients					
	0.2	0.2	0.1	0.1	0.1

Table 5: Optimized model-specific and model-robust ϕ_{ccyb} coefficients following a monetary policy shock

Notes. Panel A (B) reports the optimized model-specific (model-robust) ϕ_{ccyb} coefficients for different loss functions of the macroprudential authority following a monetary policy shock. M_10 is not included as monetary policy is not modeled in the model.

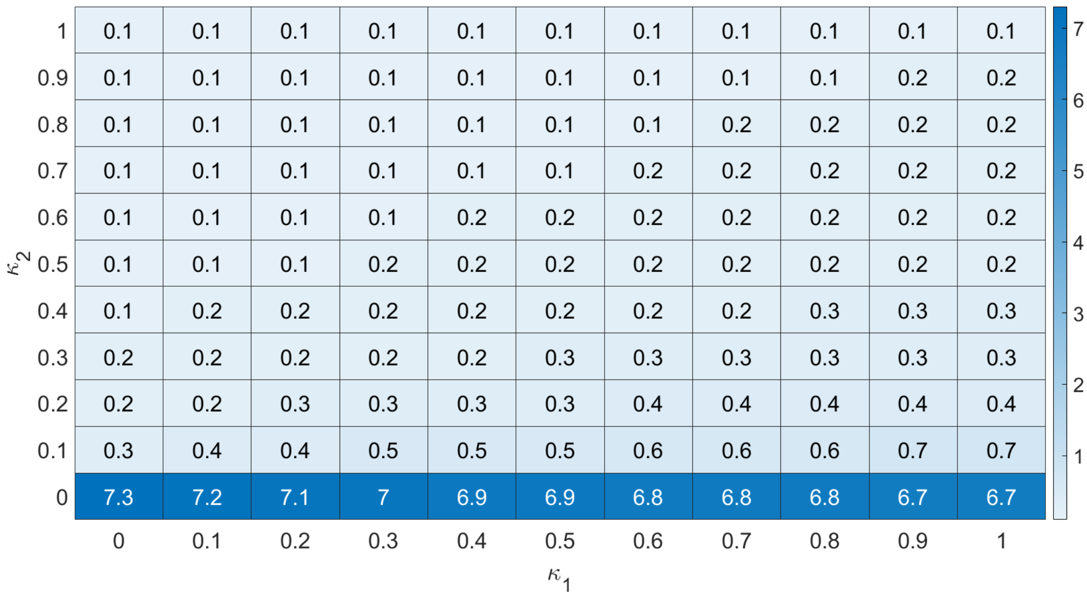


Figure 1: Optimized model-robust ϕ_{ccyb} coefficients for different combinations of κ_1 and κ_2, with $\kappa_1, \kappa_2 \in [0, 1]$, in the macroprudential authority loss function

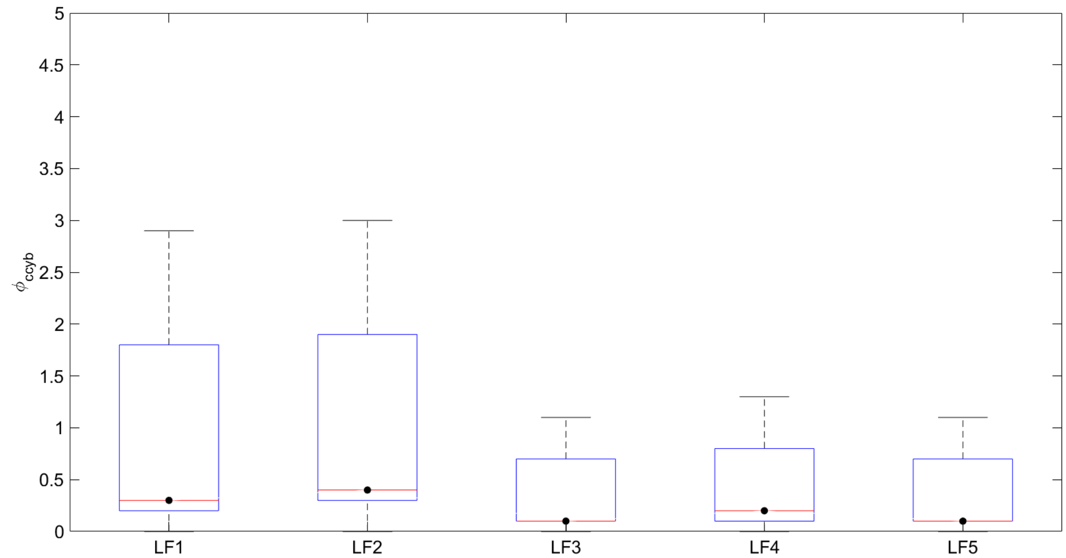


Figure 2: Optimized model-robust ϕ_{ccyb} for different combinations of models

Notes. In each box, the red line displays the median across models, the boundaries of the box depict the 25 % and 75 % percentiles, and the whiskers outside of the box mark the 90 % confidence interval of the distribution. Black dots denote the results using 12 models. LF1 to LF5 refer to the loss function with $\kappa_1 = 0$ and $\kappa_2 = 0.1$, $\kappa_1 = \kappa_2 = 0.1$, $\kappa_1 = 0.1$ and $\kappa_2 = 0.5$, $\kappa_1 = \kappa_2 = 0.5$, and $\kappa_1 = \kappa_2 = 1$, respectively.

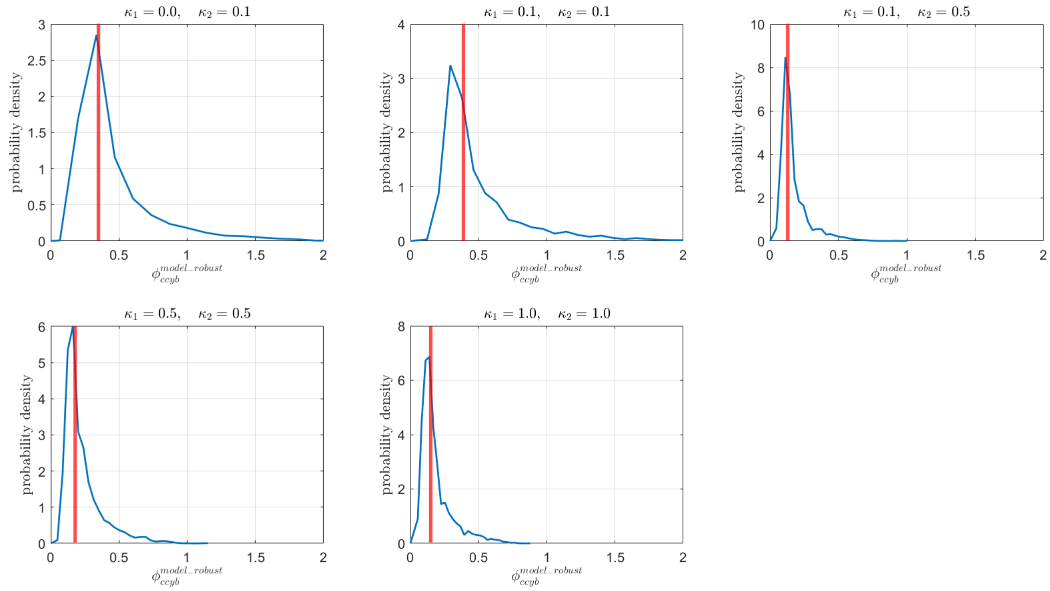


Figure 3: Distributions of optimized model-robust ϕ_{ccyb} for 10000 randomly selected combinations of models' weights

Notes. This figure shows the distribution of the optimized $\phi_{ccyb}^{model-robust}$ coefficient for each of the five loss function specifications. The red vertical line in each plot denotes the median for that specification of the loss function.

Online appendix of

"Robust design of countercyclical capital buffer rules"

Dominik Hecker* Hun Jang†

Margarita Rubio‡ Fabio Verona§

Contents

* Deutsche Bundesbank and University of Kiel (hecker@economics.uni-kiel.de)
† Economic Research Institute, Bank of Korea (janghun@bok.or.kr)
‡ University of Nottingham (margarita.rubio@nottingham.ac.uk)
§ Bank of Finland – Monetary Policy and Research Department, and University of Porto – *Cef.up* (fabio.verona@bof.fi)

1 Description of the models

Angelini, Neri and Panetta (2014) (M_1)

The model is built upon Gerali, Neri, Sessa and Signoretti (2010). There are two borrowers, the impatient household and entrepreneurs. Both are subject to borrowing constraints, depending on the expected value of collaterals (housing stocks and capital goods, respectively.) In the model, the banking sector is not perfectly competitive. The authors introduce a cost for banks to adjust retail rates. Due to these adjustment cost, the pass-through of monetary policy comes with a lag. Banks have some market power, which allows them set different lending rates for households and firms. Banks face the following constrained maximization problem:

$$\max_{\{B_t,D_t\}} R_t^b B_t - R_t^d D_t - \frac{\kappa_{K^b}}{2}\left(\frac{K_t^b}{B_t} - v_t^{CA}\right)^2 K_t^b \tag{1}$$

$$s.t.\ B_t = D_t + K_t^b \ , \tag{2}$$

where R^bdenotes the gross interest rate on loans with B as the risk-weighted sum of real loans to households and entrepreneurs. R^d denotes the gross rate on deposits with D as the level of real deposits. K^brepresents the level of bank capital. As shown above, banks have to raise capital when their capital-to-assets ratio deviates from the target level v^{CA} facing convex increasing cost governed by the parameter κ_{K^b}. Departing from Gerali et al. (2010), the authors allowed v^{CA} to be time dependent to introduce time-varying capital requirement rule. Turning to loans, B_t is defined as follows:

$$B_t = w_t^E B_t^E + w_t^H B_t^H \ , \tag{3}$$

where w_t^E denotes the risk-weight associated with loans to entrepreneurs, and w_t^Hdenotes the risk-weight associated with loans granted to households. It is assume that risk weights w_t^E and w_t^H move countercyclically, increasing when the current output grows compared to four periods earlier.

Banks solving the maximization problem face the following interest rate-setting rule:

$$R_t^b = R_t^d - \kappa_{K^b}\left(\frac{K_t^b}{B_t} - v_t^{CA}\right)\left(\frac{K_t^b}{B_t}\right)^2 . \tag{4}$$

v_t^{CA} is determined by the macroprudential authority, governed by a rule considering deviation of credit-to-output ratio from its steady-state level. In particular, the rule is as follows:

$$v_t^{CA} = (1-\rho_v)\bar{v} + (1-\rho_v)\left[\chi_v\left(\frac{B_t}{Y_t} - \frac{B}{Y}\right)\right] + \rho_v v_{t-1} . \tag{5}$$

The parameter χ_v shows the aggressiveness of macroprudential policy to manage the financial cycle. When the credit-to-output ratio increases, the required bank capital is raised with a higher v_t^{CA}. Then, an increase in v_t^{CA} leads banks to increase both lending rates through 4, resulting in low loan demand and negatively influencing consumption and investment. The policy's effect is amplified by the convex increasing cost that banks face when adjusting their capital stock.

Meh and Moran (2010) (M_2)

The model features for a double moral hazard problem between entrepreneurs and banks, and banks and households, respectively. The first moral hazard arises from the limited ability to monitor the entrepreneur's investment decisions. There are three project, differing in probabilities of success and amount of private benefits which are secured by entrepreneurs. While the project (denoted as 'G') with the highest success probability (α^G) generates zero private benefits, the project (denoted as 'B') with the lower probability ($\alpha^B < \alpha^G$) guarantees the greatest private benefits (B). The remained project lies in between these two project, having the same success probability with the 'B' but a smaller private benefit than B (say, b where $b < B$). Banks can imperfectly monitor entrepreneur's decision, forcing them not to choose the project 'B' in any circumstances. The monitoring cost is μi_t, where i_t is the size of project. The second moral hazard problem stems from inability of depositors, resulting in requiring banks to secure funding through banks' net worth (a_t) to invest in entrepreneurs' project. Thus, the entrepreneur holds n_t as its net worth need to procure $i_t - n_t$ amount of external funding from banks. Banks offer the fund by aggregating their net worth (a_t) and deposits (d_t) from households. All in all, entrepreneurs maximize their expected return, considering each agent's incentive and participation constraints, as well as feasibility conditions:

$$\max_{\{i_t, a_t, d_t, R_t^e, R_t^b, R_t^h\}} q_t \alpha^g R_t^e i_t$$

$$\text{s.t.} q_t \alpha^g R_t^e i_t \geq q_t \alpha^b R_t^e i_t + q_t b i_t, \tag{6}$$

$$q_t \alpha^g R_t^b i_t - \mu i_t \geq q_t \alpha^b R_t^b i_t, \tag{7}$$

$$q_t \alpha^g R_t^b i_t \geq (1 + r_t^a) a_t, \tag{8}$$

$$q_t \alpha^g R_t^h i_t \geq (1 + r_t^d) d_t, \tag{9}$$

$$a_t + d_t - \mu i_t \geq i_t - n_t, \tag{10}$$

$$R_t^e + R_t^b + R_t^h = R \tag{11}$$

where q_t is the price of capital goods, R_t^e, R_t^b and R_t^h are returns from investment project for entrepreneurs, banks and households, respectively, r_t^a and r_t^d are market returns if a_t and d_t are invested to outside options. Inequality 6 means that choosing 'G' should be sufficiently incentive compatible to entrepreneurs. Inequality 7 shows that exerting banks' efforts to induce entrepreneurs to take 'G' has to be profitable enough. Inequalities 8 and 9 are the participation constraints of banks and households, respectively. Finally, inequality 10 represents the condition that amount of funds to entrepreneurs should not exceed resources available for banks. By introducing all conditions hold equality and taking steps, the investment project level in equilibrium is given as follows:

$$i_t = \frac{a_t + n_t}{1 + \mu - \frac{q_t \alpha^g}{1 + r_t^d} \left(R - \frac{b}{\Delta \alpha} - \frac{\mu}{\Delta \alpha q_t} \right)} \ . \tag{12}$$

This equation shows that the size of investment project is positively related to banks' net worth. Therefore, imposing a cap on the level of net worth, which can be used as a source of project in order to make banks to sustain a certain level of bank capital would be introduced as a cyclical macroprudential tool, as outlined by Binder, Lieberknecht, Quintana and Wieland (2018). In this case, a higher regulatory requirement on bank capital reduce the funds available which can be used for external source of investment project, leading to decreases in both credit and investment levels.

Darracq Paries, Kok Sorensen and Rodriguez-Palenzuela (2011) (M_3)

The banking sector is modelled in a similar way to Gerali et al. (2010) and Angelini et al. (2014). In line with Angelini et al. (2014), there are two borrowers, impatient household and entrepreneurs. However, in contrast to Angelini et al. (2014), the borrowers can default unless the expected value of their collateral, which is subject to idiosyncratic shock, is sufficiently greater than the cost of full repayment. In case of default, commercial banks will seize the collateral valued in real terms apart from the cost associated asymmetric information, such as monitoring cost. Thus, to ensure bank operations, the banks' expected profit should be non-negative after taking into account the risk of default, and such participation constraints are considered for both impatient household's and entrepreneurs' maximization problem. Besides, the cost imposed when bank capital-to-asset ratio deviate from the target level is different from that of Angelini et al. (2014) as it takes the following form:

$$-\frac{\kappa_{K^b}}{2}\left(\frac{K_t^b}{0.5B_t^{HH}+B_t^E}-v_t^{CA}\right)^2 K_t^b \ . \tag{13}$$

In equation (13), the risk-weight is time-invariant as opposed to Angelini et al. (2014). In addition, the time-varying capital requirement rule is also different and takes the following a log-linear form:[1]

$$v_t^{CA}=\rho^{bc}v_{t-1}^{CA}+r_y^{bc}y_t+r_{\Delta y}^{bc}\Delta y_t+r_{\Delta h}^{bc}\Delta B_t^{HH}+r_{\Delta e}^{bc}\Delta B_t^{E}+r_{\Delta T_D}^{bc}\Delta t_{D,t}+r_{\Delta Q}^{bc}\Delta q_t \ , \tag{14}$$

where $\Delta t_{D,t}$ and Δq_t refer to changes in house and asset (capital owned by entrepreneurs) prices, respectively. Different from equation (5), this rule factors in collateral price changes and does not account for credit-to-output ratios.

[1] Such a time-varying capital rule was adopted later in their discussion. The baseline rule was a constant capital requirement of 0.11 under the Basel I framework.

Malmierca (2023) (M_4)

The borrowers are entrepreneurs who purchase capital goods (k_t) and rent it to production sector, using their net worth and loans from financial intermediaries. The financial contract between the borrower and financial intermediaries is subject to a costly-state verification (CSV) problem, outlined by Bernanke, Gertler and Gilchrist (1999). It is assumed that return (R^k_{t+1}) from investment (purchasing capital goods) is dependent on idiosyncratic shock ($\omega_{t+1} \sim \log normal\left(-\frac{\sigma^2_{\omega,t}}{2}, \sigma^2_{\omega,t}\right)$), which is private information to borrowers but financial intermediaries have to pay costs, a fraction (μ) of borrowers' payoff to observe the borrower's gross payoff ($\omega_{t+1}R^k_{t+1}P_{H,t}q_tk_t$, where $P_{H,t}q_t$ is the relative price of capital measured in domestic price level). Borrowers should pay gross interest on their borrowing (b_t) at a rate of R^l_{t+1} unless they default. In other words, borrowers default if their total debt repayment, $R^l_{t+1}b_t$ is greater than payoff expected from investment ($\omega_{t+1}R^k_{t+1}P_{H,t}q_tk_t$). If this happens, financial intermediaries receive $(1-\mu)\omega_{t+1}R^k_{t+1}P_{H,t}q_tk_t$. It implies that there exists a threshold value of idiosyncratic shock ($R^l_{t+1}b_t = \varpi_{t+1}R^k_{t+1}P_{H,t}q_tk_t$), below which the borrower default and ensures zero profit from investment. Under the assumption that financial intermediaries operate in a perfectly competitive market, their zero-profit condition is given as follows:

$$[1-F(\varpi_{t+1}, \sigma_{\omega,t})]R^l_{t+1}b_t + (1-\mu)\int_0^{\varpi_{t+1}} \omega dF(\omega, \sigma_{\omega,t})R^k_{t+1}p_{H,t}q_tk_t = R_t(a_t + B_t) \ , \qquad (15)$$

where $F(\cdot)$ is the cumulative distribution function, R_t is an interest rate applied on financial intermediaries liabilities, a_t and B_t refer to domestic and foreign deposits, respectively. The left-hand side of equation (15) is the sum of expected revenues of when borrowers make a full repayment of debt and when they default, while the right-hand side shows the cost of financial intermediary businesses.

The countercyclical macroprudential policy affects the right-hand side of equation (15). It is assumed that $a_t + B_t = \eta_t b_t$ in equilibrium, where η_t stands for a financial regulation, meaning that financial intermediaries can lend a share of their total liabilities. The author suggested two different countercyclical prudential regulation, as a function nominal credit growth of the economy only or counting foreign nominal credit growth as well:

- Domestic macroprudential policy, $\eta_t = \left(\frac{b_t}{b_{t-1}} \frac{\Pi_t}{\Pi} \right)^{\gamma_\eta}$;

- Supranational macroprudential policy, $\eta_t = n \left(\frac{b_t}{b_{t-1}} \frac{\Pi_t}{\Pi} \right)^{\gamma_\eta} + (1-n) \left(\frac{b_t^*}{b_{t-1}^*} \frac{\Pi_t^*}{\Pi^*} \right)^{\gamma_\eta^*}$

$\gamma_n > 0$, b_t is borrower's debt level and variables denoted with '$*$' refer to those of foreign country. Since $\gamma_n > 0$, if credit growth is positive, η_t increases, leading to declines in b_t given deposit level. Thus, the macroprudential policy is countercyclical. Finally, by plugging $R_{t+1}^l b_t = \varpi_{t+1} R_{t+1}^k P_{H,t} q_t k_t$ into equation (15) and rearranging it, the lending-deposit spread equation is given by:

$$\frac{R_{t+1}^l}{R_t} = \frac{\eta_t}{\left[1 - F\left(\varpi_{t+1}, \sigma_{\omega,t}\right)\right] + \frac{(1-\mu)}{\varpi_{t+1}} \int_0^{\varpi_{t+1}} \omega dF\left(\omega, \sigma_{\omega,t}\right)} \ . \tag{16}$$

The equation above shows how the macroprudential policy propagates. A higher level of regulation widens the lending-deposit spread, thereby deterring borrower's demand for loans.

Lozej, Onorante and Rannenberg (2022) (M_5)

Banks lend to households (L_t) by using domestic (D_t) and foreign deposits (B_t), and bank equity (E_t) received from the exit banks and transferred from households. Bank's balance sheet condition is as follows:

$$L_t = D_t + B_t + E_t \ . \tag{17}$$

Let $\tilde{R}$ and R denote the return from lending to households and interest rate on deposits, respectively. Besides, it is assumed that loans to households are subject to an idiosyncratic shocks ($\omega_{b,t+1} \sim \log normal\left(-\frac{\sigma_b^2}{2}, \sigma_b^2\right)$) so that the revenue from lending at time $t+1$ is equal to $\tilde{R_{t+1}} \omega_{b,t+1} L_t$. On the cost side of banking operations, banks should make a repayment on total deposit, $R_t(B_t + D_t)$ and also assumed that they must pay fines, as a fraction of L_t (i.e., $\chi_b L_t$) if $\omega_{b,t+1} \tilde{R_{t+1}} L_t - R_t(B_t + D_t) < \omega_{b,t+1} g_t \tilde{R_{t+1}} L_t$ where g_t stands for the minimum capital requirement. In other words, the inequality means that banks should maintain their capital ratio ($\frac{E_{b,t}}{L_t}$) above the g_t in order to avoid to pay fines. The bank thus solves the following maximization problem, using equation (17) and probability that bank are undercapitalized ($\Phi\left(\frac{R_t(L_t-E_t)}{(1-g_t)\tilde{R_{t+1}}L_t}\right)$ since $\frac{R_t(L_t-E_t)}{(1-g_t)\tilde{R_{t+1}}L_t}$ is the threshold point of idiosyncratic shocks that cause undercapitalization:

$$\max_{L_t}\mathbb{E}_t\left\{\beta\frac{\Lambda_{t+1}}{\Lambda_t}\left[\tilde{R_{t+1}}L_t-R_t(L_t-E_t)-\chi_b L_t\Phi\left(\frac{R_t(L_t-E_t)}{(1-g_t)\tilde{R_{t+1}}L_t}\right)\right]\right\}\ , \tag{18}$$

where $\beta\frac{\Lambda_{t+1}}{\Lambda_t}$ is the stochastic discount factor. Solving the maximization problem yields the following equation:

$$\mathbb{E}_t\left\{\beta\frac{\Lambda_{t+1}}{\Lambda_t}\left[\widetilde{R}_{t+1}-R_t\right]\right\}=\mathbb{E}_t\left\{\beta\frac{\Lambda_{t+1}}{\Lambda_t}\chi_b\left(\Phi(\omega_{b,\bar{t}+1})+\phi(\omega_{b,\bar{t}+1})\frac{R_t\frac{E_t}{L_t}}{(1-g_t)\widetilde{R}_{t+1}}\right)\right\}\ . \tag{19}$$

This equation implies that increasing bank lending by a unit must compensate all default costs associated undercapitalization and cost of funding. A higher g_t in fact increases the expected penalty related to leverage and so raise lending rate, resulting in a lower level of lend to households.

The CCyB rules considered are as follows: (1) $g_t=0.08+\psi_L gap_t+\psi_{PH} price\,gap_t$, where $gap_t=\left(\frac{L_t}{Y_t+Y_{t-1}+Y_{t-2}+Y_{t-3}}-\frac{\bar{L}}{4\bar{Y}}\right)$, $price\,gap_t=\frac{P_{H,t}/P_t-\bar{P_H}/P}{\bar{P_H}/P}$ and P_H/P is the relative price of housing goods, and (2) $g_t=0.08+x$ where $x=0$ if $gap_t\leq 0.1$; $x=0.3125gap_t-0.625$ if $0.02<gap_t\leq 0.1$; $x=0.025$ otherwise. The rule (1) takes into account housing price gap since a higher housing price level would lower the probability of household default[2], thus increasing bank lending. The rule (2) refers to the ESRB rule.

Alpanda, Cateau and Meh (2018) (M_6)

The model introduces monitoring costs for all types of financial instruments, which are paid by each supplier of funds as a form of financial friction. As the authors describe, it can be interpreted as costs of purchasing default insurance under the assumption that a certain fraction of the financial contracts are unhealthy (e.g. non-performing loans). In particular, saver households incur costs, $1+\Upsilon_{d,t}$ per unit of

[2] Housing wealth is also subject to idiosyncratic shocks, making possibilities that households may default if their housing values is insufficient to make full repayment of bank lending. In case of default, households are required to pay a fraction of total debt with costs associated with default. However, the authors assume that the total cost after default is equal to the full debt repayment.

deposit:[3]

$$1+\Upsilon_{d,t} = \chi_{d1}\left(\frac{\omega_I P_{I,t} b_{I,t} + \omega_E P_{E,t} b_{E,t}}{A_t}\right)^{\chi_{d2}} \gamma_t^{\chi_{d3}} \tilde{\varepsilon}_{d,t} \ , \tag{20}$$

where $\omega_I P_{I,t} b_{I,t} + \omega_E P_{E,t} b_{E,t}$ is bank's risk-weighted assets of their debt positions to borrower households and entrepreneurs, P stands for the price of each debt, A_t is bank capital, γ_t is the capital requirement imposed by the macroprudential authority, $\tilde{\varepsilon}_{d,t}$ is an AR (1) shock and χ_ds are parameters. Equation (20) shows that the monitoring cost increases if the bank is less capitalized or the capital requirement ratio is tightened. The parameters χ_{d2} and χ_{d3} determine the elasticity of the monitoring cost to bank's leverage ratio and capital requirements. When monitoring costs increase, households pass these costs on to the deposit rate, causing the deposit rate to rise. This leads to higher debt rates as bank's funding cost increases, resulting in negative pressure on credit levels. The regulatory authority determines the level of γ_t in a countercyclical way bay taking into account household credit growth rate. The policy rule is as follows:

$$\gamma_t = \gamma + \alpha_\gamma \log \frac{b_{I,t}}{b_{I,t-1}} \ . \tag{21}$$

Agenor and Jackson (2022) (M_7)

The model allows for possibility of excess bank capital, which is endogeneously determined. Banks in the model conduct financial intermediary business by receiving deposits from households, issuing bank capital, and borrowing from central bank. It is assumed that holding bank capital also provides returns to households. Banks provide loans to capital good produces who use such funding sources to make investment decisions. The financial contract between banks and capital good producers requires collateral as a form of housing stocks, a fraction of which is seized by banks in the event of default. The probability of full payment (default), denoted as q_t^i $(1-q_t^i)$, is assumed be a control variable for banks, and is exactly the same as bank's monitoring efforts. Besides, as briefly introduced, bank i's total capital (V_t^i) is categorized into two parts, required capital ($V_t^{R,i}$) and excess capital ($V_t^{E,i}$). While, the supply of excess capital is determined by the bank's profit maximization decision, by comparing its

[3] Bank also should pay monitoring costs for debt to borrowing households and entrepreneurs. The costs are increasing function of each borrower's leverage position.

costs (returns guaranteed to be paid to household plus costs associated with its issuance) and benefits (expected pecuniary benefits by sending a signal to the market, indicating that the bank is healthy), the required capital is determined by the financial regulator under the following rule:

$$V_t^{R,i} = \left(\rho^D + \rho_t^C\right)\left(\frac{q_t^i}{\widetilde{q}}\right)^{-\phi_q} l_t^{K,i} \ , \tag{22}$$

where ρ^D is the time-invariant capital requirement ratio, ρ_t^C is the countercyclical capital requirement ratio, governed by $\frac{1+\rho_t^C}{1+\tilde{\rho}^C} = \left(\frac{l_t^K}{l_{t-1}^K}\right)^{\chi_2}$, q_t is the probability of full repayment of investment loans, $l_t^{K,i}$ is the loan to capital good producers, and ϕ_q and χ_2 are parameters presenting the elasticity of required capital with respect to the repayment probability and credit growth, respectively. The variables with $tilde$ refer to its steady-state value. Note that the repayment probability is derived from bank's profit maximization problem as well. Although a higher level of q_t^i increases banks' expected return by enhancing repayment probability, it also entails costs associated with exerting monitoring efforts which is an increasing function of the loan-to-collateral ratio and a decreasing function of output level. The final functional form of q_t derived from banks' decision is as follows:

$$q_t = \varphi_0 \left(\frac{\kappa \mathbb{E}_t p_{t+1}^H H_t / \tilde{p}^H \tilde{H}}{l_t^{K,i} / \tilde{l}^K}\right)^{\varphi_1} \left(\frac{Y_t}{\tilde{Y}}\right)^{\varphi_2} \ , \tag{23}$$

where P_t stands for price of collateral (housing stock), Y_t is the economy's output level and φs are parameters. Equations (22) and (23) show that required capital level tightens as credit growth is steeper, loan-to-collateral ratio deviates upward from its steady state and the economy experiences recession. As required capital level is greater, banks are forced to pay a higher level of return with increased level of capital and also expected to pay additional costs of issuing capital. They pass such costs on lending rates, resulting in reduced amount of lending which leads to a lower investment. Thus, the rule is countercyclical to credit growth but might be procyclical to deviation of output from its steady state.

Poutineau and Vermandel (2017) (M_8)

The model trade relationships between core and peripheral countries within the euro area. Both representative countries comprise liquid and illiquid banks, which gives rise to a national and international interbank market. While liquid banks directly access the central banks fundings, illiquid banks borrow from either domestic or foreign liquid banks. The introduction of CCyB rule is nearly similar to that used in Gerali et al. (2010) in that both types of bank are subject to face a quadratic cost function ($0.5\chi^k(rwa_{i,t} - v_{i,t})^2$, where $rwa_{i,t}$ is bank capital-to-risky asset ratio, and $v_{i,t}$ is the macroprudential authority's policy target). While illiquid banks lend only to corporate sector, liquid banks provide a loan not only to corporate sector but also illiquid banks. Thus, there are differences in the composition of risk asset across types of bank, giving a smaller weight on interbank loans relatively to corporate loan in assessing total value of risky assets of liquid banks. The setting of $v_{i,t}$ influences deposit and lending rates of liquid and illiquid banks by affecting their profit maximization process, making impacts on the rest of the economy by disturbing the households' and entrepreneurs' deposit and borrowing decisions. The authors investigate an optimal domestic and foreign macroprudential rule taking a variety of specifications of the rule into account. The general formulation of the rule reads:

$$v_{i,t} = (1 - \rho_i^v)\bar{v} + \rho_i^v v_{i,t-1} + \phi_i \left(T_{i,t} - \overline{T_i}\right) \ , \tag{24}$$

where ρ_i^vdenotes the inertia within the macroprudential rule, $\bar{v}$ the rules' steady state, and ϕ_i the elasticity towards the gap between the target variable$T_{i,t}$ and its respective steady state. The central point of the paper is the specification of $T_{i,t}$ and the macroeconomic effect of these specifications across the core and peripheral country. Three possible candidates for $T_{i,t}$ are suggested: (1) the loan supply-to-GDP ratio, (2) the loan demand-to-GDP ratio, and (3) the capital inflows-to-GDP ratio. Additionally, both (1) and (2) can be further categorized into two distinct cases: (i) considering the union-wide level of loans, or (ii) considering only national loans.

Tayler and Zilberman (2016) (M_9)

This model assumes the possibility of default (credit risks) by borrowers (intermediate good producers) as a source of financial frictions. Intermediate goods producers should pay wages in advance before their output ($Y_t = A_t \varepsilon_t^F N_t$) is realized, thereby borrowing exact amount of funds to compensate labor cost ($L_t = W_t N_t$).[4] Output is a function of technology and labor, and is also subject to an idiosyncratic shock (ε_t^F), uniformly distributed over the interval ($\underline{\varepsilon}^F$, $\overline{\varepsilon}^F$). They offer their output as collateral for financial contracts, which is seized by the bank with the probability χ_t in the event of a default. In other words, with the probability $1 - \chi_t$, the bank can recover nothing when default occurs. Similar to M_4 and M_5, borrowers default when they anticipate the full loan repayment ($R_t^L L_t$) exceeds the expected loss due to the foreclosure on collateral ($\chi_t Y_t$). Thus, there is a threshold point $\varepsilon_t^{F,M} = \frac{R_t^L W_t}{\chi_t A_t}$ below which the borrower defaults. Given the assumption that the idiosyncratic shock follows uniform distribution aforementioned, the probability of default can be expressed as follows:

$$\Phi_t = \int_{\underline{\varepsilon}^F}^{\varepsilon_t^{F,M}} f(\varepsilon_t^F)\, d\varepsilon_t^F = \frac{\varepsilon_t^{F,M} - \underline{\varepsilon}^F}{\overline{\varepsilon}^F - \underline{\varepsilon}^F} \ . \tag{25}$$

Together with equation (25) and $\varepsilon_t^{F,M}$, it is evident that a greater output level, arising from technology shock reduce the credit risk and vice versa. Turning to the banking sector, they acquire funds from household deposit (D_t), bank capital (V_t) and central bank's liquidity injection (X_t) and provide credits (L_t) to intermediate goods producers. Thus, following balance sheet condition must be hold:

$$L_t = D_t + V_t + X_t \ . \tag{26}$$

Assuming that banking sector is a perfectly competitive market, the bank obtains zero profit such that:

$$\int_{\underline{\varepsilon}_t^{F,M}}^{\overline{\varepsilon}^F} \left[R_t^L L_t\right] f(\varepsilon_t^F) d\varepsilon_t^F + \int_{\underline{\varepsilon}^F}^{\varepsilon_t^{F,M}} \left[\chi_t Y_t\right] f(\varepsilon_t^F) d\varepsilon_t^F = R_t^V V_t + R_t^D (D_t + X_t) + cV_t \ , \tag{27}$$

[4] There are numerous intermediate good producers, denoted by j but I dropped this notation for simplicity.

where R_t^L is the bank lending rate, R_t^V is the return rate on bank capital, R_t^D is the interest rate applied to deposits from household and central bank, and c is the cost associated issuing bank equity. The left-hand side of equation (27) is the sum of the returns when borrowers do not default and the expected value of recoveries when borrowers default. The right-hand side presents the funding costs of banking businesses. By combining $\varepsilon_t^{F,M}$, equations (26) and (27), and using the identity$R_t^L L_t \equiv \int_{\underline{\varepsilon}^F}^{\varepsilon_t^{F,M}} \left[R_t^L L_t\right] f(\varepsilon_t^F) d\varepsilon_t^F + \int_{\varepsilon_t^{F,M}}^{\overline{\varepsilon}^F} \left[R_t^L L_t\right] f(\varepsilon_t^F) d\varepsilon_t^F$, the lending rate can expressed as follows:

$$R_t^L = \nu_t \left[\Delta_t (R_t^V + c) + (1 - \Delta_t) R_t^D\right] \ , \tag{28}$$

where $\Delta_t \equiv \frac{V_t}{L_t}$, the bank capital-to-loan ratio, and $\nu_t \equiv \left[1 - \frac{\int_{\underline{\varepsilon}^F}^{\varepsilon_t^{F,M}} \left[\varepsilon_t^{F,M} - \varepsilon_t^F\right] f(\varepsilon_t^F) d\varepsilon_t^F}{\varepsilon_t^{F,M}}\right]^{-1} > 1.$

Δ_t is subject to follow central bank's capital requirement regulation:

$$\frac{V_t}{L_t} \equiv \Delta_t = (\Delta_{t-1})^{\phi_\Delta} \left[\rho \left(\frac{\Phi_t}{\Phi}\right)^{\theta_c}\right]^{1-\phi_\Delta} \ , \tag{29}$$

where ρ is the minimum capital adequacy ratio, and ϕ_Δ is a persistence parameter, assumed to be $0 < \phi_\Delta < 1$. As long as $\theta_c < 0$, the required capital adequacy ratio decreases with a higher credit risk (Φ_t). In other words, the rule is countercyclical since the credit risk is negatively related to output level. As output increases, Φ_t lowers, thus central bank require a greater accumulation of bank capital. This, in turn, raises the lending rate through equation (28), resulting in a lower level of lending.[5]

Clerc, Derviz, Mendicino, Moyen, Nikolov, Stracca, Suarez and Vardoulakis (2015) (M_10)

The model adopts a similar framework with M_4 and M_5 which are based on Bernanke et al. (1999). Borrowing households and entrepreneurs are bound by financial contracts with the following conditions: (i) they agree to make full debt repayments unless they default, and (ii) the returns on their assets (housing

[5] However, the model also allows another channel that a higher Δ_t decreases the lending rate by lowering default risks associated with bank capital. As the bank accumulates more capital, it can absorb losses stemming from borrowers' defaults, resulting in a lower return rate on bank capital, reflecting reduced risks. Accordingly, it negatively affects the lending rate through equation (28). Even so, the existence of the banking equity issuance cost (c) guarantees such negative effects cannot outweigh the positive effects explained in the main text.

stocks and physical capital) are subject to idiosyncratic shocks, and such assets are seized by banks if they default after deducting verification costs related to revealing each asset's exact return value. Thus, for each asset, there exists a cut-off point in returns where the decision between full repayment and default becomes indifferent. Banks compute the expected returns from lending to households and entrepreneurs, and continue their banking businesses only if the returns exceed those from outside options. Since a portion of funding sources depends on bank equity, the banks' participation constraints can be expressed as follows:

$$Expected\ return_t^i \geq \rho_t \phi_t^i b_t^i \ , \tag{30}$$

where i refers to households (H) or entrepreneurs (E), ρ_t is the market return from outside option, ϕ_t^i is the regulatory capital requirement and b_t^i is the loan levels. Given that equation (30) holds equality, ϕ_t^i governs the incentive to participate in financial intermediary businesses. As it takes on higher values, the funding opportunity for borrower households and entrepreneurs decrease. ϕ_t^i is determined by the rule below, varying countercyclically considering the total debt level of the economy:

$$\phi_t^j = \bar{\phi}_0^j + \bar{\phi}_1^j \left[\log(b_t^H + b_t^E) - \log(\bar{b}^H + \bar{b}^E)\right] \ , \tag{31}$$

where $\bar{\phi}_0^j > 0$ and $\bar{\phi}_1^j > 0$. The restriction on accessible funds for borrowing households limits their ability to acquire housing stocks, further suppressing funding capacity. For entrepreneurs, the same mechanism is applicable in that it restrains their capability to purchase physical capital.

Gertler and Karadi (2011) (M_11)

The model introduced the costly enforcement problem (moral hazard) as the banking sector friction. Financial intermediaries (bankers) source funding from household and provides financial claims (S_t) to the borrower (intermediate good producers). The borrower needs loans to purchase capital (K_{t+1}), i.e., $Q_t K_{t+1} = Q_t S_t$ where Q_t refers to the relative price of the financial claims. Each financial intermediary (j) adheres to the balance sheet condition, the total asset ($Q_t S_{jt}$) must be equal to the sum of their net worth (N_{jt}) and deposits from households (B_{jt+1}):

$$Q_t S_{jt} = N_{jt} + B_{jt+1} \ . \tag{32}$$

Denote $R_{kt+1}$and R_{t+1} as the gross return on financial claim and household deposits. Then, the financial intermediary's net worth evolves as follows:

$$N_{jt+1} = R_{kt+1} Q_t S_{jt} - R_{t+1} B_{jt+1} = (R_{kt+1} - R_{t+1}) Q_t S_{jt} + R_{t+1} N_{jt} \ . \tag{33}$$

Under the assumption that each banker remains as bankers again at the next period with probability θ (i.e., they exit with probability $1-\theta$), their accumulated wealth expected at period t (V_{jt}) is as follows:

$$V_{jt} = E_t \sum_{i=0}^{\infty} (1-\theta)\theta^i \beta^{i+1} \Lambda_{t,t+1+i} \left[(R_{kt+1+i} - R_{t+1+i}) Q_{t+i} S_{jt+i} + R_{t+1+i} N_{jt+i} \right] \ , \tag{34}$$

where $\beta^i \Lambda_{t,t+i}$ is the stochastic discount factor. It is also assumed that bankers choose to default and divert a fraction (λ) of available funds ($Q_t S_{jt}$). In such cases, the depositor forces banks into bankruptcy and can claim the remained fraction ($1-\lambda$) of the funds. To make bankers in operations, the following incentive constraint should be satisfied:

$$V_{jt} \geq \lambda Q_t S_{jt} \ . \tag{35}$$

V_{jt} can be expressed as a recursive form by considering equation (34). Thus, the left-hand side of the IC 35 can be written as as follows:

$$V_{jt} = \nu_t Q_t S_{jt} + \eta_t N_{jt} \ , \tag{36}$$

where $\nu_t = E_t \left[(1-\theta)\beta\Lambda_{t,t+1}(R_{kt+1} - R_{t+1}) + \beta\Lambda_{t,t+1}\theta x_{t+1}\nu_{t+1} \right]$ (the expected marginal gain of expanding bank's financial claims by a unit), $\eta_t = E_t \left[(1-\theta) + \beta\Lambda_{t,t+1}\theta z_{t,t+1}\eta_{t+1} \right]$ (the expected gain from increasing net worth by a unit), $x_{t,t+i} \equiv \frac{Q_{t+i} S_{jt+1}}{Q_t S_{jt}}$ and $z_{t,t+i} \equiv \frac{N_{jt+i}}{N_{jt}}$. Without the moral hazard problem introduced, bankers have incentive to expand their financial assets as their marginal gains of such activity is zero (i.e., $\nu_t = 0$). However, it is impossible due to the IC 35, particularly when the condition is binding, resulting in the following condition should be hold:

$$Q_t S_{jt} = \phi_t N_{jt} \ , \tag{37}$$

where $\phi_t = \frac{\eta_t}{\lambda - \nu_t}$. Equation (37) is a break-even condition to ensure that the bank's leverage is in the position where the incentive to default is exactly offset by its cost. Thus, it limits the level of bankers' financial claim to do not exceed their net worth. Alternatively, ϕ_t can be understood as an 'asset-to-equity' ratio, which is an inverse of v_t^{CA} from the studies previously discussed, but causing indefinite cost if the financial claim exceed the net worth.

Using equations (33) and (37), one can show that $x_{t,t+1}$ and $z_{t,t+i}$ does not depend on j. Together with the fact that ϕ_t is also invariant across j, the following equation must be hold if we sum up equation (37) across the banks, determining the aggregate bank assets and net worth:

$$Q_t S_t = \phi_t N_t \ . \tag{38}$$

Finally, the author considered credit policy. Suppose that a share (ψ_t) of $Q_t S_t$ is exogenously determined by central bank and the private sector determined the rest. Then, the total bank assets of the economy is as follows:

$$Q_t S_t = \phi_t N_t + \psi_t Q_t S_t \ . \tag{39}$$

After rearranging equation (39), we obtain $Q_t S_t = \phi_{ct} N_t$ where $\phi_{ct} = \frac{1}{1-\psi_t}\phi_t$. It indicates that central bank govern the total amount of intermediated fund by adjusting ψ_t. For instance, a higher level of ψ_t, meaning easing of the regulatory leverage ratio, increases available funds to the private sector. It leads to the enhancement of capital acquisitions by intermediate goods producers. The time-varying management of the credit level is also considered by adopting a credit rule such that:

$$\psi_t = \psi + \nu E_t \left[(\log R_{kt+1} - \log R_{t+1}) - (\log R_k - \log R) \right] \ . \tag{40}$$

This is to reflect the empirical fact that countercyclical movement of credit spread, caused by increase in credit risks for instance.

Gebauer and Mazelis (2023) (M_12)

Two types of financial intermediaries, commercial banks and shadow banks, exist. Modeling commercial banking sector is identical to that of Gerali et al. (2010). The framework aforementioned for M_1 is applicable, except for that entrepreneur under collateral constraint is only borrower in this model. Meanwhile, shadow banking sector is modelled by adopting a similar approach outlined by Gertler and Karadi (2011) such that a moral hazard problem exists since the shadow banks can go bankruptcy by diverting a fraction of household deposits and relinquishing discounted net worth expected to be accumulated at terminal. Accordingly, the amount of the shadow banks' financial claim to the borrower is determined by the same way as M_11.

The CCyB is only applied to commercial banks side, following the same way in M_1. The authors consider four different types of rules, leaning against each measure of credit cycles, such as credit level deviation from steady state ($\hat{B}_t^i = B_t^i - \bar{B}^i$), credit-to-GDP level deviation from steady state ($\hat{Z}_t^i = \frac{B_t^i}{Y_t} - \frac{\bar{B}^i}{\bar{Y}}$), credit growth ($\Delta\hat{B}_t^i$) and credit-to-GDP growth ($\Delta\hat{Z}_t^i$) by two alternative types (i) of regulators, (1) The moderate; (2) The prudent. The rules follow an AR (1) process in the form of:

$$v_t^{CA} = (1-\rho_v)\bar{v} + (1-\rho_v)\chi_v V_t + \rho_v v_{t-1} \ , \tag{41}$$

where $V_t \in \{\hat{B}_t^i, \hat{Z}_t^i, \Delta\hat{B}_t^i, \Delta\hat{Z}_t^i\}$ and v_t^{CA} is the level of capital requirement to commercial banks. The difference between the moderate and the prudent is contingent on whether B_t counts loans by commercial banks only, or also those by shadow banks. In other words, while the moderate regulator sets macroprudential rule only by taking into account commercial banks credit, the prudent regulator determines the level of capital requirement by considering financial claims made by shadow banks as well. Thus, the latter would set a tighter regulation on commercial banks.

2 Models' variances

We plot the variances of the credit gap, output, and changes in the policy instrument for each models. These figures show how the models behave in terms of variances, and how they differ across models. Looking at the credit gap variability (figure 1), we observe that the general pattern, except for one outlier (M_10), is a reduction of the volatility of credit gap when increasing the aggressiveness of the rule. For macroeconomic stability (figure 2), it is more difficult to generalize the results. This is an obvious outcome of the nature of the CCyB rule, which primarily focuses on financial stability rather than on macroeconomic stability. Also intuitively, the variability of the policy instrument (figure 3) increases with the aggressiveness of the rule. Generally speaking, by being more aggressive (large ϕ_{ccyb}) the policymaker stabilizes the credit gap at the expenses of a more volatile policy instrument.

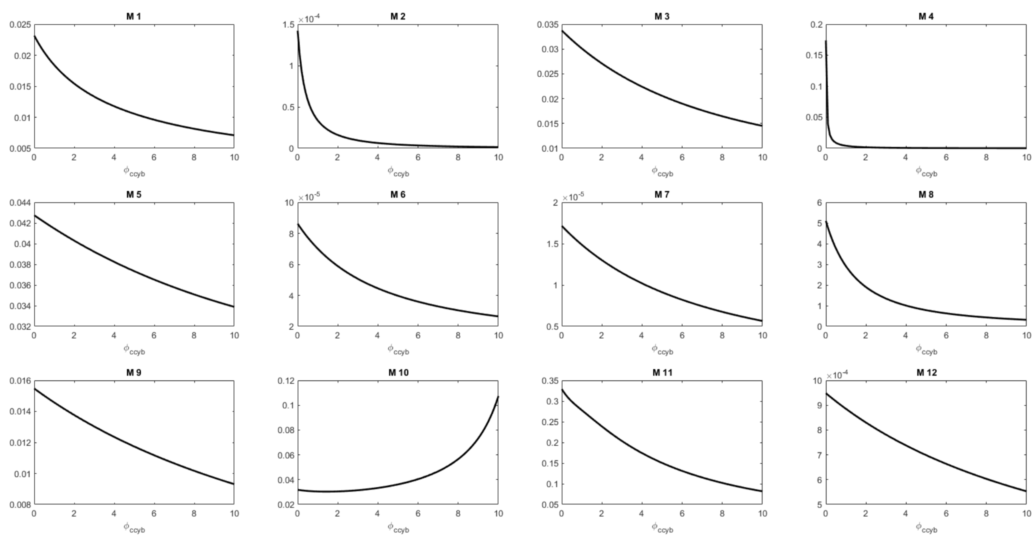


Figure 1: variance of credit gap across models for $0 \leq \phi_{ccyb} \leq 10$

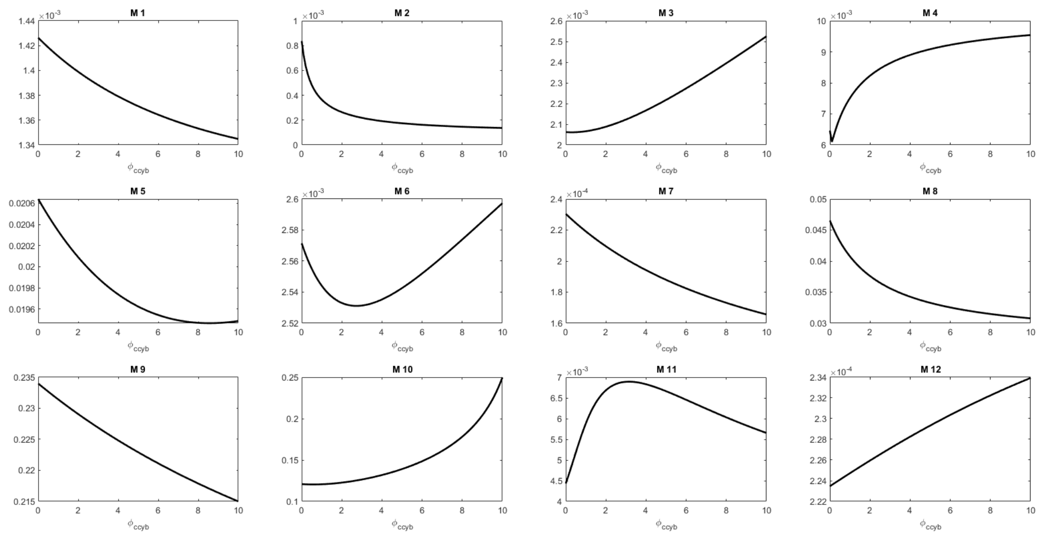


Figure 2: variance of output across models for $0 \leq \phi_{ccyb} \leq 10$

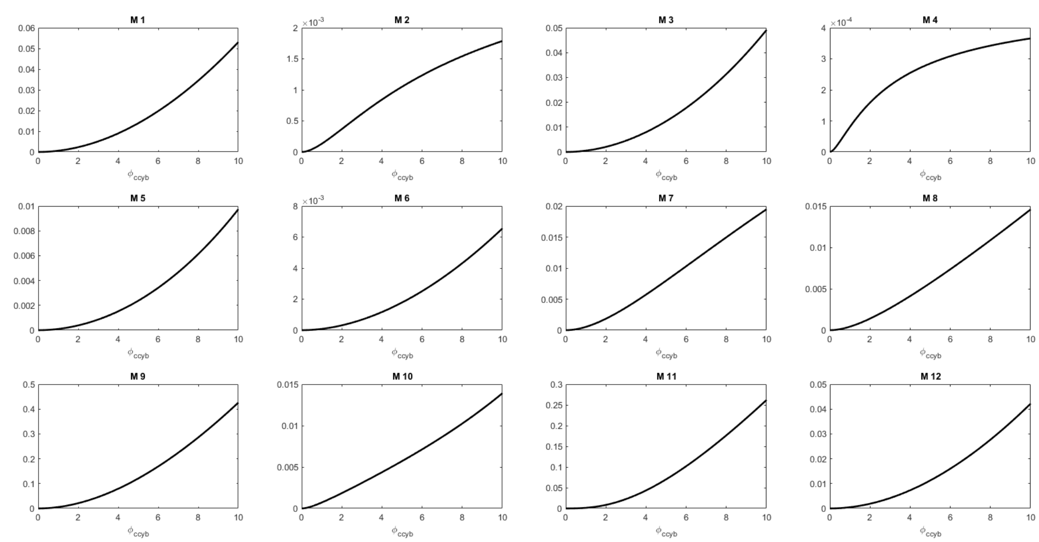


Figure 3: variance of Δcr across models for $0 \leq \phi_{ccyb} \leq 10$

References

Agenor, Pierre-Richard and Timothy P. Jackson, “Monetary and macroprudential policy coordination with biased preferences,” *Journal of Economic Dynamics and Control*, 2022, *144*, 104519.

Alpanda, Sami, Gino Cateau, and Cesaire Meh, “A policy model to analyze macroprudential regulations and monetary policy,” *Canadian Journal of Economics*, 2018, *51* (3), 828–863.

Angelini, Paolo, Stefano Neri, and Fabio Panetta, “The Interaction between Capital Requirements and Monetary Policy,” *Journal of Money, Credit and Banking*, 2014, *46* (6), 1073–1112.

Bernanke, Ben S., Mark Gertler, and Simon Gilchrist, “The financial accelerator in a quantitative business cycle framework,” in J. B. Taylor and M. Woodford, eds., *Handbook of Macroeconomics*, Vol. 1, Elsevier, 1999, chapter 21, pp. 1341–1393.

Binder, Michael, Philipp Lieberknecht, Jorge Quintana, and Volker Wieland, “Robust Macroprudential Policy Rules under Model Uncertainty,” VfS Annual Conference 2018 (Freiburg, Breisgau): Digital Economy 181503, German Economic Association 2018.

Clerc, Laurent, Alexis Derviz, Caterina Mendicino, Stephane Moyen, Kalin Nikolov, Livio Stracca, Javier Suarez, and Alexandros P. Vardoulakis, “Capital Regulation in a Macroeconomic Model with Three Layers of Default,” *International Journal of Central Banking*, 2015, *11* (3), 9–63.

Darracq Paries, Matthieu, Christoffer Kok Sorensen, and Diego Rodriguez-Palenzuela, “Macroeconomic Propagation under Different Regulatory Regimes: Evidence from an Estimated DSGE Model for the Euro Area,” *International Journal of Central Banking*, 2011, *7* (4), 49–113.

Gebauer, Stefan and Falk Mazelis, “Macroprudential regulation and leakage to the shadow banking sector,” *European Economic Review*, 2023, *154*, 104404.

Gerali, Andrea, Stefano Neri, Luca Sessa, and Federico M. Signoretti, “Credit and Banking in a DSGE Model of the Euro Area,” *Journal of Money, Credit, and Banking*, 2010, *42* (6).

Gertler, Mark and Peter Karadi, “A model of unconventional monetary policy,” *Journal of Monetary Economics*, 2011, *58* (1), 17–34.

Lozej, Matija, Luca Onorante, and Ansgar Rannenberg, “Countercyclical capital regulation in a small open economy DSGE model,” *Macroeconomic Dynamics*, 2022, pp. 1–38.

Malmierca, Maria, “Optimal macroprudential and fiscal policy in a monetary union,” *Economic Modelling*, 2023, *122*, 106238.

Meh, Cesaire A. and Kevin Moran, “The role of bank capital in the propagation of shocks,” *Journal of Economic Dynamics and Control*, 2010, *34* (3), 555–576.

Poutineau, Jean-Christophe and Gauthier Vermandel, “Global banking and the conduct of macroprudential policy in a monetary union,” *Journal of Macroeconomics*, 2017, *54*, 306–331.

Tayler, William J. and Roy Zilberman, “Macroprudential regulation, credit spreads and the role of monetary policy,” *Journal of Financial Stability*, 2016, *26* (C), 144–158.

Bank of Finland Research Discussion Papers 2024

ISSN 1456-6184, online

1/2024 Gene Ambrocio – Iftekhar Hasan – Xiang Li
Global political ties and the global financial cycle

2/2024 Michaela Elfsbacka-Schmöller – Nigel McClung
Price stability and debt sustainability under endogenous trend growth

3/2024 Diego Moreno – Tuomas Takalo
Stress test precision and bank competition

4/2024 Eleonora Granziera – Pirkka Jalasjoki – Maritta Paloviita
The bias of the ECB inflation projections: a state-dependent analysis

5/2024 Maria Eskelinen – Christopher G. Gibbs – Nigel McClung
Resolving new Keynesian puzzles

6/2024 Markus Haavio – Joni Heikkinen – Pirkka Jalasjoki – Juha Kilponen – Maritta Paloviita – Ilona Vänni
Reading between the lines - Uncovering asymmetry in the central bank loss function

7/2024 Aleksi Paavola – Ville Voutilainen
Central bank collateral policy and credit pricing: evidence from Finland

8/2024 Joni Heikkinen – Kari Heimonen
Media tone: the role of news and social media on heterogeneous inflation expectations

9/2024 Dominik Hecker – Hun Jang – Margarita Rubio – Fabio Verona
Robust design of countercyclical capital buffer rules