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Robust Macroprudential Policy Rules under Model Uncertainty

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Abstract

Against the backdrop of elevated model uncertainty in DSGE models with a detailed modeling of financial intermediaries, we investigate the performance of optimized macroprudential policy rules within and across models. Using three canonical banking DSGE models as a representative sample, we show that model-specific optimized macroprudential policy rules are highly heterogeneous across models and not robust to model uncertainty, implying large losses in other models. This is particularly the case for a perfect-coordination regime between monetary and macroprudential policy. A Stackelberg regime with the central bank as leader operating according to the rule by Orphanides and Wieland (2013) implies smaller potential costs due to model uncertainty. An even more effective approach for policymakers to insure against model uncertainty is to design Bayesian model-averaged optimized macroprudential rules. These prove to be more robust to model uncertainty by performing better across models than model-specific optimized rules, regardless of the regime of interaction between the two authorities.

Keywords: Macroprudential Policy, Optimized Policy Rules, Model Uncertainty, Bayesian Model-Averaging, Robust Policy Rules.

JEL Classification: E44, E52, E58, E61, G28.

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Contents

1 Introduction

Following the Global Financial Crisis, a large number of prerogatives have been granted to financial regulators and central banks to address financial stability at a system-wide level. This change has been characterized as a move from a "microprudential" to a "macroprudential" approach, the latter being concerned with general equilibrium effects of the financial system on the real economy (Hanson et al., 2011). This approach is based on the view that excessive leverage on part of financial intermediaries and resulting highly volatile credit cycles tend to raise the risk of a systemic event. Since individual intermediaries' contribution to systemic risk is not internalized, there is scope for policy to intervene and prevent associated detrimental effects on the real economy (Schnabel and Faia, 2015).

While the theoretical arguments supporting such reasoning are now widely accepted, actual implementation of macroprudential policy is still subject to large uncertainty. In the words of Buch (2015), "the level of knowledge and experience in [macroprudential policy] is roughly on a par with that in the field of monetary policy some years ago. The specific policy goals are difficult to quantify, transmission channels are often unknown, and the data sets and analytical methods need to be developed." In particular, there is scarce evidence about macroprudential regulation in the dynamic stochastic general equilibrium (DSGE) paradigm, which is currently the leading structural framework employed for studying monetary policy and business cycle issues at large central banks (Binder et al., 2017a).

By now, there is a large strand of DSGE models incorporating a detailed representation of the financial sector. However, a generally accepted workhorse framework has not yet emerged. Afanasyeva et al. (2016) and Binder et al. (2017a) show that this wide range of models with financial frictions implies substantially different prescriptons for monetary policy relative to earlier model generations. This is particularly the case in the class of models featuring financial intermediaries – which is the relevant framework to investigate well-defined macroprudential policy operating directly on banks' balance sheets.

Against this backdrop of elevated *model uncertainty*, macroprudential policy optimized for one particular DSGE model with financial intermediaries is likely to lack robustness in the spirit of McCallum (1988). As optimized macroprudential policy depends crucially on the exact modeling of financial intermediaries, it may not perform well in models with a different specification of banks. Levin et al. (1999), Adalid et al. (2005) and Kuester and Wieland (2010) show that the costs associated with conditioning policy design on a misspecified model can be substantial.

Given the current level of uncertainty associated with macroprudential policy in general and the modeling of financial intermediaries, we aim to characterize macroprudential policy that performs well across a range of models. Our focus is on rules-based macroprudential policy. There are compelling practical arguments for eschewing discretion in favor of greater commitment in the design of such policies (German Council of Economic Experts, 2014). Furthermore, robust policy is more easily specified in a "rule-space" invariant of special model properties (Taylor, 2016). Specifically, we aim to characterize macroprudential policy rules that are able to effectively manage the credit cycles without generating significant costs to the macroeconomy or hazard financial stability, both within and across models.

We use the models developed by Gerali et al. (2010), Meh and Moran (2010), and Gertler and Karadi (2011) as a representative sample of DSGE models with a banking sector and a detailed modeling of banks' balance sheet interaction with the real economy – such that they allow for macroprudential policy instruments to be explicitly modeled. As the macroprudential instrument, we employ the capital-to-assets (CTA) ratio, which has been widely discussed in the literature and within the regulatory community.[1]

We show that macroprudential policy rules optimized for specific models within this set substantially lack robustness, i.e., they imply large losses equivalent to a significantly worse macroeconomic performance in other models. This is particularly the case for a perfect-coordination regime between monetary and macroprudential policy; some of these jointly optimized rules even generate explosive dynamics in other models. In contrast, a Stackelberg regime in which the monetary authority is the leader improves robustness somewhat. If the central bank operates according to a rule like the one proposed by Orphanides and Wieland (2013), it acts as a stabilizing anchor ensuring determinacy and stability across models.

These results suggest that policymakers designing macroprudential policy rules based on a single banking DSGE model risk destabilizing the macroeconomy – as long as there is some positive probability that the model employed is far away from the "true" model. Instead, they can insure against model uncertainty by designing robust policy rules, a strategy that has been proposed by Kuester and Wieland (2010) and Afanasyeva et al. (2016) in the context of monetary policy. We show that macroprudential policy rules which are optimized by using a (Bayesian) model-averaging approach are effective in insuring against model uncertainty. Regardless of the regime of interaction with monetary policy, they perform better across models than model-specific optimized rules.

Our study is related to those of Agénor et al. (2013), Covas and Fujita (2009) and Angeloni and Faia (2013), among others, who study the impact of time-varying bank capital requirements on the business-cycle. In general, such studies conclude that counter-cyclical capital requirements can reduce macroeconomic volatility over the business cycle. In some cases, as in Agénor et al. (2013), optimal simple rules are derived for the conduct of macroprudential policy in the form of capital requirements. Our analysis is different in that it takes into account a wider range of model specifications for the banking sector.

This paper is also connected to the strand of literature on the regime of interaction between macroprudential and monetary policy. Angelini et al. (2011, 2014) analyze CTA rules in a modified version of the model by Gerali et al. (2010). They show that a perfect-coordination regime between the two authorities achieves substantive gains in terms of macroeconomic and financial stability relative to non-cooperation. This result is in line with Bean et al. (2010), who employ a simplified version of the Gertler and Karadi (2011) model and include a levy on bank capital as a macroprudential tool. In a similar analysis, Gelain and Ilbas (2017) employ an estimated version of the Gertler and Karadi (2011) model to compare cooperation and non-cooperation between monetary and macrprudential policy under full committment. They find that for conventional values of the simple-mandate weight corresponding to the output

[1] All our results continue to hold when assume a different instrument, i.e., the loan-to-value or loan-to-deposits ratios, see Binder et al. (2017b).

gap, both policymakers prefer cooperation over non-cooperation. In contrast to these papers, we also consider a Stackelberg interaction between monetary and macroprudential policy as an intermediate regime between perfect-cooperation and non-cooperation. We furthermore investigate the monetary-macroprudential policy interaction across several modeling specifications for financial intermediaries, using a harmonized common macroprudential instrument and report the associated optimized rule as well as implied macro-financial dynamics.

Finally, our paper is related to the literature on model comparison and insurance against model uncertainty. While there are several studies utilizing the model-comparison approach to draw insights on monetary (Taylor and Wieland, 2012; Wieland et al., 2016) and fiscal (Coenen et al., 2012; Binder et al., 2016) policies, the same is not yet true for macroprudential policy. We aim to address this issue following the strategy proposed by Wieland et al. (2012, 2016) for a systematic comparison of policies across models. With respect to model uncertainty, we use the methodology proposed by Kuester and Wieland (2010) and Afanasyeva et al. (2016) to compute robust monetary policy rules and adapt it for the design of robust macroprudential policy rules.

The remainder of the paper is organized as follows. Section 2 provides a brief exposition of the employed set of models and their specification of financial intermediaries. Section 3 outlines the implementation of well-defined macroprudential instruments in these models. In Section 4, we derive the model-specific optimized policies. Section 5 analyzes model-averaged policies rules, Section 6 concludes.

2 Model Uncertainty

In this section, we describe the set of models we use in our analysis and assess some of the complications that arise from model uncertainty when drawing out policy prescriptions. In choosing the models we use to analyze macroprudential policy, we follow Angelini et al. (2011) and consider models that satisfy the following three requirements: (i) They must incorporate a depiction of the financial sector's interaction with the macroeconomy, (ii) they must contain a representation of financial intermediaries with sufficient detail for macroprudential policy to be explicitly modeled, and (iii) they must include a sufficient number of frictions so as to realistically describe the transmission mechanism of monetary policy. The models we consider are those of Gerali et al. (2010), Meh and Moran (2010) and Gertler and Karadi (2011).[2]

2.1 Description of Models

All three models belong to the class of New Keynesian DSGE models, which features forward-looking behavior and intertemporal optimization by households and firms. Firms' price setting behavior is subject to nominal rigidities, which generates real effects from monetary policy. On top of this, the models exhibit several real rigidities such as habit formation in consumption, investment adjustment costs and capital utilization. At the core, these models are thus close to the canonical medium-scale framework proposed by Smets and Wouters (2003, 2007) and Chris-

[2] All models are drawn from the *Macroeconomic Model Database*, which is an archive of macroeconomic models for policy analysis (Wieland et al., 2012, 2016).

tiano et al. (2005). As shown by the latter, this model framework generates impulse-responses following a monetary policy shock well in line with empirical evidence. As a result, such models represent a suitable framework for the analysis of monetary policy. Table 1 summarizes the key features of the employed models.

Table 1: Key Features of Employed Models

	Gertler and Karadi (2011)	**Meh and Moran (2010)**	**Gerali et al. (2010)**
Model structure			
Key agents	Representative household	Representative household, risk-neutral entrepreneurs, risk-neutral bankers	Patient and impatient households, utility-maximizing entrepreneurs, monopolistic competitive banks
Production sector	One-sector Cobb-Douglas technology	One-sector Cobb-Douglas technology	One-sector Cobb-Douglas technology
Real and nominal rigidities			
Consumption habit formation	Yes	Yes	Yes
Expenditure adjustment cost	Investment adjustment cost	No	Investment adjustment cost
Capital utilization	Yes	Yes	Yes
Consumer prices	Calvo pricing, partial indexation	Calvo pricing, partial indexation	Rotemberg pricing, partial indexation
Nominal wages	Flexible	Calvo pricing, partial indexation	Rotemberg pricing, partial indexation
Housing prices	-	-	Flexible
Financial frictions			
The role of the bank	Moral hazard problem between depositors and financial intermediaries	Holmstrom and Tirole (1997) double moral hazard; first between depositors and banks and second between banks and entrepreneurs	Adjustment cost of the bank capital to asset ratio, stickiness in deposit and lendig rates
Collateral constraints	-	-	Kiyotaki and Moore (1997) type, nominal terms
Parameters and shocks			
Estimation / Calibration	Calibration, U.S. data	Calibration, U.S. data	Bayesian estimation, EA data: 1998Q1-2009Q1
Shocks	Technology, monetary policy, fiscal policy, capital quality, bank capital	Technology, monetary policy, bank capital	Technology, monetary policy, consumption preference, housing preference, firms' LTV, HH's LTV, deposit rate markdown, HHs loans markup, firms loans markup, investment efficiency, price mark-up, wage mark-up, bank capital

Note: Parts of this table reproduce Table 10 in Wieland et al. (2016).

Most notably, however, these models represent three distinct approaches to the incorporation of a more detailed characterization of the financial sector into DSGE models. Following Binder et al. (2017a), they can hence be classified as third-generation New Keynesian DSGE models. Broadly speaking, they incorporate the notion of Bernanke and Blinder (1988) and Bernanke and Gertler (1995), i.e., the idea that balance sheets of financial intermediaries – and in particular bank net worth – are crucial for business-cycle dynamics and policy transmission (Gambacorta and Mizen, 2017).[3] In the following, we shortly describe how the financial sector is integrated in each of these three models.

In the model by Gertler and Karadi (2011) (GK henceforth), banks obtain deposits from households in order to finance loans to entrepreneurs. However, a moral hazard problem exists between banks and depositors. Bankers maximize expected terminal net wealth and have the ability to divert a fraction of deposits towards their personal accounts. If funds are diverted by the banker, the financial intermediary is immediately forced into bankruptcy. In equilibrium, an incentive compatibility constraint rules out such behavior. In turn, this generates an endogenous leverage constraint which links the amount of intermediated loans to bank capital. Financial intermediation accordingly inherits the pro-cyclicality of bank capital, which leads to an amplification of business cycles.

Meh and Moran (2010) (MM henceforth) also propose a framework in which bank capital is crucial to mitigate informational asymmetries in the banking sector. Similar to the GK model, they assume a moral hazard problem between banks and depositors. Households cannot monitor entrepreneurs directly, inducing them to refrain from direct lending and delegating the respective task to the banks at which they deposit their funds. Since monitoring is costly and not publicly observable, the bank has an incentive for imperfect monitoring. It can mitigate this moral hazard problem by investing own net worth in the projects by entrepreneurs. In addition, Meh and Moran (2010) assume that the lending relationship between banks and entreneurs is subject to a moral hazard problem as well. Entrepreneurs have the choice between three projects, some of which are associated with private benefits and lower success probabilities. Due to the imperfect monitoring technology, entrepreneurs must be induced to choose a project with high success probabilities by investing their own net worth. This double moral hazard problem is in the spirit of Holmstrom and Tirole (1997).

The approach by Gerali et al. (2010) (GNSS henceforth) is quite different. They assume that the banking sector is imperfectly competitive such that banks possess market power in conducting their intermediation activities. They act as price setters on loan rates, but are subject to nominal rigidities in the form of quadratic adjustment costs. Moreover, banks are assumed to have a target capital-to-asset ratio and incur quadratic costs whenever the actual ratio deviates from the specified target. As a consequence, credit supply crucially depends on bank capital. In this model, the financial sector has an attenuator effect on shocks that affect the economy via a change in real rates or in the value of collateral. In contrast to the calibrated models by GK and MM, GNSS estimate their model by means of Bayesian techniques on Euro Area data from 1998Q1 - 2009Q1. The model thus also features a larger set of shocks relative to the other two models.[4]

[3]This is in contrast to the canonical financial accelerator mechanism by Bernanke et al. (1999), which assigns a crucial role to firm net worth. In this framework, lenders (which can be interpreted as banks) are assumed to be perfectly competitive intermediaries and appear only implicitly in the model. Their balance sheet is irrelevant for business cycle dynamics.

[4]In implementing this model, we follow the authors in employing an alternative definition (compared to the one reported in the published paper) of output to define the output gap, to which the central bank responds. The alternative definition is the sum of aggregate consumption and new capital, abstracting from the adjustment costs associated with bank capital.

In sum, these three models feature quite distinct modeling approaches to integrating financial intermediaries into New Keynesian DSGE models and making their balance sheets relevant for business cycles. The models are part of a relatively new, emerging strand of the literature encompassing numerous alternative modeling approaches. Binder et al. (2017a) show that this class of third-generation New Keynesian DSGE models features an elevated degree of model uncertainty relative to earlier model generations, i.e., both policy prescriptions and shock transmissions are highly heterogeneous across types of financial frictions. The absence of a workhorse modeling approach in this respect, as well as the outlined quantitative uncertainty about the efficiency of macroprudential policy inherently calls for an analysis of robust macroprudential policies within this class of models.

2.2 Heterogeneity of Policy Implications

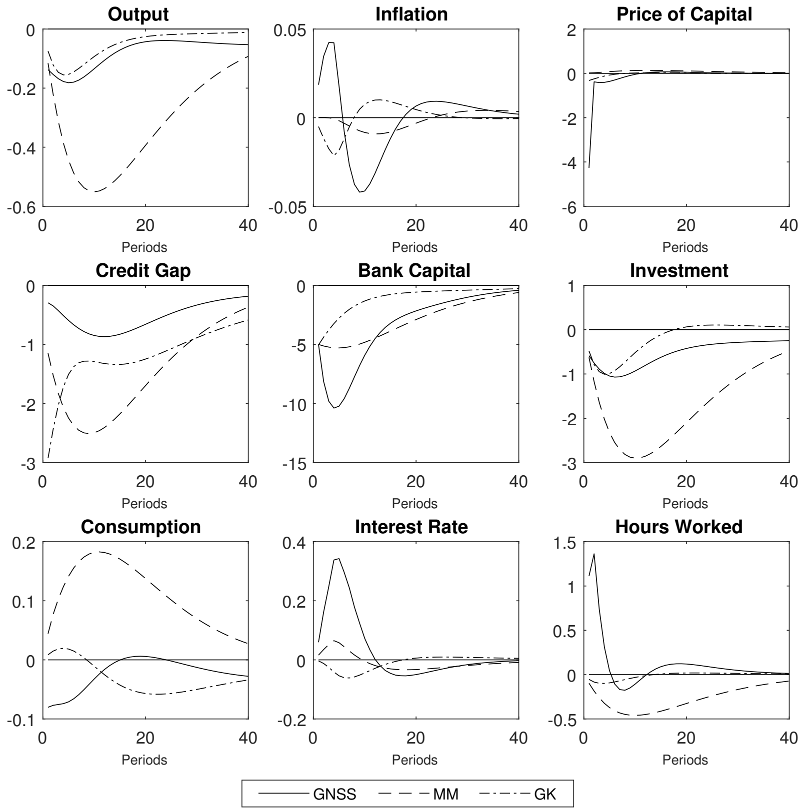
In order to intuitively frame the issues we are concerned with, consider a monetary policymaker that faces a financial sector shock that exogenously lowers the level of capital in the banking sector. For simplicity, we assume that the policymaker operates under full commitment to a simple interest rate rule. In order to draw out the dynamic consequences of such a shock and derive precise prescriptions for the central bank's interest rate path, the policymaker must condition her expectations on an economic model. As mentioned above, given the present level of uncertainty about the "correct" banking sector specification, policy prescriptions can vary widely across models of this type. Figure 1 presents the impulse-response functions for a financial shock that unexpectedly leads to a fall of 5% in banks' net worth. The monetary authority conducts policy by following an interest rate rule as in Orphanides and Wieland (2013).[5]

As should be expected given financial intermediaries' balance sheet constraint, an exogenous fall in bank capital causes a contraction in the credit gap, which we define as the difference between the log-deviation of credit from its non-stochastic steady state over that of output. In turn, this leads to a fall in output and investment. However, the general equilibrium effects and policy prescriptions differ markedly across models, as the propagation mechanism is quite different between models.

While the shock is inflationary in the GNSS and MM models, leading the central bank to raise the monetary policy interest rate, it is deflationary in the GK model, where the central bank lowers the interest rate. Further, the degree of persistence – both endogenous and exogenous – varies substantially across models. In the GNSS model, the shock is naturally amplified by the dynamics of the financial sector. The initial fall in capital causes banks' costs to increase substantially due to convex adjustment costs in bank capital, which severely limits their ability to rebuild their net worth through retained earnings. Consequently, the price of capital falls significantly after the shock as well. This has a strong effect on consumption, both by lower-

[5]This exercise follows Wieland et al. (2012), but differs in that we keep the policy rule constant across models in order to clearly identify heterogeneous effects due to model uncertainty, rather than differences stemming from different monetary policies. The rule by Orphanides and Wieland (2013) is a first-difference rule for the nominal interest rate, with the central bank responding to inflation and output gap growth. It has been shown to accurately characterize the conduct of monetary policy in the euro area leading up to the Great Financial Crisis and is explained in more detail in Section 4.

Figure 1: Bank Capital Shock



Note: Impulse response functions for a five-percent fall in bank net worth. Monetary policy is modeled according to the rule in Orphanides and Wieland (2013). A period is a quarter and all variables are expressed in percentage deviations from their non-stochastic steady state value.

ing the collateral value of homes (not shown) and through the higher interest rates that are required to curb inflation. The negative wealth effect leads to a sharp increase in hours worked, which limits the fall in output to some extent. Nevertheless, investment and output remain at depressed levels even after forty periods since the initial shock. In general, the GNSS model has the clear prescription that inflation risks immediately following the financial shock grossly outweigh other costs and the central bank should raise interests rates accordingly.

The MM model, in contrast, calls for a much more modest rise in interest rates. Although the fall in net worth also leads to a contraction in lending and investment, the propagation mechanism is much less severe as banks do not face convex adjustment costs. In addition, since the shock causes the price of capital to increase, household consumption and leisure rises somewhat as these goods become relatively cheaper. This notwithstanding, the fall in output and investment is substantially larger than in the other two models. The overall implications for the central bank is that the policy rate should observe a modest rise to check inflation, followed by a prolonged period of accommodative policy.

The GK model features dynamics which cause the financial shock to be deflationary on impact. The fall in banks' net worth leads to the deepest contraction in lending among these models. This is due to the fact that banks' incentive comparability constraint is directly related to banking profits, which are significantly compressed after the shock. Consequently, as bank capital falls, external finance premia rise to the detriment of investment and output. Households lower both consumption and hours worked in the medium term and inflation falls. Thus, the policy rate is lowered in this model in order to support economic activity.

This exercise serves to illustrate the potential for conflicting policy prescription arising from model uncertainty, in particular with respect to the transmission of shocks hitting the economy.[6] It also brings to the foreground the question of whether a better macro-financial performance may be achieved by extending the set of policy instruments to include macroprudential regulations. Since these instruments act directly on banks' balance sheets, they may supplement the interest rate as a means of mitigating the spillovers of financial sector shocks onto the macroeconomy. Further, this illustration of the policymaker's dilemma reveals the importance of characterizing rules that are robust to model uncertainty. These, however, will be predicated on the form of interaction that is assumed between the monetary and macroprudential authorities, as discussed further below.

3 Macroprudential Policy

In this section, we expand the models to incorporate a macroprudential instrument and look at the uncertainty surrounding the transmission of macroprudential policy, which constitutes a highly relevant instrument when financial shocks are a source of macroeconomic fluctuations. We outline our implementation of macroprudential policy in these models and analyze the transmission of a contractionary macroprudential shock. Although here we look exclusively at the capital-to-assets (CTA) ratio, our main results hold as well for the loan-to-value and loan-to-deposits ratios (Binder et al., 2017b).

The motivation for employing the CTA ratio as a macroprudential instrument is to force banks to shore up their balance sheets in order to curb the likelihood of a systemic event in the banking sector – which could result, for instance, following a generalized fall in bank capital. As Hanson et al. (2011) point out, in requiring banks to increase their CTA ratio, it is not *ex ante* clear to what extent they will do so by raising capital versus shedding assets. If banks comply by cutting assets, this would likely have negative macroeconomic effects as the economy would experience a credit crunch, whereas raising bank capital to satisfy regulatory requirements is not expected to be detrimental to growth. This speaks to the importance of accounting for general equilibrium effects in order to correctly appreciate the net benefit of employing the CTA ratio as a macroprudential tool.

3.1 Implementation

Here, we detail the modifications to the models implemented for the analysis of macroprudential policies. Our approach follows Wieland et al. (2012, 2016) in specifying for each model the policy instruments in a way that is both model-consistent and comparable across models.

We seek to modify the models in a minimal way, so that the core structure remains the same as in the original specification, while being able to accurately identify the models' implications for macroprudential policy. Thus, we require that: (i) When macroprudential policy is passive,

[6] The uncertainty with respect to the transmission of financial shocks also applies to other shocks. In the appendix, we show that a technology shock implies substantially different dynamic effects across models as well.

model dynamics must be identical to those of the original. (ii) The non-stochastic steady state of the modified model must be the same as that of the original.[7] (iii) Macroprudential policies should be approximated such that they are unequivocal in their regulatory interpretation. (iv) Macroprudential policies must be comparable between models, both qualitatively and quantitatively. This will allow us to study features of macroprudential policy while taking into account model uncertainty. Our approach follows Wieland et al. (2016) in specifying for each model the policy instruments in a way that is both consistent within models and comparable across models.

Generally speaking, introducing macroprudential instruments into these models implies appending constraints which are not present in the original. In order to incorporate macroprudential policy without affecting the dynamics of the core model, we substitute (in each model) the banks' balance sheet identity with a constraint on the amount of loanable funds at their disposal (i.e., a balance sheet *constraint*). A "link function" is then imposed to connect the macroprudential instrument to banks' balance sheet constraint. The introduction of "auxiliary variables" into banks' balance sheets guarantees that both macroprudential policy requirements and banks' balance sheet constraints are satisfied in equilibrium and capture the idea that macroprudential policy acts directly on financial intermediaries' balance sheets. These auxiliary variables are best understood as the endogenous variations in financial intermediaries' balance sheet items required to meet regulatory requirements.

In what follows we present, for each model, the key equations which determine the structure of financial intermediaries and influence the dynamics of financial sector variables. For ease of reference, we follow the original papers' notation throughout.

Gerali et al. (2010) In modifying the model of Gerali et al. (2010), we follow Angelini et al. (2011, 2014), who introduce a time-varying CTA ratio requirement while appending a specification for loan risk-weights which reflects the counter-cyclical nature of lending risk. Thus, the CTA ratio requirement is modeled as a target ratio of bank capital over risk-weighted assets, deviations from which generate a cost which banks have to cover. Specifically, in the GNSS model, the maximization problem faced by wholesale banks in granting loans and collecting deposits is given by

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

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

where $B = B^H + B^E$ denotes real loans as the sum of household and entrepreneurial loans, D real deposits, R^b the gross interest on loans, R^d the gross interest on deposits and K^b the level of bank capital. Financial intermediaries incur convex increasing costs – determined by the value

[7] This restriction has the implication of keeping the non-stochastic steady state value of the macroprudential instrument model-specific. The models' original parameterizations imply the following CTA steady-state values: GNSS 0.09, MM 0.15 and GK 0.25. Clearly, there is a non-negligible level of variation. However, given that we emphasize mostly percent changes in models' loss functions (as opposed to the level of the loss functions), we prefer to allow for these differences rather than carry out a full reparameterization of the models, which would be necessary to make their steady states perfectly consistent between each other.

of the parameter κ_{K^b} – when their CTA ratio deviates from the exogenously given target level of ν^{CA}. The constraint faced by banks in this setup is the balance sheet identity. The modification implemented in order to account for the effect of CTA requirements makes the capital-to-(risk-weighted-)assets target level a decision variable of the macroprudential authority, possibly following a policy rule. Thus, the banks' optimization problem is altered and specified as follows:

$$\max_{\{\tilde{B}_t, D_t\}} R_t^b B_t - R_t^d D_t - \frac{\kappa_{K^b}}{2}\left(\frac{K_t^b}{\tilde{B}_t} - \nu_t^{CA}\right)^2 K_t^b \tag{3}$$

$$s.t. \quad B_t = D_t + K_t^b \tag{4}$$

where $\tilde{B} = w^E B^H + w^H B^E$ are risk-weighted assets, w^E denotes the risk weight on entrepreneurial loans, w^H is the risk weight on household loans and ν^{CTA} is the time-varying CTA ratio set by the macroprudential authority. The risk-weights are given by

$$w_t^i = (1-\rho_i)\,\bar{w}^i + (1-\rho_i)\,\chi_i\,(Y_t - Y_{t-4}) + \rho_i w_{t-1}^i \quad i = H, E \tag{5}$$

where Y denotes real GDP. The estimation of these rules is reported in Angelini et al. (2014). The solution to this problem yields the following relationship for bank interest rates:

$$R_t^b = R_t^d - \kappa_{K^b}\left(\frac{K_t^b}{\tilde{B}_t} - \nu_t^{CA}\right)\left(\frac{K_t^b}{\tilde{B}_t}\right)^2 \tag{6}$$

We assume that the regulatory constraints hold with equality in equilibrium and that the non-stochastic steady state values ν^{CA} is set such that the values of all the variables are identical to the original model.

Meh and Moran (2010) The model of Meh and Moran (2010) is characterized by a double moral hazard problem; one between entrepreneurs and bankers and one between bankers and investors (households). In equilibrium, both moral hazard problems are solved by means of incentive compatibility and participation constraints being satisfied. Specifically, the loan contract stipulates the provision of funds to finance an investment project with gross return R (if successful) and the allocation of project returns such that it solves the following problem:

$$\max_{\{i_t, a_t, d_t, R_t^e, R_t^b, R_t^h\}} \quad q_t \alpha^g R_t^e i_t \tag{7}$$

$$s.t. \quad q_t \alpha^g R_t^e i_t \geq q_t \alpha^b R_t^e i_t + q_t b i_t \tag{8}$$

$$q_t \alpha^g R_t^b i_t - \mu i_t \geq q_t \alpha^b R_t^b i_t \tag{9}$$

$$q_t \alpha^g R_t^b i_t \geq (1 + r_t^a)\, a_t \tag{10}$$

$$q_t \alpha^g R_t^h i_t \geq \left(1 + r_t^d\right) d_t \tag{11}$$

$$a_t + d_t - \mu i_t = i_t - n_t \tag{12}$$

$$R_t^e + R_t^b + R_t^h = R \tag{13}$$

where i denotes investment in real capital, a the bank's capital or net worth, d the deposits investors place in the bank, n the entrepreneur's net worth, q the price of capital goods, r^a and r^d the net return on bank capital and deposits, respectively, and R^e, R^b and R^h the gross project returns of the entrepreneur, the bank and the investor, respectively. The parameters μ, b, α^g and α^b represent the bank's monitoring costs, the entrepreneur's private benefits from misbehaving, the probability that the project is successful conditional on the entrepreneur behaving, and the probability that the project is successful conditional on the entrepreneur misbehaving, respectively. Thus, equations (8) and (9) represent the entrepreneur and bank's incentive compatability constraints, equations (10) and (11) are the bank and investor's participation constraints, equation (12) represents the banks' balance sheet identity (where μi_t are interpreted as operational costs), and equation (13) implies that all returns are distributed between the relevant parties.

Given this setup, Meh and Moran (2010) show that in equilibrium all constraints hold with equality with the level of investment given by

$$i_t = \frac{a_t + n_t}{G_t} \tag{14}$$

such that i is increasing in bank capital and entrepreneurial net worth and where $1/G$ represents the leverage of the investment project; defined as:

$$G_t \equiv 1 + \mu - \frac{q_t \alpha^g}{1 + r_t^d}\left(R - \frac{b}{\alpha^g - \alpha^b} - \frac{\mu}{q_t\left(\alpha^g - \alpha^b\right)}\right) \tag{15}$$

As stressed by Meh and Moran (2010), this specification implies that leverage is equal across all contracts in the economy. We introduce macroprudential policy in this framework by modifying the financial contract to account for regulatory requirements on the CTA ratio. We introduce an auxiliary variable into the representative bank's balance sheet constraint, which endogenously adjust such that both the balance sheet and regulatory constraints are satisfied. Thus, we substitute the balance sheet identity (12) with the following expression which specifies the loanable funds of the bank (i.e., the bank's balance sheet constraint):

$$\gamma_t^{CA} a_t + d_t - \mu i_t \geq i_t - n_t \tag{16}$$

We can interpret the auxiliary variable γ^{CTA} as standing in for regulatory restrictions on the amount of bank capital that can be used to finance the loan granted to the entrepreneur, $i - n$. This variable is adjusted endogenously such that both banks' balance sheet constraint and regulatory restrictions are satisfied in equilibrium.[8] As in Meh and Moran (2010), all constraints continue to hold with equality and the level of investment is given by:

$$i_t = \frac{\gamma_t^{CTA} a_t + n_t}{G_t} \tag{17}$$

Now, note that because bank assets are given by $i - n$, this expression implies that $1/\gamma^{CTA}$ from equation (17) is approximately the CTA ratio of the bank:

$$\frac{1}{\gamma_t^{CTA}} = \frac{a_t}{G_t i_t - n_t} \approx \frac{a_t}{i_t - n_t} \tag{18}$$

[8] For more stringent regulations, banks are assumed to simply hold their capital and not lend it out, while more lax policies allow banks to leverage their net worth in order to fund more loans.

Thus, we approximate the macroprudential authority's policy regarding the CTA ratio through the link function $\nu^{CTA} = 1/\gamma^{CTA}$, which assures that in equilibrium both the regulatory constraint and the balance sheet identity are satisfied. As above, the non-stochastic steady state values ν^{CTA} is set such that the values of all the variables are identical to those in the original model.

Gertler and Karadi (2011) In the model proposed by Gertler and Karadi (2011) financial frictions are characterized as the result of a moral hazard problem between investors (households) and bankers. Banks obtain funds from investors in order to finance loans to entrepreneurs. The moral hazard problem arises from banker's ability to divert a fraction λ of investors' funds towards their personal accounts, instead of using them to finance investment projects – which is done by purchasing claims offered by entrepreneurs. If funds are diverted by the banker, the financial intermediary is immediately forced into bankruptcy. Gertler and Karadi (2011) study an equilibrium where bankers are induced to behave and investors continue to provide funds to finance investment projects. This is achieved through the following incentive compatibility constraint:

$$v_t Q_t S_t + \eta_t N_t \geq \lambda Q_t S_t \tag{19}$$

where Q is the relative price of claims on entrepreneurs, S are claims on entrepreneurs or banks assets, N is the bank's net worth or capital, v is the marginal gain from expanding assets (holding N constant), and η is the marginal gain of increasing bank capital (holding S constant). Thus, the left hand side of equation (19) represents the gains of the banker from behaving, while the right hand side captures the private benefits from diverting funds. This expression holds with equality in equilibrium and already accounts for banks' balance sheet identity, which is specified as follows:

$$Q_t S_t = N_t + B_{t+1} \tag{20}$$

where B denotes the liabilities of the bank which have to be paid in the next period; that is, deposits held by the household sector. The equilibrium CTA ratio, CA, is given by:

$$CA_t \equiv \frac{N_t}{Q_t S_t} = \frac{\lambda - v_t}{\eta_t} \tag{21}$$

To incorporate macroprudential policy into this model, we proceed in analogous fashion to our strategy employed previously. Specifically, we add as above the variable γ^{CTA} to banker's constraints; it should be interpreted as determining the proportion of bank capital which can be used to fund investment projects. Thus, equation (19) (holding with equality) becomes:

$$v_t Q_t S_t + \gamma_t^{CA} \eta_t N_t = \lambda Q_t S_t \tag{22}$$

The new incentive compatibility constraint contraint implies that in equilibrium, the CTA ratio, $\widetilde{CA}$, is composed of two components: (i) the market-determined component which induces the banker to behave (i.e., $(\lambda - v)/\eta$) and (ii) the regulatory requirement defined as $\nu^{CA} = 1/\gamma^{CA}$:

$$\widetilde{CA}_t = \nu_t^{CA} \frac{\lambda - \upsilon_t}{\eta_t} = \frac{N_t}{Q_t S_t} \tag{23}$$

Thus, in this model, we interpret the macroprudential authority as specifying a capital buffer that banks have to hold in addition to the market-determined level. Again, the non-stochastic steady state value of ν^{CTA} is set such that the values of all the variables are identical to those of the original model.

3.2 The Transmission Mechanism of Macroprudential Policy

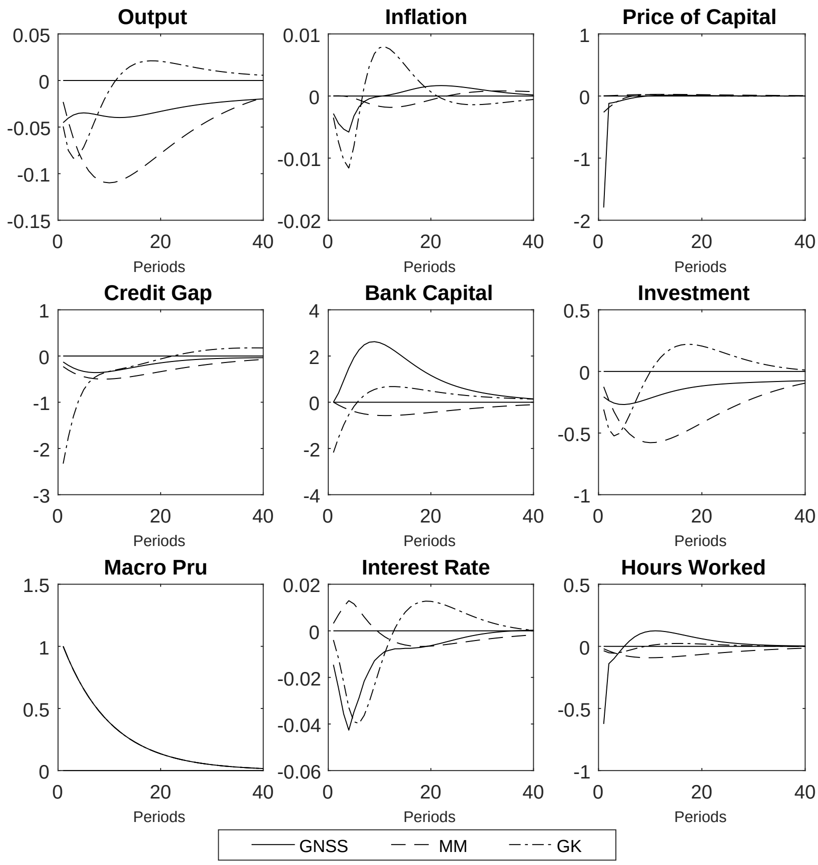
Achieving an efficient design of macroprudential policy requires taking into account not only each instrument's effects on the financial sector, but also on the wider economy and its interaction with monetary policy. While the central bank's interest rate policy can influence the supply of credit through various channels associated with financial frictions, it inevitably also works on macroeconomic variables through more traditional channels. The transmission mechanism of macroprudential policy is distinct in that its instruments act directly and exclusively on financial intermediaries' balance sheets. This, however, leaves much room for overlap and conflicting effects between the corresponding authorities. Hence, this creates the need to disentangle the effects of macroprudential policy from those of monetary policy and to explicitly account for their interaction in designing an efficient macro-financial stability framework.

We analyze the transmission of macroprudential policy by looking at a set of impulse-response functions following an exogenous variation in the CTA ratio, modeled for simplicity as an AR(1) process with an autoregressive coefficient of 0.9. Although macroprudential policy does not follow an autoregressive process in our main analysis and in practice, this exercise serves to build intuition on the workings of the CTA ratio within each model and to identify key features of its interaction with the monetary policy rate that will prove important later on. Our setting accounts furthermore for the general equilibrium effects of such policies on key macroeconomic variables, such as investment and employment. This allows us to discuss questions of complementarity between macroprudential and monetary policy. In all cases, we hold the monetary policy rule constant across models, employing the rule from Orphanides and Wieland (2013). Figure 2 plots the impulse-response functions for a tightening of macroprudential policy, i.e., a one-percent increase in the regulatory requirement on the CTA ratio.

As should be expected, an exogenous increase in the CTA ratio leads to a fall in the credit gap. This is, indeed, one of the desired outcomes of such a policy. However, the specific dynamic responses differ markedly across models. In the GNSS model, banks respond by increasing their capital through retained earnings. As credit is falling, they can only do so by increasing the interest rate on loans (not shown). This depresses both investment and the price of capital, as well as employment. However, the fall in output and investment is attenuated by a decrease in the monetary policy rate which reacts both to the economic slump and falling inflation. In general, this macroprudential shock works similarly to a restrictive monetary policy shock.[9] We can interpret this result as meaning that in the GNSS model, the regulatory requirement on

[9] An important difference is that the response in bank capital never turns negative, as it does in the case of a monetary policy shock.

Figure 2: Transmission of Capital-to-Assets Shock



Note: Impulse response functions for a one-percent tightening of macroprudential policy. The CTA ratio is modeled as an AR(1) process with autoregressive coefficient equal to 0.9. Monetary policy is modeled according to the rule in Orphanides and Wieland (2013). A period is a quarter and all variables are expressed in percentage deviations from their non-stochastic steady state value.

the CTA ratio and monetary policy act as *substitutes*, in the sense that both policy instruments move in *opposite* directions. In this case, we would expect there to be less danger for conflicting policies between the monetary and macroprudential authorities and, potentially, more space for gains in macro-financial stability.

In the case of the MM model, the increase in the CTA ratio does not elicit a marked adjustment in bank capital. The fall in the credit gap is mild, but comes at a large cost in terms of output. This is mainly the result of a persistent fall in investment as the reactions of the price of capital and employment are small. In this case, the macroprudential shock is inflationary and so the central bank responds by increasing the interest rate, which aggravates the fall in output. In this case, macroprudential policy is better understood as a *complement* to monetary policy; both instruments move in the *same* direction, conditional on the macroprudential shock.

Finally, the model of GK implies a strong decrease in the credit gap following the macroprudential shock, with a similar response in bank capital. Along with the deterioration in the banking sector's balance sheets, there is a strong negative response in output and inflation, but it is less persistent than in the MM model. This is due to the shock being deflationary and causing the central bank to ease monetary policy, which supports aggregate demand. The shock does not generate a significant response in the price of capital or employment. Analogous to the GNSS model, the GK model seems to imply that the CTA ratio serves as a *substitute* to monetary policy.

One of the messages that emerges from this analysis is that understanding the interaction between the monetary and macroprudential instruments in a general equilibrium framework is essential for designing an efficient macroprudential policy framework. Specifically, in choosing and specifying macroprudential instruments it is important to clearly identify if they function as complements or substitutes to the monetary policy interest rate, since this will determine the type of coordination which is needed to achieve the dual goals of price and financial stability in an efficient and robust way. Given the wide heterogeneity in terms of transmission mechanisms across models, it seems advisable to consider policies that are robust to model uncertainty.

4 Model-Specific Optimized Macroprudential Policy Rules

In this section, we compute macroprudential policy rules optimized for each of the specific models we consider. Generally speaking, we refer to a policy rule as optimized for model m if its coefficients are the outcome of a policymaker's optimization problem subject to the structure of model m. To that end, we allow the macroprudential authority to operate according to the following policy rule:

$$\nu_t = (1-\rho_\nu)\,\bar{\nu} + \rho_\nu \nu_{t-1} + \chi\,(b_t - y_t)$$

The macroprudential authority sets the CTA ratio ν according to an autoregressive component and in response to the credit gap, which is defined as the difference, $b-y$, between credit b and output y, both expressed in log-deviations from their non-stochastic steady state value. Thus, for $\chi = 1$, the macroprudential authority increases the CTA ratio by one percent in response to an increase in the credit gap of one percent.[10]

We assume that the objective is a loss function following the "revealed-preferences approach" by Angelini et al. (2011, 2014), which posits that the macroprudential authority should be concerned about credit cycles and the volatility of economic activity. These are interpreted as intermediate targets for the regulatory authorities, as lowering such volatilities is deemed to reduce systemic risk. Accordingly, we let the macroprudential authority minimize a loss function consisting of the weighted sum of the variance of the credit gap, σ^2_{b-y}, and the variance of the outputgap, σ^2_x.[11] Furthermore, the variance of the CTA ratio is included in the loss function to exclude rules implying unreasonably volatile policies. The optimization problem of the macroprudential authority, for each model $m \in M$, is hence given by:

[10] In Angelini et al. (2011, 2014), the macroprudential authority responds to the ratio of credit to output. We choose the credit gap instead as it has been identified as a key target variable for conducting rules-based macroprudential policy (German Council of Economic Experts, 2014). It also exhibits much more well-behaved dynamics across all the models in our set. This does not limit the comparability to Angelini et al. (2011, 2014) significantly, since the dynamics of the credit gap and the credit-to-GDP ratio are fairly similar in the Gerali et al. (2010) model.

[11] Minimizing this loss function is not equivalent to maximizing household welfare. In the appendix, we show that the credit gap is not a good proxy for welfare. This can be attributed to the lack of systemic risk and associated welfare gains from financial stability in these types of models. Hence, our analysis should be interpreted as being positive rather than normative. In contrast to Angelini et al. (2011), we nevertheless choose the output gap because it is a better indicator of household welfare than output in standard DGSE models (Debortoli et al., 2017).

$$
\begin{aligned}
\min_{\{\rho_\nu,\chi\}} \quad L_m^{mp} &= \sigma_{b-y}^2 + \lambda_x^{mp}\sigma_x^2 + \lambda_\nu \sigma_{d\nu}^2 \\
s.t. \quad \nu_t &= (1-\rho_\nu)\,\bar{\nu} + \rho_\nu \nu_{t-1} + \chi\,(b_t - y_t) \\
0 &= E_t\left[f_m\left(\boldsymbol{z}_t, \boldsymbol{x}_t^m, \boldsymbol{x}_{t+1}^m, \boldsymbol{x}_{t-1}^m, \boldsymbol{\theta}^m\right)\right]
\end{aligned}
$$

We exclude solutions leading to unstable or multiple equilibria since we consider uniqueness and stability as desireable from a policy perspective. The macroprudential authority is constrained by the model structure, represented by the last line, where $f_m(.)$ denotes equations in model m, z denotes harmonized variables across models, x^m endogenous variables in model m and θ^m model-specific parameters. In particular, the model structure includes the stance of the monetary authority. This requires an assumption about the way how macroprudential authority and monetary authority are interacting, i.e. the institutional regime. We consider two regimes: (i) A *perfect-coordination regime* where the monetary and macroprudential authority set policies simultaneously and aim to minimize a common loss function and (ii) a *Stackelberg* regime where the central bank acts as Stackelberg leader, deciding on a monetary policy rule first, and the macroprudential authority moving second.

Since the solution to this problem depends crucially on the type of shocks and the respective variance-covariance matrix, we take the estimated GNSS model as a benchmark. We recalibrate the variance-covariance matrix of shocks in MM and GK such that (i) the sum of the variance of output and the variance of inflation is roughly equal to that of GNSS, and (ii) the proportion of the 2-year forecast error variance decomposition of financial, macroeconomic and monetary shocks is roughly equal to that of GNSS.[12] We use the 2-year forecast because this is typically considered to be the horizon at which monetary policy seeks to target inflation. The variance of monetary policy shocks is set to zero. The models are solved using a second-order perturbation approach, and the coefficients are computed by employing a global optimization algorithm.

4.1 Perfect-Coordination Regime

A perfect-coordination regime between monetary and macroprudential policy is one in which both authorities set policies simultaneously so as to minimize a common objective function, defined as the *sum* of their individual mandates. The converse case is the *non-cooperation regime*: Each authority aims to fulfill its mandate individually and optimized policy rules consitute the equilibrium outcome of a non-cooperative Nash equilibrium. Angelini et al. (2011, 2014) show that macroeconomic and financial stability is substantially worse in the non-cooperation regime. Furthermore, both the monetary and macroprudential authorities prefer the perfect-cooperation regime over the Nash game. Thus, there are compelling reasons for setting in place institutional structures that induce cooperation among institutions and avoid the non-cooperation outcome.

We hence start by computing the perfect-coordination regime, leading to jointly optimized macroprudential *and* monetary policy rules. The optimization problem is specified as:

[12]In the appendix, we report the results of our exercises, where the standard deviation of bank capital shocks is doubled in each model. This exercise serves to corroborate that our results hold even in a scenario where financial shocks are more prominent relative to other shocks.

$$\begin{aligned}\min_{\{\rho_i,\phi_\pi,\phi_x,\phi_{dx},\rho_\nu,\chi\}} L_m = L_m^{cb} + L_m^{mp} &= \sigma_\pi^2 + \sigma_{b-y}^2 + (\lambda_x^{cb} + \lambda_x^{mp})\sigma_x^2 + \lambda_i \sigma_{di}^2 + \lambda_\nu \sigma_{d\nu}^2 \\ s.t.\ \nu_t &= (1-\rho_\nu)\,\bar{\nu} + \rho_\nu \nu_{t-1} + \chi\,(b_t - y_t) \\ i_t &= \rho_i i_{t-1} + \phi_\pi \pi_t + \phi_x x_t + \phi_{dx}\,(x_t - x_{t-4}) \\ 0 &= E_t\left[f_m\left(\boldsymbol{z}_t, \boldsymbol{x}_t^m, \boldsymbol{x}_{t+1}^m, \boldsymbol{x}_{t-1}^m, \boldsymbol{\theta}^m\right)\right]\end{aligned}$$

The joint objective function consists of the sum of central bank and macroprudential objectives.[13] The central bank aims to minimize the weighted sum of the volatility of inflation, output gap and changes in the nominal interest rate. The latter term penalizes changes in the policy instruments in order to rule out unrealistically volatile policies. The central bank sets the quarterly annualized nominal interest rate i as a response to the lagged interest rate, annual inflation π, the output gap x and annual output gap growth, where all variables are expressed in percentage deviation from their non-stochastic steady state levels. Similar to the CTA ratio, these variables are harmonized across models. We use relative weights $\lambda_x^{cb} = \lambda_x^{mp} = 0.5, \lambda_i = \lambda_\nu = 0.5$ as a baseline.[14] As a benchmark for this exercise, we compute optimized model-specific monetary policy rules with passive macroprudential policy, using the joint loss function as objective. This amounts to a scenario where the central bank is endowed with the macroprudential mandate on top of its mandate of inflation stabilization and is operating according to a standard monetary policy rule.[15] The results are presented in Table 2.

Table 2: Model-Specific Optimized Perfect-Coordination Policy Rules

Model	Macro Pru Policy	Loss L	Standard Deviation			Monetary Policy Rule				Macro Pru Policy Rule	
			π	x	$b-y$	ρ_i	ϕ_π	ϕ_x	ϕ_{dx}	ρ_ν	χ
GNSS	Passive	26.72	1.74	1.68	4.42	0.895	0.198	-0.052	-0.266	-	-
	Active	6.33	1.59	1.25	1.24	0.982	0.117	-0.005	0.038	0.934	0.947
MM	Passive	65.66	3.94	2.51	7.58	0.262	0.793	-0.218	0.403	-	-
	Active	7.22	1.40	0.72	1.28	0.348	1.387	-1.837	1.386	0.836	2.252
GK	Passive	1269.21	3.70	4.27	35.17	0.525	0.476	-0.046	-0.022	-	-
	Active	32.13	1.76	3.47	0.61	0.997	0.003	0.000	-0.008	0.950	9.747

The joint optimization of monetary and macroprudential policies yields significant reductions in the loss in all models. Relative to the passive macroprudential policy benchmark, most of the gains stem from the dampening of credit cycles, but inflation and output gap volatilities are also reduced. This indicates that macroprudential policy is a potent instrument to dampen credit cycles, without interfering with the monetary policy mandate. As such, the perfect-coordination regime strictly dominates the passive macroprudential case, where monetary policy is the only stabilizing force.

[13]This specification implicitly assumes an equal weight of monetary and macroprudential mandate in the joint loss function. In particular, the weight on the credit gap relative to inflation is unity.

[14]Debortoli et al. (2017) show that a unit weight on the output gap relative to inflation approximates household welfare in the canonical medium-scale New Keynesian model by Smets and Wouters (2007). In the appendix, we show that our results continue to hold under a lower overall weight on the output gap assigned solely to the central bank, i.e., $\lambda_x^{cb} = 0.5, \lambda_x^{mp} = 0$. Regarding the penalty terms, Angelini et al. (2011, 2014) use $\lambda_\nu = 0.1$, a value which generates unreasonably volatility policy rules for some of the models in our set, as shown in the appendix.

[15]We thus abstract from any considerations of leaning-against-the wind, i.e., we do not allow the monetary policy authority to respond directly to financial conditions. For an analysis of leaning-against-the-wind monetary policies within the Bayesian model averaging framwork, see Afanasyeva et al. (2016).

The jointly optimized monetary and macroprudential rules are substantially heterogenous across models. In GNSS, both policy rules prescribe relatively modest reactions. As monetary and macroprudential policies are substitutes, monetary policy acts weaker (relative to the passive macroprudential policy case), allowing for a stronger macroprudential policy. Monetary policy is thus geared towards dampening credit cycles. In contrast, the MM model implies complementarity of the instruments and hence leads to more aggressive monetary and macroprudential policies. A strongly countercyclical macroprudential policy performs well in minimizing credit cycles, yet implies a corresponding opposite reaction of monetary policy. As such, both optimal policies need to be designed sufficiently aggressive in order to prevent that they offset each other. In the model by GK, the CTA ratio should be set according to a highly aggressive rule. Interestingly, the optimized central bank stance turns out to be almost passive. This result can be attributed to three factors. First, the model by GK features a sizable volatility of the credit gap *per se*, such that stabilizing credit cycles is the most effective means for lowering losses. This calls for a strong macroprudential policy. Second, there is a strong degree of substitutability of policies in this model, such that macroprudential policy can almost entirely replace monetary policy in stabilizing inflation and output gap. Accordingly, the central bank is geared towards dampening credit cycles by acting almost passively. Third, the macroprudential rules in GK tend to be much more volatile compared to other model, which makes a more aggressive macroprudential stance suboptimal given the penalty term on changes in the instrument.

We now investigate the robustness of model-specific jointly optimized monetary and macroprudential policy rules in other models. Following McCallum (1988), a policy rule is referred to as robust to model uncertainty if it performs well across a range of models. We simulate each of the models using the policy rules optimized for the other two models, respectively. Table 3 shows the percent increase in the loss relative to the loss under the model-specific optimized macroprudential policy rule. By construction, this indicator is zero when using an optimized policy rule in the model it was designed for. In the spirit of Kuester and Wieland (2010), we also report the implied inflation gap premium (IGP), defined as the increase in the standard deviation of inflation relative to the outcome under the model-specific optimized policy rules that is necessary to match the loss under the alternative policy.

Table 3: Robustness of Model-Specific Optimized Perfect-Coordination Policy Rules

		Model		
		GNSS % [IGP]	MM % [IGP]	GK % [IGP]
	GNSS	-	186 [3.66]	191 [7.83]
Rule	MM	1484 [9.69]	-	595 [13.83]
	GK	∞	∞	-

Note: Percent increase in the loss relative to the loss under the model-specific jointly optimized monetary and macroprudential policy rules. The implied inflation gap premium (IGP) is the increase in the standard deviation of inflation relative to the outcome under the model-specific optimized policy that is necessary to match the loss under the alternative policy.

The model-specific jointly optimized rules substantially lack robustness across models. The losses incurred when using "wrong" policy rules in a given model are vast. This can be traced back to the optimized policy rules being highly heterogeneous across models. In particular, the joint rules optimized for GK generate explosive dynamics in the other two models; they imply an almost passive monetary policy authority, which is not sufficient in stabilizing inflation dynamics in the other models. For the GNSS and MM rules, the respective inflation gap premia are very high, i.e., a multiple of the volatility of inflation under optimized rules.

From this exercise, we can derive the following implications of the perfect-coordination regime: (i) A joint optimization of macroprudential and monetary policy is well suited to substantially dampen credit cycles. (ii) This dampening of credit cycles does not interfere with the central bank mandate of inflation and output gap stabilization, but rather supports it. Macroeconomic performance under perfect-coordination thus dominates the passive macroprudential policy case. (iii) The optimized joint rules are highly heterogenous across models, depending on the interaction between both instruments. (iv) Due to their heterogeneity, the perfect-coordination rules are not robust to model uncertainty, featuring cases of unstable equilibria as well as high inflation gap premia when evaluated in other models. (v) In light of model uncertainty, this would advise against the perfect-coordination regime where monetary policy is endowed with a macroprudential mandate.

4.2 Stackelberg Regime

One could suspect that the perfect-coordination regime produces optimized rules not robust to model uncertainty because the setup endows monetary policy with a (too dominant) macroprudential mandate. Following that reasoning, the central bank is inherently geared towards dampening credit cycles, neglecting the traditional mandate of stabilizing inflation and economic activity. As a result, the monetary policy rules are biased toward credit stabilization, featuring unreasonable coefficients that lead to large losses in other models. In the following, we will refute this line of argument by contemplating an alternative regime for the interaction between the two authorities.

We consider a *Stackelberg regime*, as proposed by Galati and Moessner (2013) for the interaction of monetary and macroprudential policy. In this regime, one policymaker decides first upon a policy, and the other authority moves second and takes the decision of the first policymaker as given. De Paoli and Paustian (2013) show that such a leader-follower interaction between monetary and macroprudential policy authorities leads to lower welfare losses relative to non-cooperation under Ramsey policy and committment.[16] For the interaction of monetary and fiscal policy, Lambertini and Rovelli (2003) find that the Stackelberg solution is preferred by each policymaker to the Nash solution, regardless of whether they are the first or the second mover. Thus, the Stackelberg regime can be considered as an intermediate regime between the perfect-coordination and non-coordination.

We analyze a Stackelberg regime where the central bank acts as Stackelberg leader, deciding on a monetary policy rule first, and the macroprudential authority moving second. Given the relatively novel nature of macroprudential policy, this may also be seen as more accurately reflecting the real world, in which monetary policy is already well established. Since the central bank is modeled as the Stackelberg leader, we need to choose an appropriate monetary policy

[16]However, they do not study equilibria in which the authorities commit to a simple rule.

rule for our analysis. In order to strengthen the empirical validity of our results, we assume that the monetary authority operates according to a policy rule that is in line with the observed behavior of the central bank in the Euro Area in the period before the zero lower bound took effect. Specifically, we employ the 1^{st}-difference rule by Orphanides and Wieland (2013) (henceforth OW rule):

$$i_t = i_{t-1} + 0.5\pi_t + 0.5\left(x_t - x_{t-4}\right)$$

Note that the functional form for the monetary policy rule assumed in the perfect-coordination regime nests the OW rule for $\rho_i = 1, \phi_\pi = \phi_{dx} = 0.5, \phi_x = 0$. Taking central bank behavior as given, the macroprudential authority then solves the following optimization problem:

$$\begin{aligned}
\min_{\{\rho_\nu,\chi\}} \; L_m^{mp} &= \sigma_{b-y}^2 + \lambda_x^{mp}\sigma_x^2 + \lambda_\nu \sigma_{d\nu}^2 \\
s.t. \;\; \nu_t &= \left(1-\rho_\nu\right)\bar{\nu} + \rho_\nu \nu_{t-1} + \chi\left(b_t - y_t\right) \\
i_t &= i_{t-1} + 0.5\pi_t + 0.5\left(x_t - x_{t-4}\right) \\
0 &= E_t\left[f_m\left(\boldsymbol{z}_t, \boldsymbol{x}_t^m, \boldsymbol{x}_{t+1}^m, \boldsymbol{x}_{t-1}^m, \boldsymbol{\theta}^m\right)\right]
\end{aligned}$$

The macroprudential authority is hence constrained by the structure of the economy, including the stance of the monetary authority operating according to the OW rule. We again use relative weights $\lambda_x^{mp} = 0.5, \lambda_\nu = 0.5$ in the objective function. For all models, we compute the loss of a completely passive macroprudential authority as a benchmark, that is $\rho_\nu = \chi_\nu = 0$, and the only policy stabilizing the economy being the OW rule. Results are presented in Table 4.

Table 4: Model-Specific Optimized Stackelberg Policy Rules

Model	Macro Pru Policy	Loss L^{mp}	Standard Deviation			Macro Pru Policy Rule	
			π	x	$b-y$	ρ_ν	χ
GNSS	Passive	37.16	1.34	0.73	6.07	-	-
	Active	7.31	1.36	0.77	2.25	0.910	0.892
MM	Passive	183.62	0.81	1.07	13.53	-	-
	Active	8.68	0.78	1.08	1.45	0.786	3.046
GK	Passive	4179.08	0.46	1.04	64.64	-	-
	Active	119.04	0.41	1.14	2.62	0.900	6.131

Note: The rule by Orphanides and Wieland (2013) is used as a common monetary policy rule throughout.

The OW policy rule successfully stabilizes inflation and output gap, confirming the results by Orphanides and Wieland (2013) that this rule performs well across a large range of models in terms of the traditional monetary policy mandate. It is, however, not optimized for the models considered here, in particular not with respect to the macroprudential loss. It is thus not surprising that the OW rule is not well suited to mitigate credit cycles, as evident by the high credit gap volatilities. This underlines the advisability of a separate set of macroprudential policy instruments.

Indeed, active macroprudential policy is able to substantially dampen credit cycles relative to the passive benchmark scenario. If the macroprudential authority operates according to an optimized rule, the credit gap volatility is notably lower in all models. Relative to the perfect-coordination regime, credit cycles are more volatile because the perfect-coordination monetary policy rule is geared to dampen credit cycles. However, it continues to be a stabilizing anchor for inflation and economic activity even in the presence of active macroprudential policy. The volatilities of inflation and output gap are barely altered under active macroprudential policy, indicating minimal interference with the central bank mandate.

The optimized macroprudential policy rules converge somewhat relative to the perfect-coordination regime, but remain largely heterogeneous. In GNSS and GK, the OW rule implies a tougher monetary policy stance than under perfect-coordination. With macroprudential policy being a substitute, the optimized macroprudential rules thus prescribe a more modest reaction relative to the perfect-coordination regime. In contrast, the macroprudential rule in MM is more aggressive in the Stackelberg regime. As macroprudential policy is a complement to monetary policy, the response of macroprudential policy to the credit gap needs to be stronger if there is no coordination among institutions.

Turning to the robustness of model-specific Stackelberg policy rules, we perform the same exercise as before by computing the percent increase in the loss relative to the loss under the model-specific optimized rules. Table 5 shows the results.

Table 5: Robustness of Model-Specific Optimized Stackelberg Policy Rules

		Model		
		GNSS	MM	GK
		% [IGP]	% [IGP]	% [IGP]
	GNSS	-	60 [2.28]	113 [11.62]
Rule	MM	89 [2.54]	-	15 [4.17]
	GK	330 [4.91]	17 [1.23]	-

Note: Percent increase in the loss relative to the loss under the model-specific optimized macroprudential policy rule. The rule by Orphanides and Wieland (2013) is used as common monetary policy rule. The implied inflation gap premium (IGP) is the increase in the standard deviation of inflation relative to the outcome under the model-specific optimized policy that is necessary to match the loss under the alternative policy.

Model-specific optimized macroprudential policy rules in the Stackelberg regime are more robust than the jointly optimized rules under perfect-coordination. None of the rules implies unstable equilibria in other models. This can be attributed to the OW rule, which alone performs well in inducing determinacy and stable equilibria across a wide range of models. However, the losses incurred when using “wrong” macroprudential policy rules in a given model are still substantial.[17] The inflation gap premia remain at a multiple of inflation volatility under optimized rules. Across models, for any given policy rule, the additional credit cycle volatility is highest in the GK model, while the MM model admits non-optimized policy rules without sizable further losses.

The results from model-specific optimized macroprudential policy rules under the Stackelberg regime can thus be summarized as follows. (i) For all models, macroprudential policy is

[17] The lack of robustness would be even higher if the monetary policy authority would operate according to a model-specific policy rule optimized according to its own mandate – instead of the harmonized OW rule. This would consitute an additional degree of heterogeneity in policy rules.

able to achieve substantial decreases of the volatility of the credit gap and macroprudential loss relative to a (non-)optimized monetary policy rule only. (ii) The optimized macroprudential rules remain quite heterogeneous. (iii) Model-specific optimized macroprudential policy do not imply unstable dynamics or multiple equilibria in other models. The OW rule acts as a favorable anchor. (iv) While improving robustness relative to the perfect-coordination regime, the Stackelberg macroprudential rules still imply sizeable inflation gap premia. (v) The lack of robustness of macroprudential policies is thus not solely attributable to the regime of interaction with monetary policy, but stems from model uncertainty with respect to the financial sector. (vi) Against this background, designing macroprudential policy rules robust to model uncertainty seems advisable.

5 Model-Averaged Policy Rules

In this section, we employ a Bayesian model-averaging framework to derive policy rules. This approach, in the context of monetary policy, has been shown by Kuester and Wieland (2010) and Afanasyeva et al. (2016) to provide an effective means for insuring against model uncertainty. We consider both of the regimes analyzed above for the interaction between the monetary and macroprudential authorities. The policymaker's loss function is given by:

$$\mathcal{L} = \sum_{m=1}^{M} \omega_m \left[\frac{\mathcal{L}_m - \min\left(\mathcal{L}_m\right)}{\min\left(\mathcal{L}_m\right)} \right]$$

where ω_m is the Bayesian weight attached to model m, and $\min\left(\mathcal{L}_m\right)$ denotes the value of the loss function $\mathcal{L}_m$ when macroprudential policy is set following the model-specific optimized policy. The policymaker hence minimizes the weighted sum of percent-increase in models' loss functions relative to their model-specific minimum loss, rather than the absolute value of the loss function. This specification has been shown to moderate the influence of loss outliers – i.e., model with high values of the loss function such as the GK model here – on model-averaged policies (Afanasyeva et al., 2016). The constraint set includes the respective model structures and is regime-specific as described in Section 4. We use equal Bayesian weights $\omega_m = 1/M \; \forall m$ for our analysis, both for simplicity and because these are sufficient to illustrate that model-averaged rules can improve robustness substantially.[18] The resulting policy rules are presented in Table 6.

Bayesian model averaging in the perfect-coordination regime calls for a first-difference monetary policy rule. This feature coincides with the interest rate rule by OW assumed in the Stackelberg regime. Monetary policy, in both regimes, reacts more strongly to annual changes in the output gap than to the level of the output gap. Macroprudential policy is prescribed to be highly persistent and strongly countercyclical in both regimes. As these features are common

[18]The issue of how to choose model weights optimally in exercises that require mixing models is a large area of research and closely related to that of model selection. In general, these weights can be assigned according to the Bayesian score or forecasting performance of the models. Doing so, however, would require reestimating all models conditional on a common dataset and is beyond the scope of this paper. For detailed treatments on this topic, see Kapetanios et al. (2006), Del Negro et al. (2016), and Deak et al. (2017). For an approach that is implemented in an application very closely related to our analysis, see Kuester and Wieland (2010).

Table 6: Model-Averaged Optimized Rules

Regime	Monetary Policy Rule				Macro Pru Policy Rule	
	ρ_i	ϕ_π	ϕ_x	ϕ_{dx}	ρ_ν	χ
Perfect Coordination	1.000	0.014	-0.005	0.110	0.914	2.184
Stackelberg	1.000*	0.500*	-	0.500*	0.896	1.883

Note: The monetary policy rule under the Stackelberg regime is not optimized, but specified as the rule by Orphanides and Wieland (2013).

across regimes, one can surmise that they are relatively strict requirements for policies that aim to induce stable dynamics in this class of models.

There is, however, a key difference between the policies prescribed under these regimes. The perfect-coordination regime induces the central bank to actively seek to stabilize the credit gap, relative to the interest rate policy set in the Stackelberg regime. This is clear by comparing the coefficients of the macroprudential policy instruments to those of the Stackelberg regime. The model-averaged macroprudential policy rules are very similar across regimes and may be characterized as hybrid versions of the model-specific counterparts. Accordingly, the shift in policies comes almost entirely from the central bank, which significantly moderates its response to inflation and the annual change in the output gap, and reduces its reaction to the output gap. The reason is that movements in the monetary policy rate elicit strong responses in the credit gap across all models. Thus, to minimize the perfect-coordination loss function, whose largest component is the variance of the credit gap, the monetary authority must become much more passive. While macroprudential policy continues to be countercyclical and persistent, the response of the monetary policy rate to variations in inflation and the output gap is close to zero.

The macro-financial implications of this regime shift can be seen in Table 7, which shows the rules' performance in terms of their losses and the standard deviations of inflation, the output gap and the credit gap. As compared to the Stackelberg regime, it is noteworthy that in every case the standard deviation of inflation and the output gap deteriorates under the perfect-coordination regime. As suggested above, this is due to the fact that monetary policy is now geared towards credit cycle stabilization, rather than exclusively targeting inflation and the output gap. But, whereas the interest rate is a very efficient instrument for macroeconomic stabilization, it is too blunt for financial stabilization. Consequently, only modest gains pertain in terms of credit cycle stabilization, relative to the Stackelberg regime, at the expense of increased macroeconomic volatility. Hence, there is a clear preference on part of the monetary authority for the Stackelberg regime over the perfect-coordination regime. The macroprudential authority, on the other hand, will prefer the perfect-coordination regime. In terms of robustness, the Bayesian rules derived under the Stackelberg regime prove to be more robust than those of the perfect-coordination regime; as was the case for the model-specific optimized rules. While the perfect-coordination regime leads to an increase in the Bayesian loss of 31.53 percent, this figure is only 20.10 percent in the Stackelberg regime.

Overall, the performance of Stackelberg policy rules is notably good across models. This is clear from the standard deviations of the main components of the macroprudential authority's

Table 7: Performance of Model-Averaged Optimized Rules

Perfect Coordination

Model	Loss L		Standard Deviation		
	%	IGP	π	x	$b-y$
GNSS	26.65	1.30	1.88	1.53	0.79
MM	36.49	1.62	0.98	1.10	1.54
GK	31.46	3.18	1.57	3.00	3.22
Average	31.53	2.19	1.48	1.88	1.85

Stackelberg

Model	Loss L^{mp}		Standard Deviation		
	%	IGP	π	x	$b-y$
GNSS	28.23	1.44	1.36	0.80	1.81
MM	8.31	0.85	0.78	1.08	1.86
GK	23.74	5.32	0.41	1.12	7.73
Average	20.10	3.22	0.85	1.00	3.80

loss function. Indeed, it is remarkable that the dynamics of inflation and the output gap are maintained in check, relative to the passive macroprudential policy case reported in Table 4, while the standard deviation of the credit gap is also effectively stabilized. The standard deviation of inflation exhibits a maximum value of only 1.36 percent in the GNSS model and that of the output gap a level of 1.12 percent in the GK model; both should be interpreted as very sound from the central bank's perspective. Further, in all cases, the standard deviation of the credit gap is substantially reduced with respect to the passive macroprudential case. The standard deviation of the credit gap is lower in all cases under the perfect-coordination regime, but not greatly different from the Stackelberg case. Thus, the model-averaged rule under the Stackelberg regime suggests that moderately countercyclical and persistent macroprudential policies can be efficient in stabilizing the credit gap while effectively insuring against model uncertainty.

In conclusion, these results show that (i) model-averaged macroprudential policy rules can serve as a very constructive and effective supplement to monetary policy by stabilizing the credit gap without disrupting the dynamics of inflation and the output gap. (ii) Under the Stackelberg regime, we find that monetary policy rule of Orphanides and Wieland (2013) is a good benchmark for central banks. Under model-averaging, the Stackelberg regime produces better inflation dynamics without significantly increasing the standard deviation of the credit gap. (iii) In this context, model-averaged rules for both macroprudential and monetary policy can further insure against model uncertainty.

6 Conclusion

In this paper, we employ three state-of-the-art DSGE models that explicitly model banks and show that these models imply vastly different dynamic properties due to their heterogeneity in modeling the role of banks' balance sheets for the business cycle. We augment each model by including macroprudential policy operating according to a policy rule for the capital-to-assets ratio. Given that these instruments act directly on banks' balance sheets, they may supplement the interest rate as a means of mitigating the spillovers of financial sector shocks onto the macroeconomy. Against the backdrop of the elevated uncertainty, we then analyze the performance and features of optimized macroprudential policy rules both within and across models. As regards to the interaction of macroprudential and monetary policy, we consider both a perfect-coordination and a Stackelberg regime.

Our main results indicate that a perfect-coordination regime between monetary and macroprudential policy is well suited to dampen credit cycles without interfering with the central bank mandate. However, the optimized joint rules are highly heterogeneous across models and thus lack robustness to model uncertainty in the spirit of McCallum (1988), implying vastly suboptimal performance in other models. In contrast, a Stackelberg regime – with the monetary policy moving first – model-specific optimized policies imply smaller potential costs due to model uncertainty than those under the perfect-coordination regime. If the central bank operates according to the rule by Orphanides and Wieland (2013), it acts as a stabilizing anchor and is able to induce determinacy and stability in the set of financial frictions models considered. The Stackelberg regime also yields less volatile inflation dynamics than a perfect-coordination regime, without significantly increasing the standard deviation of the credit gap.

Against this background, policymakers following macroprudential rules based on one particular model risk destabilizing the macroeconomy. Designing macroprudential policy rules robust to model uncertainty seems highly advisable. Indeed, we show that optimized policy rules derived by means of Bayesian model averaging can further insure against model uncertainty in either of the two regimes. The Stackelberg model-averaged optimized rules produce superior inflation dynamics without significantly increasing the standard deviation of the credit gap. In the context of model uncertainty, model-averaged policies under a Stackelberg regime thus appear to be an effective means to insure against model uncertainty. The best-performing model-averaged optimized macroprudential policy rule appears to be moderately countercyclical and highly persistent, yielding a low credit-gap-based loss while achieving stable dynamics in inflation and the output gap.

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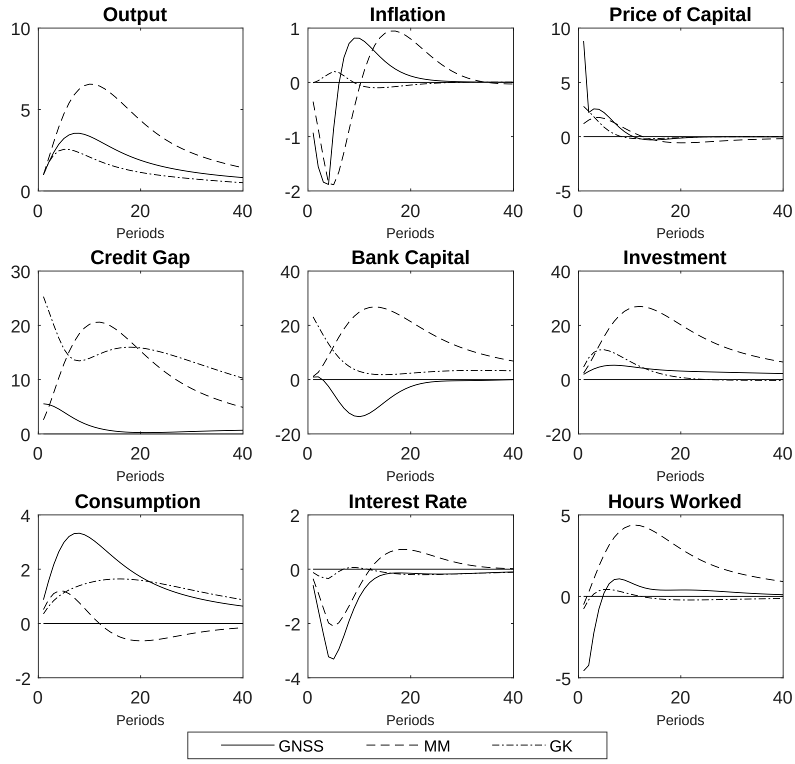
Appendix

A Impulse Response Functions for Productivity Shocks

In this section, we look at the degree of uncertainty in macroeconomic and financial variables' dynamic response to productivity shocks that is accounted for by model uncertainty. Figure A1 plots the impulse-response functions for a positive technology shock that leads to a one-percent increase *on impact* in output in all models. The monetary policy interest rate rule is kept constant across all models and is specified as in Orphanides and Wieland (2013).

Figure A1: Productivity Shock



Note: Impulse response functions for productivity shock that causes a one-percent immediate increase in output. Monetary policy is modeled according to the rule in Orphanides and Wieland (2013). A period is a quarter and all variables are expressed in percentage deviations from their non-stochastic steady state value.

The graphs show significant differences between models in the response of macroeconomic and financial variables to the shock. In all models, the policy response following the shock is characterized by a decrease in the interest rate. This follows due to a drop in the output gap (not shown), as the productive capacity of the economy is significantly expanded. This, in turn, puts downward pressure on inflation. The medium term implications for output vary widely across models. In the GNSS model, the peak response of output is around three percent. In contrast to the models of MM and GK, this expansion is mostly driven by a strong increase in the consumption of households, who experience a significant wealth effect. Consequently, hours worked fall. Investment and the price of capital rise. The increase in investment is accompanied by a rise in the credit gap, but – in contrast to other models – banks draw down their capital in order to reach their capital-to-assets ratio target.

The MM model features the largest peak response of output at over five percent. In this case, the economic boom leads to a marked, hump-shaped increase in investment, credit and bank capital. The shock is deflationary in a similar magnitude to the GNSS model, but the responses of household consumption and the price of capital are more moderate. In this model, however, hours worked increase substantially due to a strong increase in wages (not shown).

Finally, the peak response of output is smallest in the GK model. Although in neither investment nor consumption are the model's responses the weakest, they are in both cases mild. These mild responses contrast further with those of the GNSS and MM models due to the shallow response of the interest rate to the shock. Since the shock is not strongly deflationary, the interest rate need not fall by much. Hours worked are largely unchanged. Banking sector variables, however, respond strongly to the shock. Both the credit gap and bank capital exhibit peak responses of over twenty percent, but in contrast to the GNSS and MM models, the peak occurs immediately after the shock.

Similar to the bank capital shock considered in the main part, the general equilibrium effects and policy prescriptions differ markedly across models, as the propagation mechanism of technology shocks is quite different between models. This model uncertainty can be mainly attributed to the financial sectors, which propagate the shock differently. Accordingly, the potential for conflicting policy prescriptions due to model uncertainty in these banking DSGE models arises as well in the face of non-financial shocks.

B Optimal Simple Mandate

For our main analysis, we follow Angelini et al. (2011, 2014) by employing a loss function for the macroprudential authority consisting of the variance of the credit gap and the weighted variance of the output gap. While this approach can be justified by revealed preferences of macroprudential regulation, it could be argued that it is not equivalent to maximizing household welfare - which should be the relevant objective of optimal policy. To investigate this issue, we derive the *optimal simple mandates* for each model, broadly following Debortoli et al. (2017). We define an optimal simple mandate for model $m \in M$ as the set $\{\lambda_x, \lambda_{b-y}\}$ which solves the following problem:

$$
\begin{aligned}
\max_{\{\lambda_x, \lambda_{b-y}\}} \quad W^m &= V^m(\boldsymbol{x}_t^m, \boldsymbol{x}_{t+1}^m, \boldsymbol{x}_{t-1}^m, \boldsymbol{\theta}^m) \\
s.t. \quad i_t &= \rho_{cb} i_{t-1} + \phi_\pi \pi_t + \phi_x x_t + \phi_{dx} (x_t - x_{t-4}) \\
\{\rho_{cb}, \phi_\pi, \phi_x, \phi_{dx}\} &= \text{arg min } L^m = \sigma_\pi^2 + \lambda_x \sigma_x^2 + \lambda_{b-y} \sigma_{b-y}^2 \\
0 &= E_t \left[f_m \left(\boldsymbol{z}_t, \boldsymbol{x}_t^m, \boldsymbol{x}_{t+1}^m, \boldsymbol{x}_{t-1}^m, \boldsymbol{\theta}^m \right) \right]
\end{aligned}
$$

In other words, the optimal simple mandate is the set of weights in a simplified ad-hoc loss function that maximizes household welfare, conditional on the monetary policy authority following policy rules optimized to minimize the resulting loss functions. We restrict the optimal simple mandate to the variances of inflation and output gap, consistent with the results of Rotemberg and Woodford (1999) and Debortoli et al. (2017), but allow for an additional mandate of financial stability in terms of stabilizing the volatility of the credit gap. We abstract from the volatility of the policy instruments as additional terms in the objective function, as they serve as penalty terms for rules implying unrealistically volatile policies rather than as an approximation of welfare. The weight on inflation is normalized to one. Table A1 reports the optimal simple mandates as well as the optimal dual mandate ($\lambda_{b-y} = 0, \lambda_x > 0$) and the optimal financial stability mandate ($\lambda_{b-y} > 0$) as a comparison.

Table A1: Optimal Simple Mandates

Model	Simple Mandate		Dual Mandate		Financial Stability Mandate	
	λ_x	λ_{b-y}	λ_x	λ_{b-y}	λ_x	λ_{b-y}
GNSS	0	0.1	0.7	-	0	0.1
MM	0	0	0.3	-	0	0.6
GK	0	0	0.1	-	0.3	0.7

As evident from the table, the optimal simple mandates feature a strong mandate for inflation targeting, while stabilization of output gap and credit gap is of minor importance for welfare. With the exception of GNSS, all models favor the central bank only caring about price stability. In GNSS, the central bank should additionally put a relatively small weight on credit gap volatility. The optimal dual mandates are broadly in line with Debortoli et al. (2017), in that they feature a significantly higher weight on the output gap relative to the canonical small-scale variant of Rotemberg and Woodford (1999), where the weight is approx. 0.048. In particular, the highest optimal value for the output gap is found in GNSS, which is explicable by its large set of shocks. The financial stability mandate favors zero weight on the output gap for GNSS and MM, but a unity weight in GK divided on output and credit gap.

The results from this exercise indicate that using monetary and macroprudential objective functions based on the "revealed-preferences" approach is not equivalent to welfare-maximizing policymakers in the three models we employ. We interpret this as a sign that current state New Keynesian DSGE models incorporating banks do not account for the potentially large welfare costs of excessive credit cycles sufficiently well enough, in particular because they do not feature systemic risk and bank failures. Especially against the backdrop of model uncertainty with respect to the modelling of the financial sector, maximizing welfare is thus equivalent to quite distinct monetary and macroprudential mandates. While the profession converges toward a consensus model incorporating systemic risk, it is thus advisable to rely on the positive "revealed-preferences-approach" to derive an objective function for monetary and macroprudential authorities in the presence of financial frictions.

C Lower Macroprudential Weight on Output Gap

In our main analysis, we use an overall unit weight on the output gap relative to inflation and the credit gap. This can be motivated by the findings of Debortoli et al. (2017), who show that a unit weight on the output gap relative to inflation approximates household welfare in the canonical medium-scale New Keynesian model by Smets and Wouters (2007). Here, we show that our results continue to hold under a lower overall weight on the output gap assigned solely to the central bank, i.e., $\lambda_x^{cb} = 0.5, \lambda_x^{mp} = 0$. The objective functions are given as before:

$$L_m^{mp} = \sigma_{b-y}^2 + \lambda_x^{mp}\sigma_x^2 + \lambda_\nu \sigma_{d\nu}^2$$

$$L_m^{cb} = \sigma_\pi^2 + \lambda_x^{cb}\sigma_x^2 + \lambda_i \sigma_{di}^2$$

Tables A2 and A3 show the results. Relative to the baseline case, monetary policy is slightly more geared towards inflation stabilization in the perfect-coordination regime, most notably in the GK model. We may take this as a sign that the lower overall weight on the output gap is equivalent to a less severe trade-off between inflation and output gap stabilization for the central bank. The macroprudential policy rules are remarkably similar compared to the case with a positive macroprudential weight on the output gap. This indicates that the macroprudential authority is not facing a significant trade-off between output gap and credit gap stabilization. As the overall results are very close to the baseline case, we interpret this as evidence that the lack of robustness of model-specific optimized rules is not attributable to the specification of the macroprudential loss function.

Table A2: Model-Specific Optimized Perfect-Coordination Policy Rules With Lower Macroprudential Weight On Output Gap

Model	Macro Pru Policy	Loss L	Standard Deviation			Monetary Policy Rule				Macro Pru Policy Rule	
			π	x	$b-y$	ρ_i	ϕ_π	ϕ_x	ϕ_{dx}	ρ_ν	χ
GNSS	Passive	25.64	1.89	1.49	4.58	0.894	0.199	−0.059	−0.271	-	-
	Active	5.48	1.62	1.35	1.14	0.976	0.125	−0.003	−0.045	0.937	0.970
MM	Passive	70.54	3.85	2.73	7.20	0.596	0.459	−0.161	0.482	-	-
	Active	7.19	1.27	0.71	1.29	0.971	1.248	−2.592	1.923	0.859	2.297
GK	Passive	1260.48	3.70	4.28	35.18	0.525	0.476	−0.046	−0.020	-	-
	Active	25.87	1.85	3.67	0.59	0.888	0.112	−0.002	−0.099	0.983	9.999

Table A3: Model-Specific Optimized Stackelberg Policy Rules With Lower Macroprudential Weight On Output Gap

Model	Macro Pru Policy	Loss L^{mp}	Standard Deviation			Macro Pru Policy Rule	
			π	x	$b-y$	ρ_ν	χ
GNSS	Passive	36.90	1.34	0.73	6.07	-	-
	Active	7.01	1.36	0.77	2.25	0.910	0.896
MM	Passive	183.05	0.81	1.07	13.53	-	-
	Active	8.11	0.78	1.08	1.40	0.776	3.267
GK	Passive	4178.53	0.46	1.04	64.64	-	-
	Active	118.39	0.42	1.14	2.62	0.899	6.136

Note: The rule by Orphanides and Wieland (2013) is used as a common monetary policy rule throughout.

D Lower Penalty Terms on Instrument Volatility

We employ relative weights $\lambda_i = 0.5, \lambda_\nu = 0.5$ in the objective functions of monetary and macroprudential authorities which are (for model $m \in M$) given by:

$$L_m^{mp} = \sigma_{b-y}^2 + \lambda_x^{mp}\sigma_x^2 + \lambda_\nu \sigma_{d\nu}^2$$

$$L_m^{cb} = \sigma_\pi^2 + \lambda_x^{cb}\sigma_x^2 + \lambda_i \sigma_{di}^2$$

Angelini et al. (2011, 2014) use $\lambda_\nu = \lambda_i = 0.1$. We restricted the response of macroprudential instruments to a maximum permissible tightening of ten percent following changes in the credit gap. We believe that this constitutes a reasonable upper bound on the feasible strength of countercyclical macroprudential regulation. As evident from Table A4 and Table A5, the weights of Angelini et al. (2011, 2014) generate unreasonably volatility policy rules in the model by Gertler and Karadi (2011) in both regimes of interaction. We thus conclude that this set of weights does not constitute a sufficient penalty in the objective functions such that the optimization yields reasonable policies for all models. For our main analysis, we thus choose $\lambda_i = 0.5, \lambda_\nu = 0.5$ as relative weights in the loss functions of monetary and macroprudential authority, respectively.

Table A4: Model-Specific Optimized Perfect-Coordination Policy Rules With Lower Instrument Volatility Penalty

Model	Macro Pru Policy	Loss L	Standard Deviation			Monetary Policy Rule				Macro Pru Policy Rule	
			π	x	$b-y$	ρ_i	ϕ_π	ϕ_x	ϕ_{dx}	ρ_ν	χ
GNSS	Passive	26.67	1.74	1.68	4.42	0.885	0.208	−0.056	−0.307	-	-
	Active	5.37	1.54	1.15	1.08	0.981	0.157	−0.011	0.125	0.897	2.094
MM	Passive	70.25	3.94	2.51	7.58	0.005	0.864	−0.411	−0.403	-	-
	Active	3.10	1.01	0.74	0.44	0.298	0.699	−0.201	0.357	0.925	8.193
GK	Passive	1269.01	3.70	4.27	35.17	0.525	0.476	−0.046	−0.022	-	-
	Active	15.72	1.28	2.60	0.82	1.000	0.000	0.000	0.065	0.962	10.000

Table A5: Model-Specific Optimized Stackelberg Policy Rules With Lower Instrument Volatility Penalty

Model	Macro Pru Policy	Loss L^{mp}	Standard Deviation			Macro Pru Policy Rule	
			π	x	$b-y$	ρ_ν	χ
GNSS	Passive	37.16	1.34	0.73	6.07	-	-
	Active	4.72	1.36	0.80	1.75	0.878	2.079
MM	Passive	183.62	0.81	1.07	13.53	-	-
	Active	2.88	0.78	1.07	0.65	0.850	7.174
GK	Passive	4179.08	0.46	1.04	64.64	-	-
	Active	26.54	0.42	1.14	1.54	0.952	10.000

Note: The rule by Orphanides and Wieland (2013) is used as a common monetary policy rule throughout.

E Larger Volatility of Financial Shocks

In this section, we verify that our main results hold under a larger variance of financial shocks. We do so given that the variance-covariance matrix of shocks for the Gerali et al. (2010) model, which served as a benchmark in our quantitative exercises, was estimated for the pre-crisis period. However, as described in Section 1, macroprudential policy has become particularly relevant *after* the Great Financial Crisis. In this new environment, one might wish to assess the constructive nature of new policy rules while attributing a greater relevance to financial shocks. We do so by deriving the model-specific policy rules, under both the perfect-coordination and the Stackelberg regime, while doubling the model-specific standard deviation of bank capital shocks in all models. The results are presented in the tables below. It can be seen that all the qualitative results from model-specific optimal policy continue to hold, which also carries over to the respective robust exercise.

Table A6: Model-Specific Optimized Perfect-Coordination Policy Rules With Large Financial Shocks

Model	Macro Pru Policy	Loss L	Standard Deviation			Monetary Policy Rule				Macro Pru Policy Rule	
			π	x	$b-y$	ρ_i	ϕ_π	ϕ_x	ϕ_{dx}	ρ_ν	χ
GNSS	Passive	46.28	2.23	1.51	6.24	0.872	0.025	-0.319	0.083	-	-
	Active	7.52	1.63	1.37	1.35	1.000	0.001	0.000	0.180	0.952	1.130
MM	Passive	200.28	3.67	4.88	12.76	0.222	0.709	-0.160	0.222	-	-
	Active	18.46	1.46	0.83	2.39	0.000	2.243	-2.816	1.629	0.864	2.064
GK	Passive	1394.97	3.81	4.29	36.90	0.525	0.476	-0.046	-0.009	-	-
	Active	34.03	1.74	3.45	1.01	0.940	0.060	0.000	-0.049	0.848	7.854

Table A7: Model-Specific Optimized Stackelberg Policy Rules With Large Financial Shocks

Model	Macro Pru Policy	Loss L^{mp}	Standard Deviation			Macro Pru Policy Rule	
			π	x	$b-y$	ρ_ν	χ
GNSS	Passive	72.97	1.36	0.85	8.52	-	-
	Active	8.33	1.37	0.92	2.31	0.910	0.892
MM	Passive	507.91	0.81	1.08	22.52	-	-
	Active	20.92	0.78	1.08	2.54	0.831	2.436
GK	Passive	4250.01	0.47	1.04	65.19	-	-
	Active	120.95	0.42	1.14	2.65	0.900	6.129

Note: The rule by Orphanides and Wieland (2013) is used as a common monetary policy rule throughout.