Monetary and macro-prudential policy: Model comparison and robustness [†]

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Abstract

The global financial crisis and the ensuing criticism of macroeconomics have inspired researchers to explore new modeling approaches. There are many new models that aim to better integrate the financial sector in business cycle analysis and deliver improved estimates of the transmission of monetary policy. In order to design effective policies policy making institutions need to compare available models of policy transmission and evaluate the impact and interaction of policy instruments. This paper proposes a framework for comparative analysis of macro-financial models and presents new tools and applications. It builds on and extends recent work on model comparison in the area of monetary and fiscal policy. The computational implementation enables individual researchers to conduct systematic model comparisons and policy evaluations easily and at low cost. It also contributes to improving reproducibility of computational research in macroeconomic modeling. An application presents comparative results concerning the dynamics and policy implications of different macro-financial models. These models account for financial accelerator effects in investment financing, credit and house price booms and a role for bank capital. Monetary policy rules are found to have an important influence on the comparisons. Finally, an example concerning the impact of leaning against credit growth in monetary or macro-prudential policy is discussed.

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1 Introduction

The global financial crisis and the ensuing criticism of macroeconomics have inspired researchers to explore new modeling approaches. There are many new models that aim to better integrate the financial sector in business cycle analysis and deliver improved estimates of the transmission of monetary policy. At the same time, failures in regulatory oversight, banking supervision and monetary policy prior to the crisis have triggered the development of new instruments for policy practice. Impact and channels of transmission of these macroprudential instruments remain imperfectly understood and subject to modeling as well as estimation uncertainty. Central bankers and regulatory authorities are already in a position to use these instruments. Yet, in order to design effective policies they need to compare available models of policy transmission and evaluate the impact and interaction of macro-prudential and monetary policy instruments.

This paper proposes a framework for comparative analysis of macro-financial models and presents new tools and applications. It builds on and extends recent work on model comparison by Taylor and Wieland (2012), Wieland et al. (2012) and Schmidt and Wieland (2013). These studies focused on monetary and fiscal policy. They led to the creation of an on-line macroeconomic model archive together with a computational platform for model comparison.[1]

Model comparison has a long tradition in the field of monetary policy.[2] Taylor (1993a), for example, credits the comparison project summarized in Bryant et al. (1993) as the crucial testing ground for what later became known as the Taylor rule. Most recently, model comparison efforts have focused on evaluating the impact of fiscal policy when monetary policy is constrained at the zero-lower-bound on nominal interest rates (cf. Cogan et al. (2010), Coenen et al. (2012)). Coenen et al. (2012), for example, report on a comparison project that was initiated by the International Monetary Fund. It involved 17 authors who employed 9 different macroeconomic models developed and simulated by authors from institutions such as the International Monetary Fund, the Federal Reserve Board, the Bank of Canada, the OECD, the European Commission and the European Central Bank.

An advantage of the model comparison approach presented in this paper is that it enables individual researchers to conduct systematic model comparisons and policy evaluations easily and at low cost. Furthermore, it is straightforward to include new models and compare their empirical and policy implications to a large number of established benchmark models from academia and policy-making institutions.

First, we briefly review formally how to derive comparable objects/implications from different models. The models have to be augmented with a space of common comparable

[1] The model archive and software are available for download at www.macromodelbase.com.

[2] See Bryant et al. (1988), Bryant et al. (1989), Klein (1991), Bryant et al. (1993), Taylor (1999), Hughes-Hallett and Wallis (2004).

variables, parameters and shocks. Common policy rules are defined as functions of common variables, policy parameters and policy shocks. Then it is possible to derive comparable objects such as impulse response functions to a policy shock.

Secondly, we discuss some practical issues in conducting model comparisons. For example, it needs to be assured that the models employed correspond to those of the original authors. Unfortunately, there is no generally accepted standard that would guarantee that models described in economic journals can be replicated. Furthermore, different authors utilize different model solution methods based on different computer languages and different operating systems. We briefly report on the strategy used to deal with these problems on a practical level and make some suggestions how replicability and comparability could be improved in the future. In addition, we present features implemented in the new release of the comparison software MACROMODELBASE2.0 that help make model simulation and comparison more accessible to researchers, practitioners and students. At this point, more than 5700 users have registered their e-mail address for downloading the software from the MMB website.

Thirdly, we describe key characteristics of models with more detailed representations of the financial sector that have been newly included in the model archive and comparison software. These models typically integrate financial frictions into a New Keynesian dynamic stochastic general equilibrium framework. The DSGE approach to macroeconomic modeling has been heavily criticized and blamed for leading economists to underestimate the risks from excessive credit growth and the need for tighter regulation and monetary policy prior to the global financial crisis (cf. Buiter, Krugman, Borio). Nevertheless, it has been very fruitful in terms of generating new macro-financial models.

In a fourth step, we proceed to conduct a range of simulations to show how MACROMODELBASE2.0 can be used to investigate the role of the financial sector in the transmission of macroeconomic shocks to the economy as a whole in different modeling structures. The extent of quantitative differences and model uncertainty is illustrated with a comparison of the effects on aggregate output and inflation in the different macro-financial models. We also consider the consequences of monetary policy shocks and the implications of different monetary policy rules. Finally, we explore the interaction of monetary and macro-prudential policy, and the consequences of leaning against credit growth in an example.

The formal setup is presented in section 2. Section 3 deals with some practical issues in preparing comparisons. Section 4 reviews the macro-financial models. Comparative simulation results are presented in sections 5 and 6. Section 7 concludes.

2 Comparing policy implications from different models

Model comparisons aim to identify policy implications that are due to different structural features of these models. Yet, quantitative simulation results may also differ because the economic concepts and variables to be compared are not defined consistently across models. Furthermore, different outcomes may be due to different assumptions about policy rather than different structures of the economy. In this section, we briefly describe how macroeconomic models can be augmented with a few equations to produce comparable output concerning policy implications for key macroeconomic aggregates, while keeping the total number of modifications quite small.

Notation for a general nonlinear model.

The following notation is used to define a general nonlinear model of the economy. The superscript $m = (1, 2, 3, ..., M)$ denotes the equations, variables, parameters and shocks of a specific model m that is to be included in the comparison. These model-specific objects need not be comparable across models. They are listed in **Table 1**. In the computational implementation m corresponds to an abbreviated model name rather than simply a number.

Table 1: Model-Specific Variables, Parameters, Shocks and Equations

Notation	Description
x_t^m	endogenous variables in model m
$x_t^{m,g}$	policy variables in model m (also included in x_t^m)
η_t^m	policy shocks in model m
ε_t^m	other economic shocks in model m
$g_m(.)$	policy rules in model m
$f_m(.)$	other model equations in model m
γ^m	policy rule parameters in model m
β^m	other economic parameters in model m
Σ^m	covariance matrix of shocks in model m

Two types of model equations are distinguished. Policy rules are denoted by $g_m(.)$ while all other equations and identities are denoted by $f_m(.)$. Together, they determine the endogenous variable denoted by the vector x_t^m. These variables are functions of each other, of model-specific shocks, $[\varepsilon_t^m \quad \eta_t^m]$, and of model-specific parameters $[\beta^m \quad \gamma^m]$. A particular model m is then defined by:

$$E_t[g_m(x_t^m, x_{t+1}^m, x_{t-1}^m, \eta_t^m, \gamma^m)] = 0 \quad (1)$$

$$E_t[f_m(x_t^m, x_{t+1}^m, x_{t-1}^m, \varepsilon_t^m, \beta^m)] = 0 \quad (2)$$

The superscript m refers to the version of the respective model originally presented by its authors. The model may include current values, lags and the expectation of leads of endogenous variables. In equations (1) and (2) the lead- and lag-lengths are set to unity for notational convenience. Additional leads and lags can be accommodated with auxiliary variables. Even so, our software implementation does not restrict the lead- and lag-lengths of participating models.

The model may also include innovations that are random variables with zero mean and covariance matrix, Σ^m:

$$E([\eta_t^m \varepsilon_t^m]') = 0 \tag{3}$$

$$E([\eta_t^{m\prime} \varepsilon_t^{m\prime}]'[\eta_t^{m\prime} \varepsilon_t^{m\prime}]) = \Sigma^m = \begin{pmatrix} \Sigma_\eta^m & \Sigma_{\eta\varepsilon}^m \\ \Sigma_{\eta\varepsilon}^m & \Sigma_\varepsilon^m \end{pmatrix} \tag{4}$$

We refer to innovations interchangeably as shocks. Some models include serially correlated economic shocks that are themselves functions of random innovations. In our notation, such serially correlated economic shocks would appear as elements of the vector of endogenous variables x_t^m and only their innovations would appear as shocks. Equation (4) distinguishes the covariance matrices of policy shocks and other economic shocks as Σ_η^m and Σ_ε^m. The correlation of policy shocks and other shocks is typically assumed to be zero, $\Sigma_{\eta\varepsilon}^m = 0$.

Introducing common variables, parameters, equations and shocks.

In order to compare policy implications from different models, it is necessary to define a set of comparable variables, shocks and parameters. They are common to all models considered. Policies can then be expressed in terms of such common parameters, variables and policy shocks, and their consequences can be calculated for a set of common endogenous variables. Our notation for comparable endogenous variables, policy instruments, policy shocks, policy rules and parameters is given in **Table 2**.

Table 2: Comparable Common Variables, Parameters, Shocks and Equations

Notation	Description
z_t	common variables in all models
z_t^g	common policy variables in all models (also included in z_t)
η_t	common policy shocks in all models
$g(.)$	common policy rules
γ	common policy rule parameters

Every model to be included in the comparison has to be augmented with common variables, parameters and shocks. Augmenting the model requires adding some equations.These additional equations serve to define the common variables in terms of model-specific variables. We denote these definitional equations or identities by $h_m(.)$. They are necessarily model-specific. Additionally, the original model-specific policy rules need to be replaced with the common policy rules. All the other equations, variables, parameters and shocks may be preserved in the original notation of the model authors. Consequently, the augmented model consists of three components: (i) the common policy rules, $g(.)$, expressed in terms of common variables, z_t, policy shocks, η_t, and policy parameters, γ; (ii) the model-specific definitions of common variables in terms of original model-specific endogenous variables, $h_m(.)$, with parameters θ^m; (iii) the original set of model-specific equations $f_m(.)$ that determine the endogenous variables. It corresponds to:

$$E_t[g(z_t, z_{t+1}, z_{t-1}, \eta_t, \gamma)] = 0 \quad (5)$$

$$E_t[h_m(z_t, x_t^m, x_{t+1}^m, x_{t-1}^m, \theta^m)] = 0 \quad (6)$$

$$E_t[f_m(x_t^m, x_{t+1}^m, x_{t-1}^m, \varepsilon_t^m, \beta^m)] = 0 \quad (7)$$

Models augmented accordingly are ready for comparing policy implications. For example, it is then straightforward to compare the consequences of a particular policy rule for the dynamic behavior of consistently defined endogenous variables across models. This approach requires only a limited number of common elements. The rest of each model remains unchanged in the authors' original notation. This includes the variable names and definitions of endogenous variables, x_t^m, the other economic shocks ε_t^m, the equations $f_m(.)$ with model parameters β^m and the covariance matrix of shocks Σ_ε^m. The covariance matrix of policy shocks Σ_η may be treated as an element of the vector of policy parameters or set to zero.

Wieland et al. (2012) provide some concrete examples for the model augmentation step, which includes setting up the additional definitional equations, $h_m(.)$, and determining their parameters, θ^m. The subsequent steps in comparing policy implications consist of solving the augmented models, constructing appropriate objects for comparison and computing a metric that quantifies the differences of interest.

Computing comparable policy implications.

Solving the augmented nonlinear structural model defined by equations (5), (6) and (7) involves expressing the expectations of future variables in terms of currently available information. To this end, one needs to define how expectations are formed. Our computational implementation and model archive MACROMODELBASE2.0 includes models using four different assumptions. While most of the models are solved under the assumption of rational model-consistent expectations, several models can also be solved under the assumption of adaptive learning as in Slobodyan and Wouters (2012). Other assumptions regarding expectations formation include the sticky-information model of Mankiw and Reis (2007) with staggered information sets of otherwise rational expectations and VAR-based expectations as in Orphanides (2003) and in a version of the Federal Reserve's FRB-US model.

Here, we proceed under the assumption of rational expectations. The solution step involves checking for existence and uniqueness of equilibrium. For linear models one can use the Blanchard-Kahn conditions. For nonlinear models one may have to rely on search by numerical methods. The solution of the structural model is given by a set of reduced-form equations:

$$z_t = k_z(z_{t-1}, x_{t-1}^m, \eta_t, \varepsilon_t^m, \kappa_z) \quad (8)$$

$$x_t^m = k_x(z_{t-1}, x_{t-1}^m, \eta_t, \varepsilon_t^m, \kappa_x) \quad (9)$$

If the structural model is nonlinear, the reduced-form equations would also be nonlinear. (κ_z, κ_x) denote the reduced-form parameters. They are complicated functions of the structural parameters, β^m, the policy parameters, γ, and the covariance matrix, Σ^m. Nonlinear models may be solved approximately by means of numerical methods, for example, perturbation-based, projection-based or two-point-boundary-value algorithms (see Judd (1998), Fair and Taylor (1983), Collard and Juillard (2001)). Alternatively, the model may first be linearized around a deterministic steady state, either analytically or numerically. Then, a range of methods are available for computing the solution to the linear system of expectational equations, including the generalized eigenvalue-eigenvector method (see Uhlig (1995)), generalized Schur decomposition (see Klein (2000)), QZ decomposition (see Sims (2001)) or the undetermined coefficients method (see Christiano (2002)).

The reduced form solution of the augmented nonlinear model can then be used to obtain particular objects for comparison defined in terms of comparable variables. With regard to policy implications, one object of interest could by the impact of a policy shock and its transmission to key macroeconomic aggregates. This object corresponds to the dynamic response of a particular common variable (an element of z) to a policy shock η_t, conditional on a certain common policy rule, $g(z_t, z_{t+1}, z_{t-1}, \eta_t, \gamma)$. Such impulse response functions describe the isolated effect of a single shock on the dynamic system holding everything else constant. Other objects of interest for comparing policy implications would be the unconditional variances and serial correlation functions. Finally, one may compute suitable metrics for measuring the distance between two or more models. Such metrics could be the absolute difference of the unconditional variances or the absolute difference of the impact effects of policy shocks under different models.

3 Some practical issues in conducting model comparisons

Large-scale systematic model comparison exercises have been rare and have only focused on a limited number of policy scenarios. These exercises are costly because they typically involve multiple meetings of several teams of model developers, with each team analyzing the policy scenarios in its own model. At the same time, the number of policy scenarios studied in these exercises has been limited. In this section, we review some practical problems that have hampered easy and frequent use of model comparison. We also report on the experience with strategies employed in the construction of the computational platform and model archive MACROMODELBASE2.0 (MMB) to overcome these problems. At this point, there are more than 60 models available for easy use by individual researchers and students. It is straightforward to introduce new models and compare their policy implications to existing benchmarks.

Replication.

The first practical problem that arises if a researcher wishes to compare her model to those of others is how to obtain their models for simulation. Replicability is a basic scientific principle. The web-course "*Understanding science 101*" at UC Berkeley summarizes as follows:

> *"Scientists aim for their studies' findings to be replicable - so that, for example, an experiment testing ideas about the attraction between electrons and protons should yield the same results when repeated in different labs. Similarly, two different researchers studying the same dinosaur bone in the same way should come to the same conclusions regarding its measurements and composition. This goal of replicability makes sense. After all, science aims to reconstruct the unchanging rules by which the universe operates, and those same rules apply, 24 hours a day, seven days a week, from Sweden to Saturn, regardless of who is studying them. If a finding can't be replicated, it suggests that our current understanding of the study system or our methods of testing are insufficient."*

Unfortunately, however, there is no general practice guaranteeing replicability of macroeconomic models. This state of the field is somewhat surprising compared to other fields of economics. In economic theory it is standard that articles in scientific economic journals provide sufficient detail on mathematical derivations and proofs such that academics and advanced students can replicate the analysis. In econometrics new methods and estimators are fairly quickly implemented in software packages such as EVIEWS, RATS, SAS, GAUSS and others. Thus, new econometric tools are not only spread to academic researchers and students but widely used by practitioners in many fields of applied economic analysis. In the last two decades, macroeconomic modeling has benefitted from a similar development with regard to numerical techniques for solving and estimating models with rational expectations. Initially, individual researchers have made particular toolkits available that have been adopted by many others in their work. Over the years, the software package DYNARE developed by Michel Juillard and collaborators has gained more and more users and contributors such that it has become a widely used tool for macroeconomic model solution and estimation (see Juillard (2001)). While new techniques for model solution and estimation can now be easily utilized by academics, students and practitioners even in a black-box manner, this is not true for most of the many new macroeconomic models.

The following problems can arise when one attempts to replicate macroeconomic models presented in scientific economic journals:

1. The published article does not contain all the equations needed to write the model code for replicating the analysis presented in the article. Typically, journals are not willing to devote space to present all the information that is needed. Also the models can be quite complex and mistakes can arise in transcribing model equations that were successfully implemented in computer code to the text file for the article.

2. The published article does not contain all the parameter values or steady state values needed to replicate the model.

3. The code for replicating the model is not available from the journal website. While many journals provide options for online archiving of supplementary materials only a few appear to insist that authors provide a reliable version of their code.

4. The code is not available from the authors' website and authors are not replying to the requests for making code available.

5. The code is available but the software needed to simulate is unavailable to individual researchers because its price is high and it is only used at large institutions. An example is the TROLL software used at some policy making institutions.

6. The code is available but the simulation results it delivers differ from the results published in the article. This can easily arise when the version the authors distribute is an earlier or later version relative to the version used for the article. Such "versioning" problems can even occur with models widely adopted by others.

7. The code that is available does not contain sufficient description and explanations such that it is easily understood by users.

8. The software platform for which the code has been written has been updated such that the code does not run anymore.

9. The replicator makes mistakes in trying to implement the model for replication.

10. The authors' work is not replicable due to mistakes in the derivation of the equations or the implementation in the code. We found this happens more frequently with working papers but sometimes also with articles published in journals. Given the complex nature of computational implementation of macroeconomic models, mistakes of this kind are to be expected and should not be considered a negative reflection on the authors' scholarship. It is useful to recognize and correct them so as to make it easier for other researchers to build on this work.

These problems are not unique to macroeconomic modeling. Replication in reference to computations is more commonly known as "*reproducible research*" and forms the subject of an expanding literature in computer science, statistics and related fields of application (see for example Fomel and Claerbout (2009), Donoho (2010), Freire et al. (2012) and Sandve et al. (2013)). Stanford statistician Donoho characterizes the central problem in these words:

> "*an article about computation result is advertising, not scholarship. The actual scholarship is the full software environment, code and data, that produced the result*".

We have pursued the following strategies for replicating models to be included in our model comparison software:

1. The ideal case is that authors or other users of the model provide the code describing the model and integrate it themselves in MMB. Generally, authors can expect wider dissemination, use and citation of their work by other researchers if they make their code available in an easy-to-use format. We have also found that policy making institutions such as central banks and international organisations have become very open towards making their models available, at least those versions that economists from these institutions have circulated in working papers or used for publications in scientific journals.

2. The next best scenario is when model authors provide the complete code that replicates the findings reported in their article and remain available for answering questions of research assistants in Frankfurt who integrate the model in MMB team.

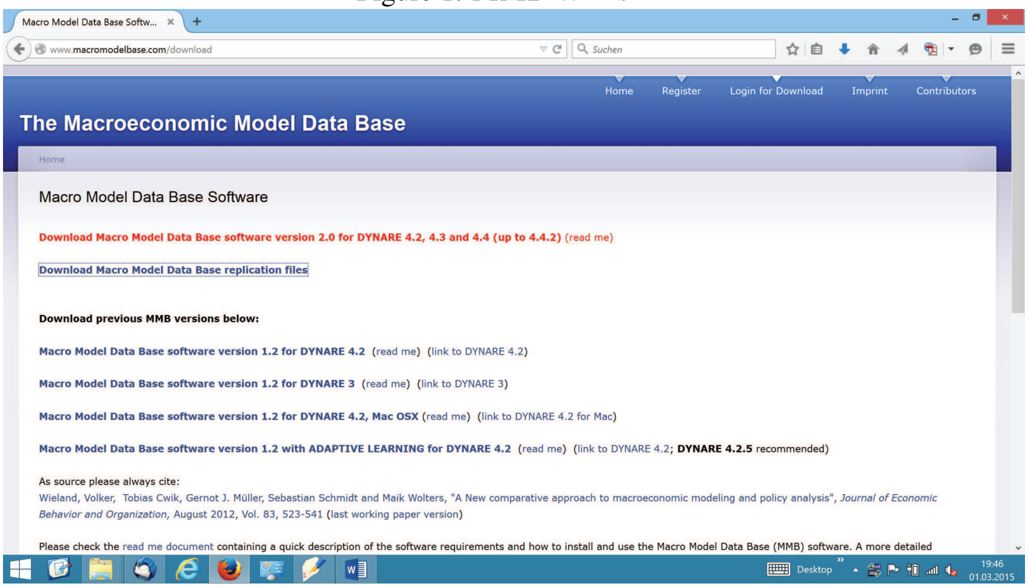
3. Research assistants in the Frankfurt MMB team have replicated a number of models using software made available on journal or author websites.

4. We teach advanced Ph.D. courses that focus on a particular area of new model development. A team of two or three students receives the task of presenting a paper from the literature, replicating the model and integrating the model in MMB. This approach has proved quite successful in terms of training Ph.D. students in model building and getting them to the research frontier, where they can work on extending existing models for new applications. Whether they succeed in replicating the model often depends on whether they receive feedback from model authors on problems or missing items. Students give presentations on the original paper and the technical replication and they also prepare a replication report.

5. Once a model has been replicated, we make the files documenting the replication available for download on the MMB website. The replication package is offered separate from the comparison software itself as shown below in Figure 1. It is not augmented for model comparison and remains as close as possible to the authors' original code or article. A readme file and graphics files make reference to the specific original research findings and provide information on how we came to matching the authors' work.

In total MMB2.0 makes available 64 model. Among these, about XX have been integrated or made ready for integration by the original authors or other users. XX models have been immplemented by the MMB team in Frankfurt and XX models have been integrated on the basis of course work by Ph.D. students.

Figure 1: MMB WEBSITE



Computational implementation.

In terms of implementing the model comparison approach outlined in the previous section computationally, there are choices to be made regarding computer language as well as model solution and simulation methods. Furthermore, problems to be dealt with concern the compatibility with earlier or subsequent version of the respective software solutions and operating systems.

Most academic researchers in the area of macroeconomic model building have adopted MATLAB as their preferred high-level programming language. This choice concerns specifically the recent development of dynamic stochastic general equilibrium (DSGE) models in the real business cycle (RBC) and New Keynesian literatures. MATLAB–the name is derived from MATrix LABoratory–is a commercial software product of MATHWORKS Inc. It is fairly widely used in engineering, physics, economics and other fields applying computationally methods. This product is not cheap but there are reductions for student licences. Also, there exists a freeware software GNU OCTAVE that is largely compatible with the proprietary MATLAB software. Thus, executables written to run on MATLAB can presumably be run on OCTAVE without needing major modifications. Competing software packages such as GAUSS or MATHEMATICA are not as popular in macroeconomic modelling but offer advantages in econometric or symbolic methods, respectively.

For many years developers of numerical solution methods for macroeconomic models with rational expectations have written routines that are MATLAB executables. Over recent years, the free software package DYNARE has been adopted by many researchers in academia, central banks and international organisations that are working in the field of macroeconomic modeling (see www.dynare.org). DYNARE runs on MATLAB but can also be used with OCTAVE. There is a growing community of researchers that is contributing freely available solution, estimation and optimization routines to DYNARE. Many central banks and international organisations also employ another software system called TROLL for simulating models used in policy formulation. TROLL is a commercial software with features that make it easy to manage large data sets.

MMB has been developed as free software to be used with DYNARE and MATLAB. Models are defined in the syntax needed for DYNARE. In principle, one is not restricted to using the solution algorithms offered within DYNARE. Other MATLAB-based algorithms can be used as long as code is created for interpreting the model files from MMB. It should also be possible to use the first version of MMB (1.2) and DYNARE with the free software OCTAVE. Yet, so far we have not had the resources to ensure that MMB is OCTAVE compatible. MMB2.0 has been extended with graphical user interfaces (GUI) to improve user friendliness. At this point, GUI facilities are apparently not yet available on OCTAVE, thus restricting MMB2.0 to MATLAB environments.

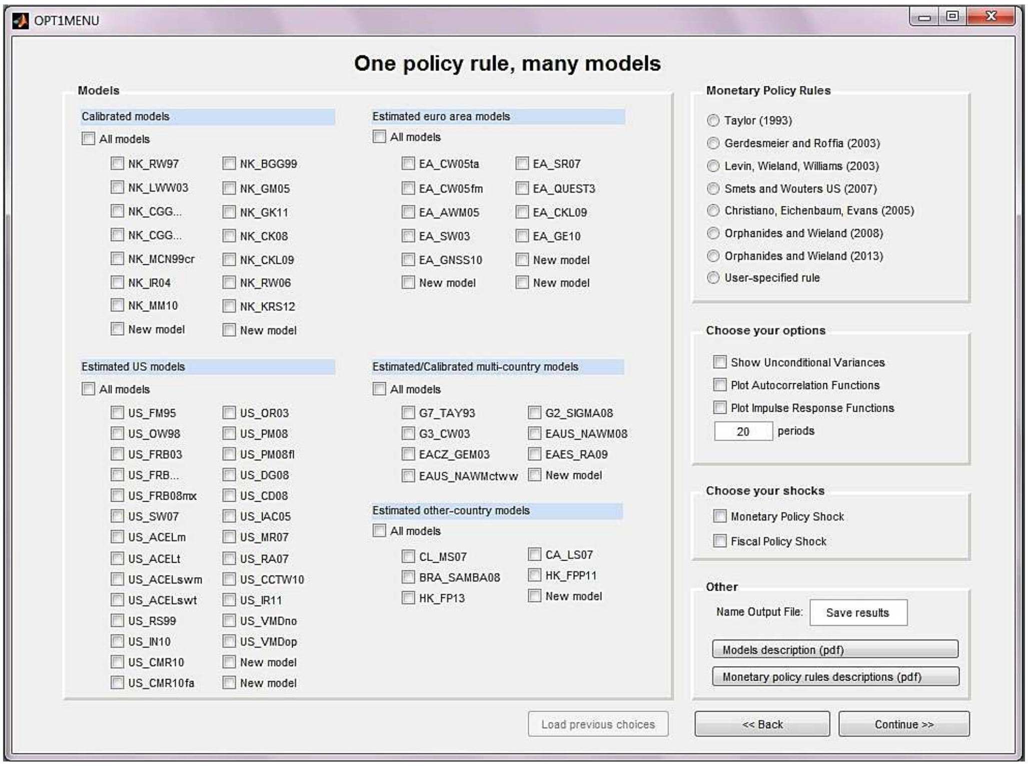
Regarding portability of MMB from a PC Windows operating system to a MAC operating system a MAC compatible version of MMB1.2 is available for download thanks to the contribution of Raymond Hawkins from the University of Arizona.

User friendliness.

The first version of MMB1.2 was intended for researchers that work on building macroeconomic models. MMB2.0 is meant to be accessible to a wider group of interested professional economists in the public and private sector and to students of macroeconomics. Thus, we have built graphical user interfaces that make it easier to simulate a wide variety of scenarios with any of the models included in the archive.

First, the user can choose among different applications such as the comparison of different models under a common policy rule, (*One policy rule, many models*), or a more detailed analysis of one specific model under different policies, (*One model, many policy rules*). Then he is presented with a menu of choices for models, policy rules, simulation scenarios and output formats.

Figure 2: MODELBASE MENU: ONE POLICY RULE, MANY MODELS



As an example, the menu for *One policy rule, many models* is shown in **Figure 2**. This menu gives access to conducting comparisons across models under the assumption that the central bank in each model implements the same interest rate rule. It corresponds to the formal representation of model comparison in section 2.

On the left-side of the menu the user can choose multiple models by clicking on the respective boxes. Models are grouped under different categories such as calibrated New Keynesian models, estimated models of the euro area economy, estimated models of the U.S. economy, models of other economies such as Canada, Chile, Brazil or HongKong and finally several multi-country models. One button on the bottom right of the menu allows access to some text with information on the particular models. On the top right side, there is a section for choosing a common policy rule from a list of rules or defining its coefficients directly in a sub-menu. Furthermore, there are various output options such us unconditional variances, autocorrelation functions and impulse response functions to monetary and fiscal policy shocks.

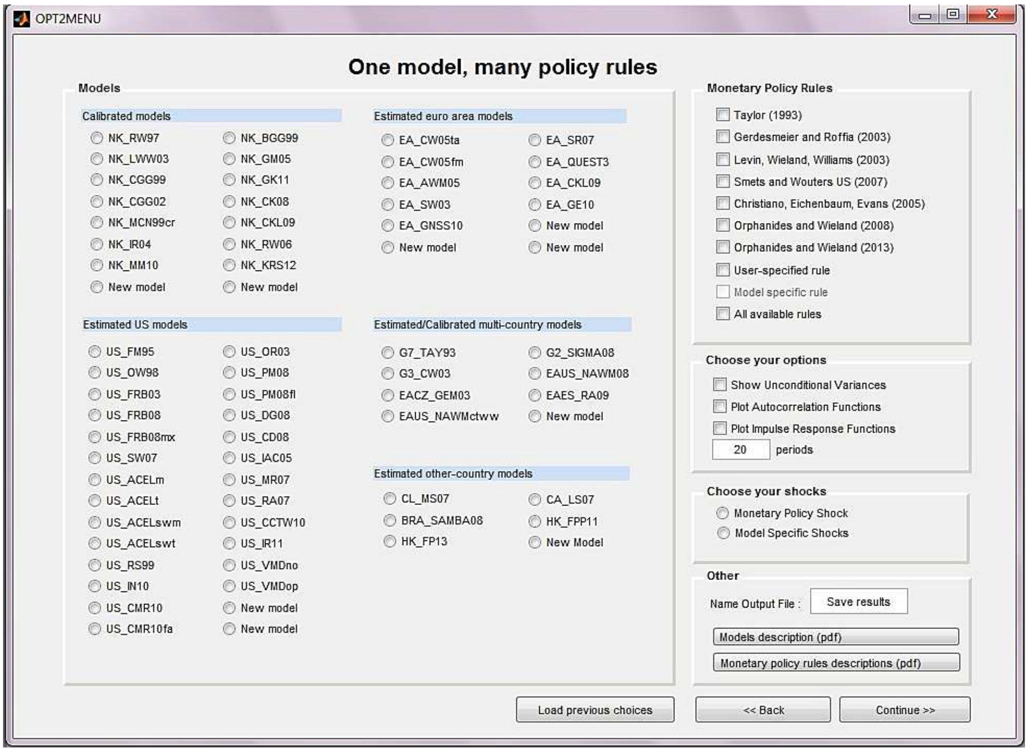
It is fairly straightforward to include additional models (for a description of the necessary steps see www.macromodelbase.com). Thus user can easily integrate their own model for comparison with these benchmark models. New models then also show up in graphical user interface.

Common and model-specific policy rules.

The comparison approach discussed above makes it possible to identify differences in policy implications that would be due to differences in model structure and parameter estimates. Yet, there are other interesting questions one might want to ask. For example, it may be of interest to explore the dynamics of one particular model under a variety of different policy rules in more detail. And there are questions that would require simulating each model under the original policy rule estimated or calibrated by the model authors. Such model specific rules would be used if one wants to compare the fit of each model to the data, if one wants to identify the typical empirical response to a particular model-specific shock, or if one wants understand differences in forecasts from different models.

The application (*One model, many policy rules*) makes it possible to investigate each model in more detail under different policy rules. Here, the user can only choose one model at a time, but multiple policy rules. It is possible to list the structural shocks in each model and simulate impulse responses for some or all of them under different policy rules. In addition to the list of rules and the user-specification of a rule, the rules menu also includes the model-specific rule estimated or calibrated by the original model authors.

Figure 3: MODELBASE MENU: ONE MODEL, MANY POLICY RULES



Model estimation and forecasting with real-time data sets.

So far the comparisons focus on the models as estimated or calibrated by the original model authors. It would be very useful to be able to re-estimate models on new data. Furthermore, the empirical relevance of different models is best compared in terms of their forecasting power out of sample. In particular, given the criticism of dynamic general equilibrium models constructed and used before the global financial crisis, it would be important to explore whether new models with improved representations of the financial sector would have performed better in terms of explaining and predicting the financial crisis and great recession.

We are currently building a data base with real-time data vintages for U.S. and euro area macroeconomic and financial data. At the same time, we are developing new applications of the model comparison software that allow model estimation and forecasting using this real-time data set. These applications build on and extend work on forecast comparison by Wieland and Wolters (2011)and Wieland and Wolters (2013)

4 Key characteristics of some recent macro-financial models

The global financial crisis has drawn attention to the need for improving the characterization of the financial sector in macroeconomic models used for business cycle and policy analysis. Many new contributions have included financial market imperfections in New Keynesian DSGE models, in particular in three areas: the financing of new investment in firms' capital for production purposes, housing finance and the role of banks and bank capital in financial intermediation. These financial frictions help explain how the consequences of economic shocks for macroeconomic aggregates can be amplified via the financial sector, and how financial sector stress and crises can spill over into the real economy.

Corporate investment financing and the financial accelerator.

Fortunately, research on integrating financial frictions in macroeconomic models for policy analysis did not need to start from scratch. A prominent starting point is the so-called financial accelerator model of Bernanke et al. (1999) (BGG99). Here, the accelerator term refers to the amplification of economic fluctuations via the financial sector. Long before the global financial crisis, they already provided a tractable approach for including information asymmetries, which are central to the relationship between borrowers and lenders, in dynamic New-Keynesian models.

Lending institutions and financial contracts aim to reduce the costs of collecting information and to mitigate principal-agent problems in credit markets. By contrast, economic shocks may increase the cost of extending credit and reduce the efficiency of matching borrowers and lenders. Hence, the credit market imperfections amplify the effects of shocks from the financial sector as well as other sectors of the economy. BGG99 focus on the financing of investment in firms' capital for production purposes. Their model includes risk-averse households, risk-neutral entrepreneurs and retailers. Entrepreneurs use capital and labor to produce wholesale goods. These are sold to the retailers. The retail market is characterized by monopolistic competition and price rigidities. Entrepreneurs borrow funds from households via a financial intermediary. These funds serve to pay for part of the new capital, which becomes productive in the next period. The agency problem arises because the return to capital is subject to idiosyncratic risk and can only be observed by the financial intermediary after paying some auditing cost. As a result, the entrepreneurs' net worth becomes a key factor determining their borrowing costs. High net worth entrepreneurs need less external funding for a given capital investment and pay lower premia. To the extent that net worth rises and falls with the business cycle, the premium to be paid for external borrowing varies counter-cyclically. Thus, it increases fluctuations in borrowing, investment, spending and production.

A version of the BGG99 model is included in MMB. The implementation differs somewhat from the handbook article because it omits entrepreneurial consumption. Its short-hand reference in MMB is NK_BGG99. The model archive also contains recent advances and empirically estimated medium-size models with the financial accelerator from BGG99. For example, Christensen and Dib (2008) (US_CD08) extend the dynamic New Keynesian model of Ireland (2003) (see US_IR04) with a financial accelerator a la BGG99 and estimate the model on U.S. data. In their model, debt contracts are written in terms of the nominal interest rate in contrast to BGG99. De Graeve (2008) (US_DG08) includes the financial accelerator from BGG99 in a medium-scale New-Keynesian model of the type developed by Christiano et al. (2005) (US_ACEL). Specifically, De Graeve (2008) builds on the version of the model by Smets and Wouters (2007) (US_SW07) and estimates it similarly to U.S. data with Bayesian methods. He documents a reasonably close match between the external finance premium estimated with non-financial macroeconomic data and lower-grade corporate bond spreads.

Housing finance.

Real estate booms and busts played a central role in triggering the global financial crisis. These include not only the "sup-prime" boom and bust in the United States but also the credit-driven housing booms in a number of European countries such as, for example, Spain and Ireland. Thus, models with more detailed housing sectors recognizing the particular financing constraints are of great interest to policy makers.

The underlying rationale of housing finance is the limited enforceability of debt contracts, as borrowers may choose to default. To overcome this limited commitment problem, lenders require collateral, typically housing (or land) and provide funds only below the value of the collateral. Thus, the borrowing capacity, and hence the size of the loan is tied to the housing value. A starting point for modeling borrowing and lending under such a collateral constraint in macroeconomic models is to introduce an incentive for households to act as lenders or borrowers. Technically, it is assumed that economic agents differ in their discount factors: Some are more patient than others. In equilibrium, the more patient agents become savers and the impatient agents become borrowers.

The collateral constraint has the following consequences: suppose an aggregate shock shifts housing demand upwards such that housing prices increase. As a result, borrowing capacity expands. On this basis, the impatient households' demand for housing rises further, putting additional upward pressure on house prices. Thus, the effect of the initial shock is amplified over time, due to the presence of the collateral constraint. In case the impatient agents are productive such that their investment decisions can raise the productivity of the overall economy, this mechanism can be even further accelerated.

Kiyotaki and Moore (1997) developed a simple dynamic model with patient (and unproductive) entrepreneurs and impatient (and productive) entrepreneurs to show that the collateral channel can generate large and persistent business cycles. Iacoviello (2005) then incorporated such collateral constraints together with nominal debt in a variant of the New-Keynesian macroeconomic model with financial frictions by Bernanke et al. (1999). In his model, housing is not only used as collateral and as an input of production, but also provides households with utility from housing services. The model is estimated with U.S. data and referred to as US_IAC05 in the MMB model archive.

In addition, we consider two other models with housing. The model of Iacoviello and Neri (2010) (US_IN10) features a multi-sector structure with housing and non-housing goods and imposes a collateral constraint only on the impatient households. They consider many real and nominal rigidities similar to medium-size New-Keynesian DSGE models such as Christiano et al. (2005) and Smets and Wouters (2007). The US_IN10 model is estimated on U.S. macro and housing data. The model by Kannan et al. (2012) (NK_KRS12) is a simplified version of Iacoviello and Neri (2010). Key elements of the model are the presence of financial intermediaries and the determination of the spread between the lending rate and the deposit rate. The functional form for the determination of the spread is assumed rather than derived from a profit maximization problem. Savers cannot lend to borrowers directly. Financial intermediaries take deposits and lend to borrowers charging a spread that depends on the net worth of borrowers. In contrast to the two aforementioned models, NK_KRS12 includes a more flexible collateral constraint. While the standard assumption would restrict borrowing to a certain fraction of collateral, leverage can be increased at higher lending rates in the NK_KRS12 model if borrowers are willing to do so.

Financial intermediation and bank capital.

Constraints on bank credit due to liquiduity and solvency concerns and counterparty risks in the interbank market played a key role in amplifying the problems in real estate and corporate lending during the global financial crisis. In contrast to financial accelerator and housing sector models discussed so far, banking sector models deal with such supply side issues of credit creation. In these models, banks' balance sheet as well as banks' decision processes are treated explicitly. Thus, shocks can originate from the banking sector and this sector plays an important role in the transmission of standard macroeconomic shocks. In what follows, we focus on three quantitative monetary DSGE models in which banking capital is a key concern.

In the model of Gertler and Karadi (2011), henceforth NK_GK11, banks act as maturity transformers and have the capacity to fund long-term asset purchasing by issuing short debt beyond their equity. There is no financial friction between banks and borrowers. However, the possibility that banks can divert funds creates a moral hazard problem between banks and depositors. In order to give an incentive to households to make deposits, banks have to satisfy an incentive constraint: The pecuniary benefit from diverting funds must be at least as small as the gain from staying in business. This condition acts as an endogenous capital constraint.

Meh and Moran (2010), henceforth NK_MM10, use the double moral hazard framework of Holmstrom and Tirole (1997) and introduce banking decisions via an optimal financial contract. The first moral hazard problem is between a representative household and a representative bank. As the bank's monitoring technology is not directly observable by the investor, the latter requires the bank to participate in the project with its own net worth to mitigate this information asymmetry. Therefore, the ability of the bank to attract loanable funds depends on its capital position. This is the bank capital channel. The second moral hazard problem is between the bank and the entrepreneur, because entrepreneurial effort is not observable by the bank. The bank requires entrepreneurs to participate financially, i.e. "to put some skin in the game".

In Gerali et al. (2010) (EA_GNSS10), banks have monopolistic power to set deposit and lending rates. These rates exhibit stickiness due to adjustment costs. Bank's capital is formed out of retained earnings and the bank faces quadratic cost whenever its capital-to-assets ratio moves away from an exogenously given target. While, the preceding two models are calibrated, the EA_GNSS10 model is a medium-size DSGE model estimated with macroeconomic data from the euro area. It can be compared to other euro area models in the model archive. For example, Orphanides and Wieland (2013) have included it in a study analyzing the robustness of simple rules for monetary policy across different generations of macroeconomic models estimated for the euro area (see also Kuester and Wieland (2010)).

5 Propagation of shocks via the financial sector: Some comparative results

In the following, we use MMB to explore and compare the dynamics of the macro-finance models presented in the preceding section. In particular, we compare impulse response functions to a monetary policy shock, a general technology shock and shocks that are more akin to aggregate demand shocks. The medium-size DSGE model estimated by Smets and Wouters (2007) (US_SW07) for the U.S. economy serves as an empirical benchmark for comparison. Furthermore, we use the monetary policy rule estimated by Smets and Wouters (2007) as the common policy rule for all models. In this manner, we can isolate differences due to structural assumptions of each model from differences due to different assumptions on monetary policy. The *SW rule* is given by:

$$i_t^z = 0.81 i_{t-1}^z + 0.39 p_t^z + 0.97 q_t^z - 0.90 q_{t-1}^z + \eta_t^i \tag{10}$$

Note, the superscript z refers to common variables in this notation. The monetary policy instrument is the annualized short-term money market rate in quarter t denoted by i_t^z. Economic outcomes are measured with regard to inflation, real output and the output gap. p_t^z refers to the annualized quarter-to-quarter rate of inflation. y_t^z is quarterly real GDP. q_t^z refers to the output gap defined as the difference between actual output and the level of output that would be realized if the price level were flexible. These variables are expressed in percentage deviations from steady state values. η_t^i refers to the common monetary policy shock.

5.1 Corporate investment financing and the financial accelerator

Monetary policy shock.

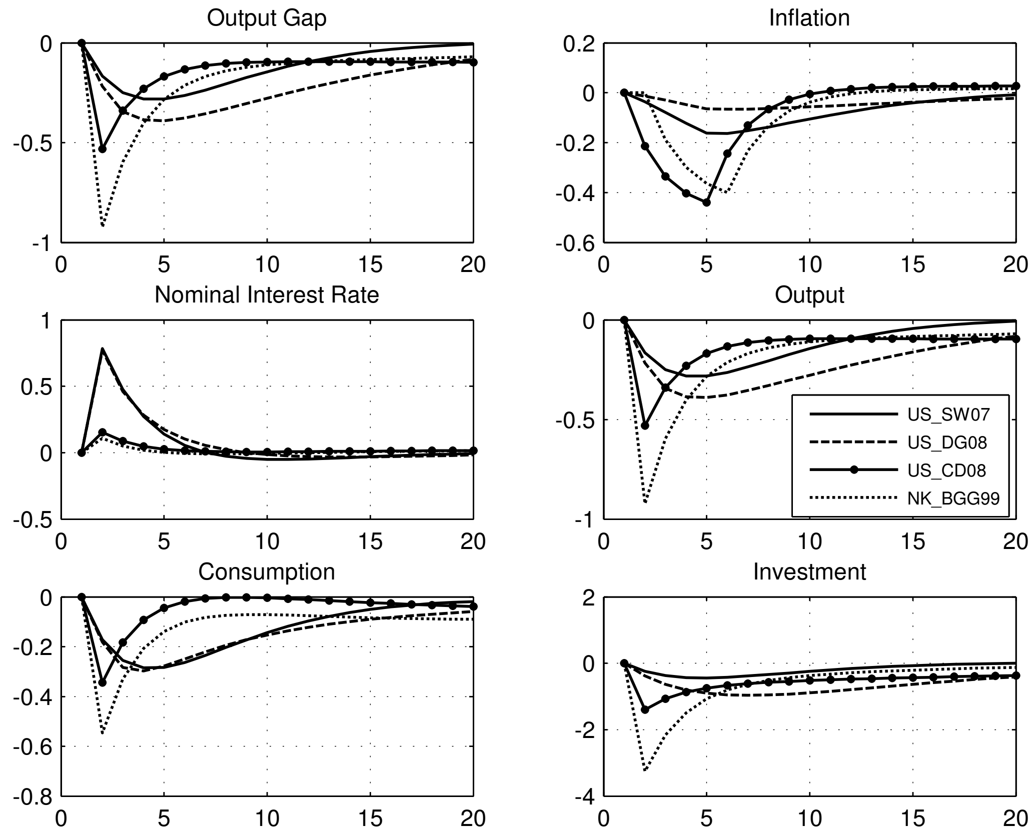


Figure 4: IRFs to a Contractionary Monetary Policy Shock under SW Rule: Macro Variables

Notes: To be added.

To begin, we compare the transmission of the monetary policy shock in the three models with financial accelerator effects due to information asymmetries in the financing of corporate investment, (NK_BGG99, US_CD08 and US_DG08), relative to the benchmark (US_SW07). Figure 4 displays the effects of an unanticipated increase in the nominal interest rate of one percentage point for the commonly defined macroeconomic aggregates. In all four models, the nominal interest rate increases while output and inflation decline. The standard channel of monetary transmission is reflected in higher real interest rates that lead households to reduce consumption today and firms to refrain from investment. The financial accelerator mechanism is at work in all three models that contain financial frictions. As can be seen from Figure 5 firms' net worth falls due to a reduction in the price and return of capital. Borrowing needs and leverage of entrepreneurs increase, and the external finance premium (EFP) rises, depressing investment. The US_CD08 model, where the financial contract is in nominal terms, also exhibits a debt-deflation mechanism.

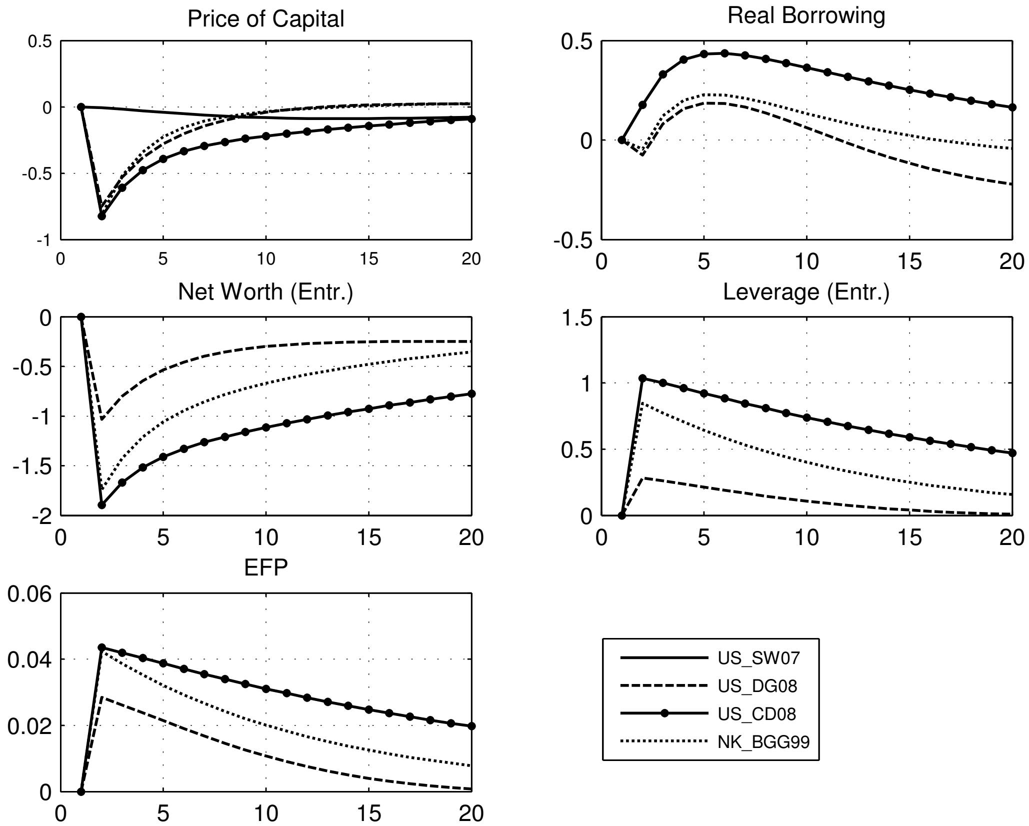


Figure 5: IRFs to a Contractionary Monetary Policy Shock under SW Rule: Financial Variables

Notes: To be added

Yet, the magnitude, timing and dynamic pattern of responses differs substantially across models. It is particularly striking that the smaller New-Keynesian models NK_BGG99 and US_CD08 display much stronger responses of output and inflation and a much smaller response of the nominal interest rate than the medium-size DSGE models US_SW07 and US_DG08.

This diversity of responses to a monetary policy shock contrasts with Taylor and Wieland (2012). They found quite similar estimates of the GDP impact of unanticipated changes in the federal funds rate for three well-known medium-size models even though these models were estimated in different periods with different methods and with different assumptions for the structure of the economy: the model of G-7 economies of Taylor (1993b) (G7_TAY93) and the DSGE models of Christiano et al. (2005) (US_ACEL) and Smets and Wouters (2007) (US_SW07). Their finding held true for a variety of policy rules such as the SW rule considered here or the rule estimated with the (US_ACEL) model. It implied that an unanticipated increase in the federal funds rate of 1 percentage point would be followed by a decline in GDP of about 30 basis points within 3 to 4 quarters. The magnitude of the impact of GDP would vary with other policy rules. Yet, it would mostly remain quite similar across models given a particular rule.

The estimated medium-size DSGE model with financial accelerator by De Graeve (2008), US_DG08, still remains close to the other medium-size models. As would be expected investment responds more strongly to the unexpected policy tightening than in US_SW07 due to the financial accelerator effect. The effect on consumption remains very similar. In sum, the impact on GDP is magnified a bit. It declines by about 40 basis points relative to 30 basis points in US_SW07.

Where does the big difference in GDP effects between US_SW07 and US_DG08 on the one side and the two smaller models with financial accelerator, NK_BGG99 and US_CD08, on the other side come from?

The reason is the different working of the financial accelerator effect on investment in the two smaller models. While the reduction in the price capital is of similar magnitude in US_DG08, NK_BGG99 and US_CD08, net worth declines further and leverage and the external finance premium increase more in NK_BGG99 and US_CD08.[3] The sharp increase in the premium translates directly into a sharp reduction in investment in these two models. In US_DG08 the response of investment is hump-shaped and persistent, reaching a substantially lower peak effect than in NK_BGG99 and US_CD08. This is due to different specifications of adjustment costs across models: US_DG08 assumes investment adjustment costs (as in Christiano et al. (2005)), whereas NK_BGG99 and US_CD08 assume capital adjustment costs. Thus, in US_DG08 it is costly to adjust the flow of investment. Consequently, forward looking agents adjust investment already today in expectation of an increase in the external finance premium. Accordingly, fluctuations in the premium have a smaller effect on the economy in US_DG08 than in NK_BGG99 and US_CD08 ceteris paribus. One might also ask why the largest impact on GDP occurs in NK_BGG99, rather than in US_CD08, where the financial accelerator is reinforced by a debt-deflation mechanism. This has to do with the calibra-

[3]Note that the financial variables have not been redefined as common variables. Thus, the differences can only be interpreted qualitatively. Yet, the impact on GDP is directly comparable.

tion of capital adjustment costs. It is less costly to adjust capital in NK_BGG99 than in US_CD08.

Another difference between the medium-size models and the smaller models concerns the behavior of the nominal interest rate. In US_DG08 and US_SW07 the nominal interest rate increases by about 1 percentage point in response to the policy shock as one might have expected. By contrast, the interest rate rises by less than 20 basis points in NK_BGG99 and US_CD08. In these two models monetary policy has a strong contemporaneous effect on GDP growth that feeds back to the interest rate via the contemporaneous response to GDP growth in the SW rule. At first sight, this finding appears odd, particularly in light of the simulations of monetary policy shocks reported in Bernanke et al. (1999) and Christensen and Dib (2008) which indicate a much stronger within-quarter effect of the policy shock on the interest rate. However, it turns out that the dynamic behavior of these models is quite different under the original monetary policy rules. To illustrate this effect, we simulate the original policy rule from Bernanke et al. (1999) (model-specific rule) in all the other models. It is given by:

$$i_t^z = 0.9 i_{t-1}^z + 0.11 p_{t-1}^z + \eta_t^i \tag{11}$$

As shown in Figure 6 the strong contemporaneous feedback to the nominal interest rate disappears when simulating this rule with lagged inflation. Since this rule implies much more accommodative monetary policy, the resulting impact of the policy shock on output and inflation is much greater.

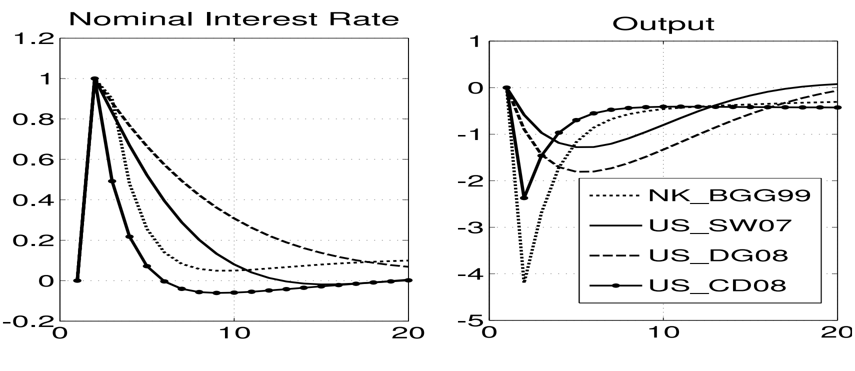


Figure 6: IRFs to a Contractionary Monetary Policy Shock under BGG99 Rule: Nominal Interest Rate and GDP

Notes: To be added

The sensitivity of interest rate dynamics to the timing assumption of the policy rule in the two smaller models suggests that the specification of dynamics in these models is not rich enough to be used to assess the transmission of monetary policy in a quantitative manner for policy purposes. It indicates the usefulness of building and estimating medium-size DSGE models for this purpose. Interestingly, the four medium-size models considered here continue to indicate fairly similar GDP impact of policy shocks under the rule from NK_BGG99 (US_SW07 and US_CD08 are shown in figure but not G7_TAY93 and US_ACEL).

Technology shock.

Figures 7 and and 8 report on the impact of a positive one-percent technology shock. The degree of exogenous persistence of this shock is assumed to be identical in the models considered. The common persistence parameter of the AR(1)-technology process is taken from the US_SW07 model. Again, the common monetary policy rule corresponds to the estimated interest rate rule in US_SW07.

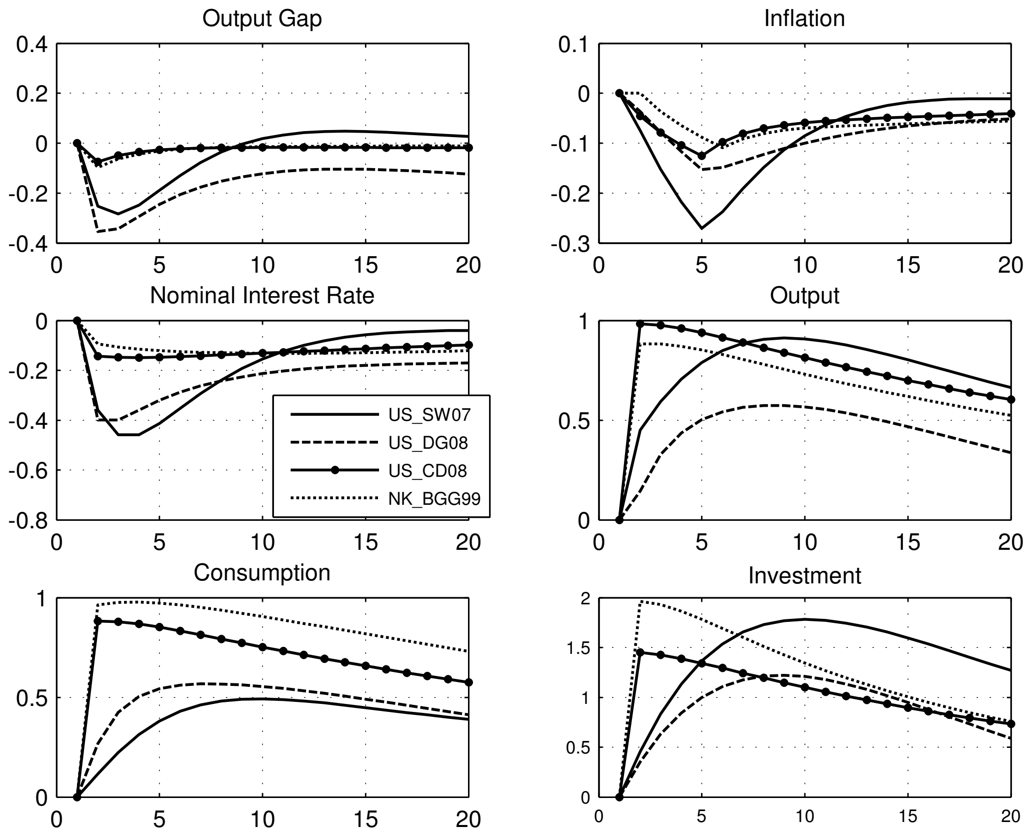


Figure 7: IRFs to a Positive Technology Shock under SW rule: Macro Variables

Notes: To be added.

In all four models output increases in response to such technological progress. This increase is also visible in investment and consumption. Due to the rigidity of price adjustment, and in the case of the US_SW07 and US_DG08 models also nominal wage adjustment, actual output increases less than the level output that would be realized under flexible prices. For some time, a gap opens up between actual output and this measure of potential output. The gap is quite small in NK_BGG99 and US_CD08 on the scale of 10 basis points. It is about three to four times larger in the two medium-size models that account for more sources of nominal rigidities. The negative output gap leads to a decline in inflation. The SW rule then implies a monetary policy easing. The nominal interest rate declines.

With regard to the financial accelerator effect, the price of capital, firms' net worth and real borrowing increase in response to the technology shock. Leverage first declines, and then rises. Similarly, the external finance premium first declines and then increases.

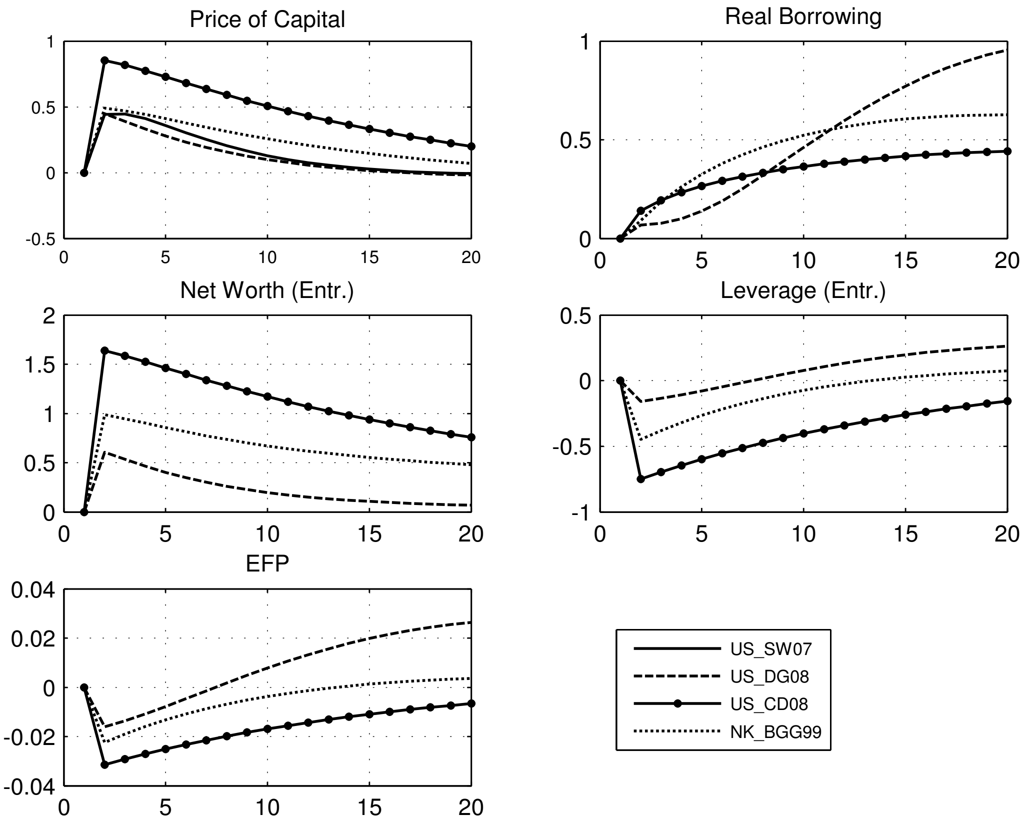


Figure 8: IRFs to a Positive Technology Shock under SW Rule: Financial Variables

Notes: To be added.

Magnitudes and dynamic patterns differ. Again, the NK_BGG99 and US_CD08 indicate a sharp positive impact of the change in financial variables on firms' investment. Investment and output dynamics in US_SW07 and US_DG08 follow a hump-shaped pattern departing from and return to steady-state more slowly than in the other two models. The presence of investment adjustment costs in the medium-size models explains the more sluggish responses than in the NK_BGG99 and US_CD08 models that assume capital adjustment costs. Bernanke et al. (1999) showed that the financial accelerator amplified the effect of technology shocks on investment and GDP relative to the benchmark without the financial friction. The model of De Graeve (2008) delivers the opposite result. Relative to the US_SW07 model, which also includes investment adjustment costs, the financial accelerator mechanism added by De Graeve (2008) actually dampens the investment and GDP response to a technology shock. As the demand for and price of capital increase, investment stays high for some time. The value of the capital stock then outgrows net worth and increases borrowing needs for quite some time. Accordingly, the external finance premium rises. As De Graeve (2008) notes, because long-lasting positive investment will be costly due to a high future premium for external finance, investment will be lower in all periods than otherwise.

In comparison to the original findings in Bernanke et al. (1999) it may be noteworthy to point out the sensitivity to the assumption for the monetary policy rule and the persistence of the technology process. Their original technology process is a random walk. In this case, the technology shock has very large and persistent effects on output. Actual output then even exceeds potential output and inflation rises.

Investment-specific shocks.

We have also simulated and compared the impact of investment-specific shocks in the US_SW07, US_DG08 and US_CD08 models. De Graeve (2008) calls this shock an investment supply shock, since it causes investment to increase and the price of capital to decrease. Smets and Wouters (2007) group it under (aggregate) demand shocks because they lead to an increase in both output and inflation. In this context, it is of interest to note that such investment-specific shocks play an important role in explaining the great recession following the global financial crisis when the US_SW07 model is extended to cover this period (see Wieland and Wolters (2013)). The comparison shows that the financial friction included in the US_DG08 and US_CD08 models strongly dampens the impact of such investment shocks on investment and GDP.

5.2 Housing finance

Next, we compare the impact of monetary, technology and demand shocks in the three models with housing finance, US_IAC05, US_IN10 and NK_KRS12 to the US_SW07 model as benchmark. Again, we start by assuming that nominal interest rates are set according to the policy rule estimated with the US_SW07 model (SW rule) in all four models.

Monetary policy shock.

Qualitatively, the three models with housing sector exhibit the same Keynesian-style features in response to a monetary policy shock as the benchmark as shown in Figure 9. Due to price rigidities, the contractionary policy shock induces an increase in the real interest rate, output declines below its flexible price level, and this gap causes lower inflation. Both, consumption and investment respond negatively to the increase in the real interest rate. Quantitatively, the impact on real GDP is much sharper and more pronounced in the US_IAC05 and US_IN10 models. The NK_KRS12 model, however, is closer to the US_SW07 benchmark. The latter two models exhibit more muted and hump-shaped responses of GDP and its components consumption and investment. Interestingly, the impact on investment is a bit greater in the NK_KRS12 than in the US_SW07, thus exhibiting at least initially an accelerator effect. The impact on consumption is smaller such that the overall impact on GDP is of similar magnitude in NK_KRS12 as in US_SW07.

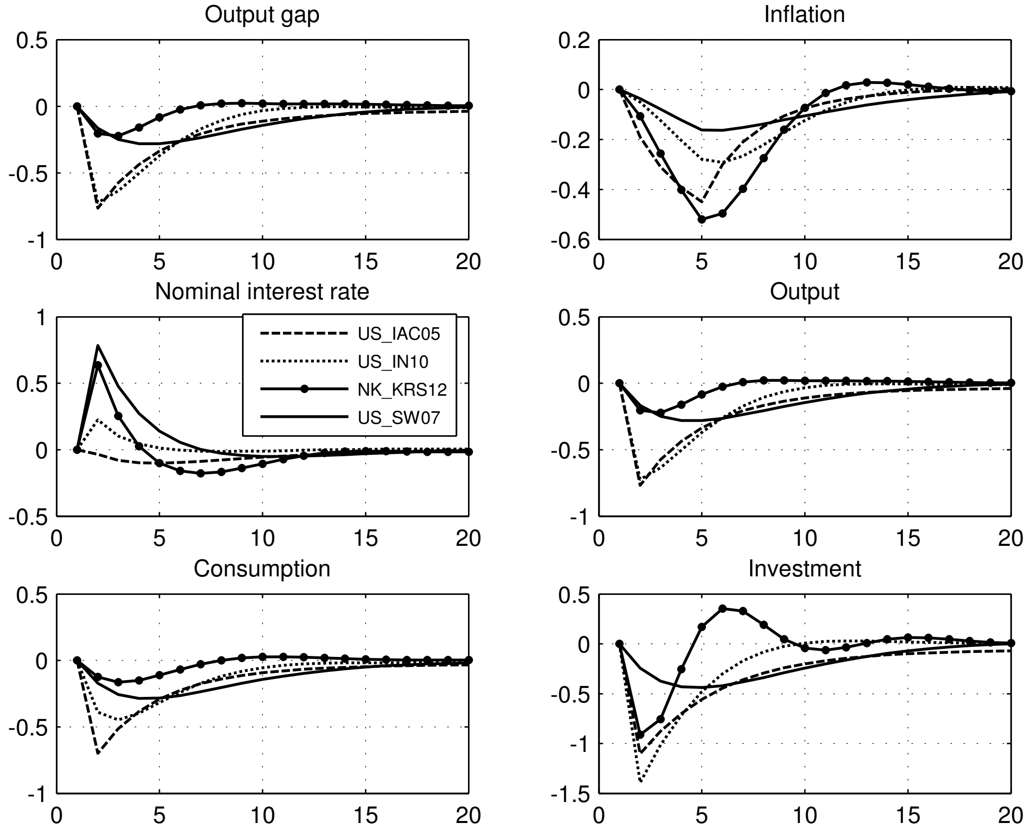


Figure 9: IRFs OF "MACRO VARIABLES" TO A CONTRACTIONARY MONETARY POLICY SHOCK UNDER SW RULE

Notes: Horizontal axis represents quarters after the shock. Vertical axis are percent deviations from steady-state values except for inflation and interest rate for which vertical axis are deviation from steady-state values. Inflation is an inflation over previous four quarters; Interest rate are annualized. The rest are expressed in a quarterly term.

Figure 10 displays the transmission of the monetary shock via housing finance. The collateral constraint of debtors and the nominal debt contracts in the US_IAC05 model and the US_IN10 models magnify the effect of unanticipated policy tightening. As inflation falls and real house prices decrease, the debt capacity of borrowers is reduced. In the US_IAC05 model impatient households and entrepreneurs are both borrowing-constrained. Consequently, impatient households cut back further on consumption, while entrepreneurs reduce non-residential investment along with consumption. Likewise, the impatient households curtail more consumption in the US_IN10 model. Moreover, residential investment declines significantly in the US_IN10 model, because sticky wages intensify the effect of a monetary shock on residential investment, coupled with flexible housing prices.

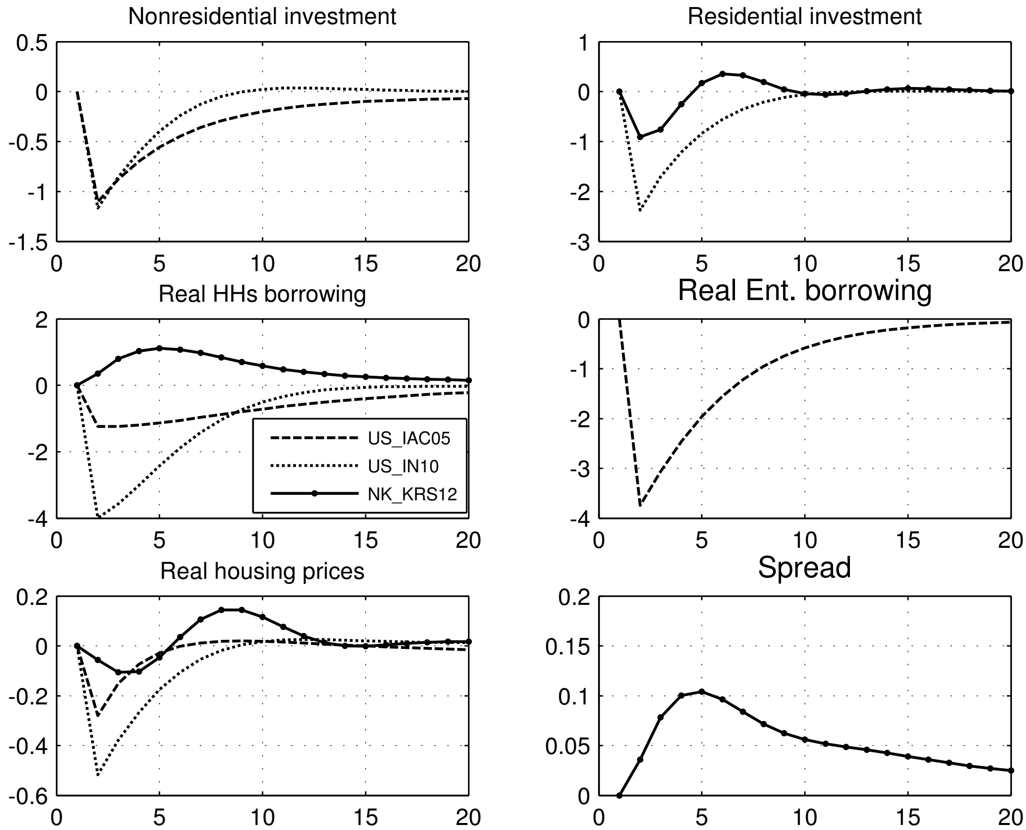


Figure 10: IRFs OF "INVESTMENT & FINANCIAL VARIABLES" TO A CONTRACTIONARY MONETARY POLICY SHOCK UNDER SW RULE

Notes: Horizontal axis represents quarters after the shock. Vertical axis are percent deviations from steady-state values except for credit spread for which vertical axis are deviation from steady-state values. Spread are annualized. The rest are expressed in a quarterly term.

The impact of the monetary shock on output is smaller in the NK_KRS12 model than in the other models. Since there is no capital in this model, aggregate demand lacks nonresidential investment which is an interest-sensitive component of GDP. Furthermore, this model employs a more flexible borrowing constraint than the collateral constraints used in the other two models with housing. Leverage, that is the ratio of debt to the housing value, can still be increased if borrowers wish to do so and accept higher lending rates. By contrast, the amount of borrowing with the standard collateral constraint is strictly restricted to a certain fraction of the collateral value. In the latter case, the decrease in the collateral value leads directly to the reduction of borrowing. In the NK_KRS12 model, impatient households still take out more loans even with higher interest rate in response to a contractionary monetary shock. This dampens the responses of consumption and residential investment.

Similarly to the NK_BGG99 and US_CD08 models in the preceding subsection, we find that the sharp contemporanous response of housing and output in the US_IAC05 and US_IN10 models strongly feeds back via the SW rule to the contemporaneous nominal interest rate. For the US_IAC05 model we even observe the odd result that the postive monetary policy shock implies a slight decline in the nominal interest rate. Yet, the SW rule is clearly a reasonably well fitting description of interest rate decisions made by the Federal Reserve, at least when estimated together with the remainder of the US_SW07 model. For comparison, we simulate these models again under the policy rule from Bernanke et al. (1999) (model-specific rule) which responds only to the lagged interest rate and lagged inflation. As shown in Figure 11 the strong contemporaneous feedback to the nominal interest rate disappears in this case as it does with some of the other rules available in MMB. Not surprisingly, the resulting impact of the policy shock on output and inflation is much greater.

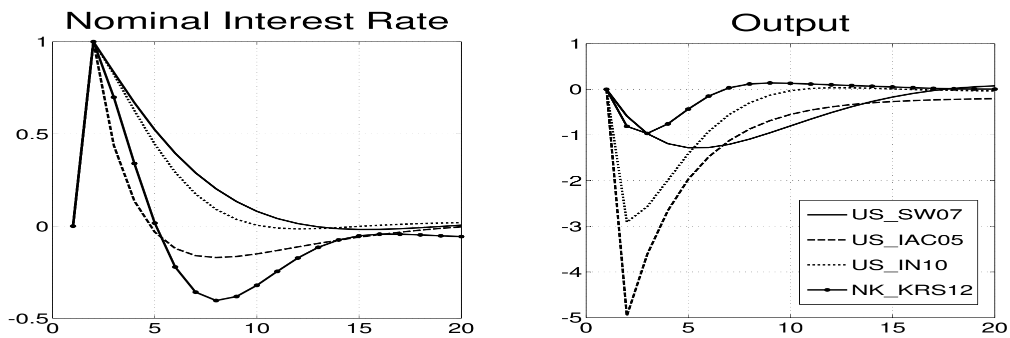


Figure 11: IRFs to a Contractionary Monetary Policy Shock under BGG99 Rule: Nominal Interest Rate and GDP

Notes: To be added

The sensitivity of interest rate dynamics to the timing assumption of the policy rule might again be interpreted to suggest that the dynamics in these models are not rich enough to be used to assess the transmission of monetary policy in a quantitative manner for policy purposes as in the case of medium-size DSGE models with more sources of endogenous persistence.

Technology shock.

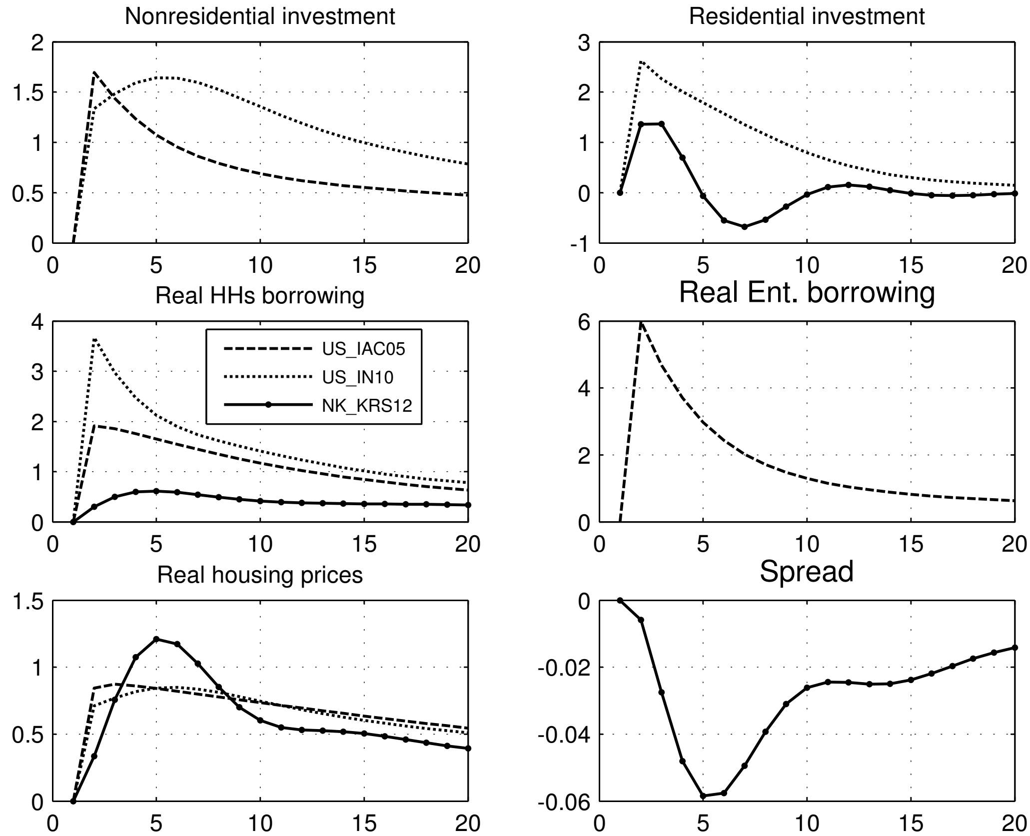


Figure 12: IRFS OF "INVESTMENT & FINANCIAL VARIABLES" TO A POSITIVE TECHNOLOGY SHOCK UNDER SW RULE

Notes: Horizontal axis represents quarters after the shock. Vertical axis are percent deviations from steady-state values except for credit spread for which vertical axis are deviation from steady-state values. Spread are annualized. The rest are expressed in a quarterly term.

Next, we implement a common technology shock in the models with housing sector that exhibits the same degree of persistence as the technology shock in the US_SW07 model. This shock increases the total factor productivity of intermediate goods firms in the nonresidential sector. As in the US_SW07 model, real GDP rises and inflation declines in response to a positive technology shock in the three models with housing sector (not shown). The persistent but temporary increase of productivity in the nonresidential sector is followed by a lower real interest rate so that aggregate demand is equated to with aggregate supply. The reduction of the real rate increases real house prices and thereby expands the collateral capacity as shown in Figure 12. This allows borrowers to obtain more funds, which are either consumed or invested. The amplifying effect of the collateral channel is most apparent in the impulse responses of consumption (not shown). In the three models with housing consumption increases two or four times more than in the US_SW07 model. Though the fall of inflation reduces the collateral values, the collateral channel outweighs the debt deflation channel.

Housing market and financing dynamics differ somewhat between the three models due to different structural assumptions:

- In the US_IAC05 model entrepreneurs produce intermediate goods making use of the stock of physical capital, the housing stock and labor input from two types of households. The persistent rise of productivity raises the expected return of each production factor so that entrepreneurs increase nonresidential investment and the housing stock. Higher expected returns on housing thus directly boost housing prices.

- In the US_IN10 model the productivity increase in the nonresidential sector raises the rental income from holding capital in future periods as well as the labor income of both households. As a result, households invest more in nonresidential investment and have more financial resources to invest in housing. This spillover from the nonresidential sector, together with the lowered real interest rate, leads to the increase of housing prices.

- In the NK_KRS12 model higher real house prices result in more favorable financial conditions for borrowers such that the credit spread declines. This, in turn, boosts residential investment as well as housing prices. However, this second-round effect in the response to a technology shock is small.

Housing demand shock

The models with housing include new types of shocks emanating from this sector that have potentially major macroeconomic consequences. In the following, we consider a housing demand shock. It could also be called a housing preference shock, since it is modeled as random disturbance to the marginal utility of housing. For comparison, the size of the shock is adjusted across the models such that it increases the real house price on impact by one percent. Yet, we ask a slightly different question than previously with the technology shock, namely what the consequences of such a housing demand shock would be when the degree of exogenous persistence remains at the different model specific parameter setting. Under this scenario, the responses of GDP and its components are quite different across models as shown in Figure 13.

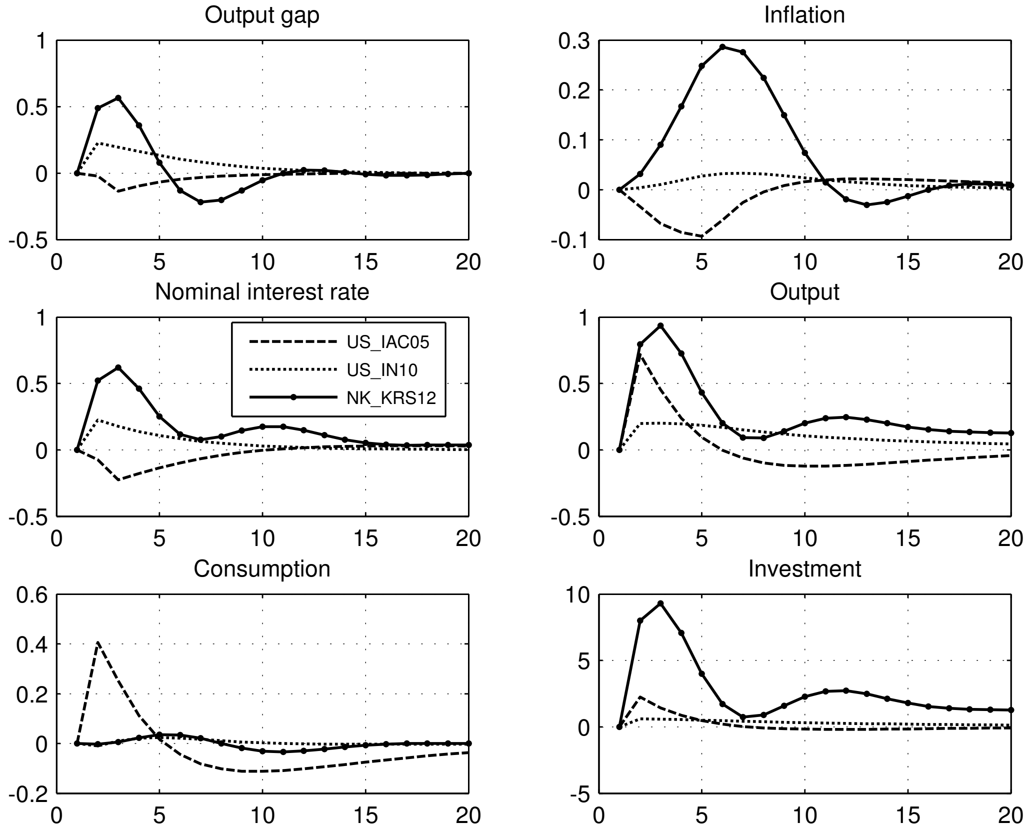


Figure 13: IRFs OF "MACRO VARIABLES" TO A POSITIVE HOUSING DEMAND SHOCK UNDER SW RULE

Notes: Horizontal axis represents quarters after the shock. Vertical axis are percent deviations from steady-state values except for inflation and interest rate for which vertical axis are deviation from steady-state values. Inflation is an inflation over previous four quarters; Interest rate are annualized. The rest are expressed in a quarterly term. A shock in each models follows an AR(1) process with the model-original autocorrelation coefficient. The size of the shock is adjusted in each models such that it increases the real house price on impact by 1%p.

The impact on investment and GDP is greatest in the NK_KRS12 model, where the financial accelerator mechanism plays a big role in the shock's propagation into the rest of the economy. In response to the positive housing demand shock, both households - the patient and the impatient - increase residential investment. Housing prices increase, which raises the net worth of the impatient households as shown in Figure 14. Due to the increased net worth of borrowers, financial intermediaries charge a lower spread of the lending rate over the deposit rate. The reduced spread results in a further increase of borrowers' housing demand, which in turn leads to another increase of housing prices. This effect builds up over the first three to five quarters. Actual GDP rises more than it would under flexible prices, hence a gap opens up and inflation goes up.

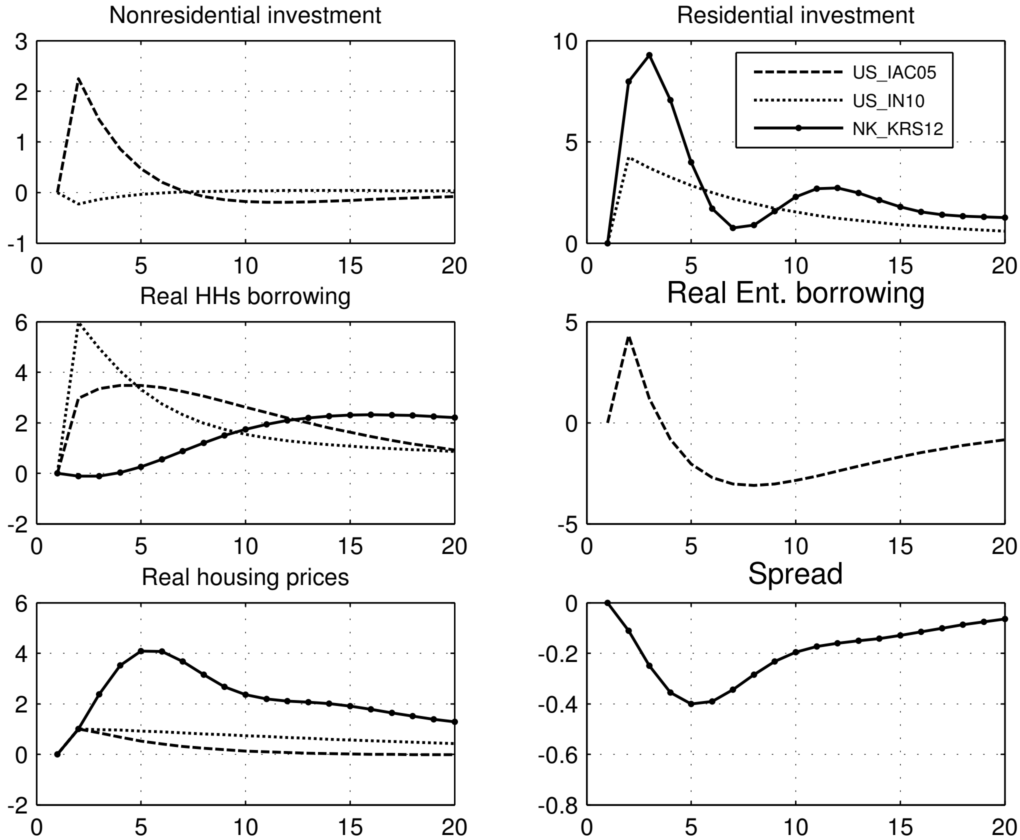


Figure 14: IRFS OF "INVESTMENT & FINANCIAL VARIABLES" TO A POSITIVE HOUSING DEMAND SHOCK UNDER SW RULE

Notes: Horizontal axis represents quarters after the shock. Vertical axis are percent deviations from steady-state values except for credit spread for which vertical axis are deviation from steady-state values. Spread are annualized. The rest are expressed in a quarterly term.

In the US_IAC05 model, the housing shock sharply pushes up investment and GDP, but the increase does not last as long as in the NK_KRS12 model. The increase in impatient households' demand for housing drives up housing prices. As a consequence, the collateral value of borrowers rises. Impatient households and entrepreneurs use the expanded borrowing capacity to buy more housing stock from patient households. The model does not exhibit hump-shaped dynamics because it does not feature habit formation in consumption and only a small adjustment cost in nonresidential investment. Inflation initially declines a bit, because flexible price output rises more than actual output. Lower marginal cost leads to lower inflation. The response of output is smallest in the US_IN10 model. The housing demand shock expands the borrowing capacity of the impatient households, so that they increase consumption and housing investment. The role of the collateral channel is illustrated by the responses of the aggregate residential investment (in first row, right column of Figure 14) and real households borrowing (in second row, left column of Figure 14). However, the patient households, who are permanent-income consumers, decrease their consumption and investment in response to the increase in interest rates. Overall, aggregate GDP increases less than in the other two models.

5.3 Banking sector modeling and the role of bank capital

We conclude this section with a comparative analysis of the macroeconomic consequences of shocks emanating from the banking sector. Specifically, we evaluate the impact of an unanticipated reduction in the banks' capital stock. To this end, we make use of the above-mentioned three macro-financial models with a detailed representation of the banking sector: The NK_GK11 model of Gertler and Karadi (2011), the NK_MM10 model of Meh and Moran (2010) and the EA_GNSS10 model of Gerali et al. (2010).

The question to be answered with this comparison exercise differs somewhat from the ones in the previous sub-sections. Rather, than investigating the consequences of such shocks under a common monetary policy and a common degree of exogenous persistence of the shock, we consider a scenario where model-specific monetary policy rules and shock processes are assumed. Such a comparison is of interest when one wants to explore the typical role of a bank capital shock in the context of the empirical fit of the particular model and its forecasting power. We consider one-unit shocks, however AR(1)-coefficients in the persistent shock processes are model-specific. In NK_GK11 the persistence is 0.81, in NK_MM10 - 0.9 and in NK_GK11 - 0. The simulations are conducted under the option 'One Model Many Rules' in the computational platform and the model-specific rule is chosen. The size of the shock is normalized so that fall in bank capital is 5% on impact in all models. Although chosen for illustrative purposes, the size of the shock appears comparable to the actual consequences of financial distress seen during the Great Recession. Figure 15 illustrates the transmission of this shock to macroeconomic and financial variables across models.

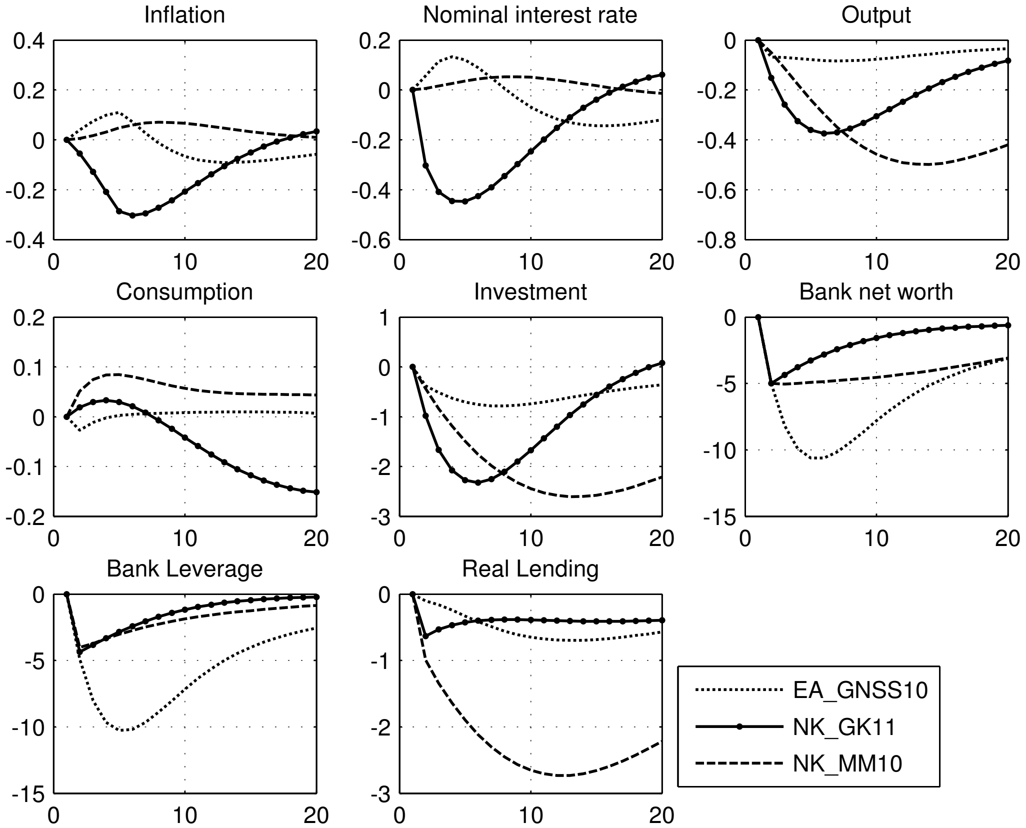


Figure 15: IRFs to a Negative Shock to Bank Net Worth

Notes: to be added

The drop in bank capital reduces banks' net worth and causes a protracted decline in lending and therefore in investment. The mechanisms leading to these effects are as follows: In EA_GNSS10, banks have monopolistic power when setting the lending rate. Thus, they increase the lending rate in order to repair their balance sheets after a drop in bank capital. The increase in lending rates depresses demand for loans and consequently investment. Since bank interest rates adjust only in a sticky fashion, tight financing conditions persist for several periods, depressing investment and output further. The decline in bank net worth is also persistent, which is due to an endogenous fall in bank retained earnings and also due to the exogenous persistence of the shock process.

In NK_MM10, the financial contract imposes a solvency condition on banks that determines banks' ability to attract funds for lending. Therefore, in response to an unanticipated fall in bank net worth, banks' ability to attract funds deteriorates and they cut lending. Decline in lending depresses investment, which lowers bank retained earnings and therefore bank net worth reinforcing the initial shock endogenously. In NK_GK11, the financial accelerator mechanism applies to the bank. Since the bank net worth drops, the financing conditions for the bank become tighter, which depresses the amount of funds intermediated by the bank. Therefore investment and output decline.

GDP contracts in all three models following the drop in bank capital. Most of this contraction comes from the decline in investment. Consumption varies much less and only declines substantially in the NK_GK11 model. Inflation varies little in EA_GNSS10 and NK_MM10 and only declines significantly in the NK_GK11 model.

6 Interaction of monetary and macroprudential policies: An illustrative example

Finally, we present some simulations to illustrate the interaction of monetary and macro-prudential policies in a macro-financial model. To this end, we employ one of the models considered previously, that is the NK_KRS12 model by Kannan et al. (2012). We follow Kannan et al. (2012) in exploring the implications of a policy that leans against credit growth, either by incorporating a reaction to credit growth in the interest rate rule or by including a rule for a macro-prudential policy instrument with such a policy reaction.

Early discussions of macro-prudential policy include Crockett (2000) and Borio (2003). These days, macro-prudential policy is considered by many the first choice for ensuring financial stability. Many central banks have been given a specific mandate to ensure financial stability together with the authority to use certain new macro-prudential policy instruments. One objective assigned to macroprudential policy is to limit systemic risk and mitigate economy-wide boom-and-bust cycles due to disturbances originating from the financial sector. The IMF (2013) defines systemic risk as "*the risk of disruptions to the provision of financial services that is caused by an impairment of all or parts of the financial system, and can cause serious negative consequences for the real economy*".

As noted previously, the NK_KRS12 model is closely related to Iacoviello (2005) and Iacoviello and Neri (2010). It includes a credit accelerator effect arising from housing finance. There are patient and impatient households consuming housing services and consumption goods. Patient households become savers, impatient ones borrow. Savers cannot lend to borrowers directly. Financial intermediaries take deposits and lend to borrowers charging an interest-rate spread related to the net worth of borrowers. The key relationship in this model links the interest rate spread on housing loans to the loan-to-value ratio. This relationship also accounts for a credit supply shock and a macro-prudential instrument. Equation (12) on page of 8 of Kannan et al. (2012) specifies this relationship as follows:

$$\frac{R_t^L}{R_t} = v_t F(\frac{B_t^B}{P_t^D D_t^B})\tau_t \tag{12}$$

where R_t^L denotes the gross lending rate, R_t the gross deposit rate, v_t a financial shock, B_t^B the debt of borrowers, P_t^D the housing price, D_t^B the housing stock of borrowers, F an increasing function of loan to value ratios, $\frac{B_t^B}{P_t^D D_t^B}$ and τ_t the macroprudential instrument. v_t constitutes an exogenous credit supply shock. It is meant to capture exogenous factors that influence banks' willingness to extend credit. For example, a reduction in v_t would occur when competition in the banking sector increases or when lending standards are relaxed because banks perceive less risk. Kannan et al. (2012) assume that there exists a macro-prudential instrument that can directly influence the credit spread. This simple specification is meant as a short cut for including the impact of an instrument such as capital charges on banks. This instrument could be set at a constant value or it could follow a rule that responds in counter-cyclical fashion to credit growth:

$$\tau_t = \tau(\frac{B_{t-1}^B}{B_{t-2}^B}) \tag{13}$$

We consider four different policy regimes in order to explore the interaction of monetary policy and macroprudential policy. They are summarized in Table 3. The first regime corresponds to a Taylor-style interest rate rule considered by Kannan et al. (2012). It is included as model-specific rule in MMB. Since, Kannan et al. (2012) investigate a variety of rules we refer to it as "KRS baseline interest rate rule". Compared to the original Taylor rule, the 'KRS baseline interest rate rule' has an interest rate smoothing term and a lower value for the coefficient on inflation compared to Taylor's rule (1.3 vs. 1.5). Also, the baseline rule is designed to react to lagged quarterly inflation and output gap while Taylor's rule reacts to the current year-on-year rate of inflation and output gap.

Table 3: Policy regimes

1. KRS baseline interest rate rule	$i_t = 0.7i_{t-1} + 0.3[i^* + 1.3(\pi_{t-1} - \pi^*) + 0.5q_{t-1}]$
2. KRS baseline & leaning rule	$i_t = 0.7i_{t-1} + 0.3[i^* + 1.3(\pi_{t-1} - \pi^*) + 0.5q_{t-1} + 0.1b_{t-1}]$
3. KRS baseline & macroprudential rule	$i_t = 0.7i_{t-1} + 0.3(i^* + 1.3(\pi_{t-1} - \pi^*) + 0.5q_{t-1})$ $\tau_t = 0.1b_{t-1}$
4. Taylor's rule	$i_t = i^* + 1.5(\pi_t^a - \pi^*) + 0.5q_t$

Notes: In all the rules, i_t denotes the annualized quarterly deposit rate, π_t the annualized quarter-to-quarter rate of inflation, π_t^a the year-on-year rate of inflation ($1/4\sum_{j=0}^{3}\pi_{t-j}$), i^* the steady-state interest rate, π^* inflation target, b_{t-1} the annualized quarterly nominal credit growth rate at period $t-1$, and q_t the quarterly output gap which is defined as the deviation of actual output from the level of output that would be realized if prices are flexible.

The second policy regime extends the baseline rule with a reaction to credit growth. It is referred to as "KRS baseline & leaning rule". The reaction coefficient on credit growth is set to 0.1. In the first two regimes, the macro-prudential instrument is held constant. The third regime combines the KRS baseline interest rate rule with a macro-prudential rule that reacts to credit growth. It is called "KRS baseline & macroprudential rule". Again, the coefficient on credit growth is set to 0.1. Finally, we consider the original Taylor rule, again with the macro-prudential instrument held constant.

Figure 16 shows the impulse responses of selected variables to a credit supply shock, which results in a reduction of the spread between lending and deposit rate by 50 basis points on impact under the KRS baseline rule. The shock is assumed to follow a first-order autoregressive process with a coefficient of 0.95. The shock process is displayed in the bottom-right panel.

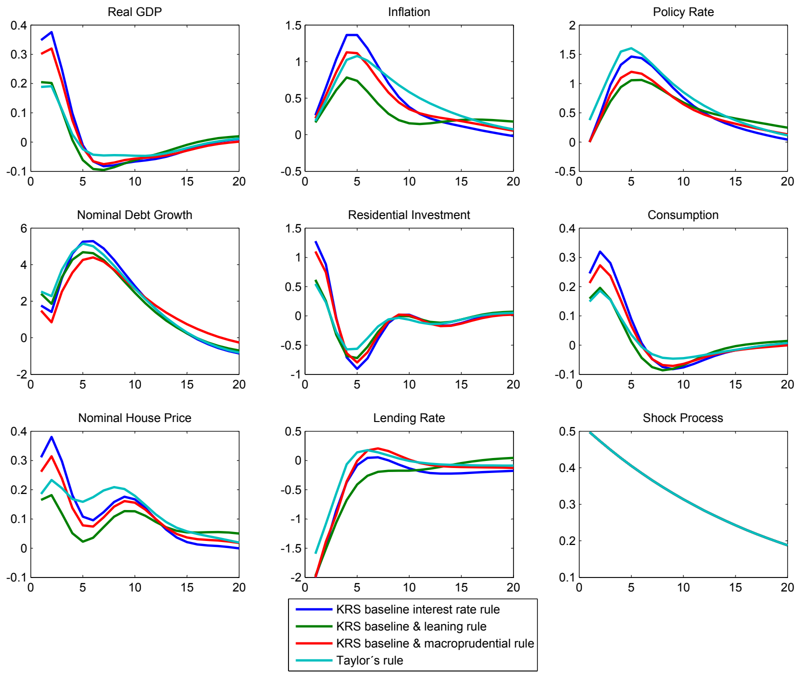


Figure 16: IRFs to a financial shock reducing the interest rate spread

Notes: Horizontal axis represents quarters after the shock and vertical axis are percent deviations from steady-state values except for inflation and two interest rates. Vertical axis are deviation from steady-state values for inflation and interest rates. Inflation is an inflation over previous four quarters; Nominal debt growth, policy rate and lending rate are annualized. The rest are expressed in a quarterly term.

We observe that the credit accelerator channel is at work. When the lending rate decreases, borrowing households take out additional loans. They spend the funds on additional consumption and residential investment. The increase in housing demand drives up house prices. The resulting increase in housing collateral value reinforces the lending boom. Nominal debt growth accelerates for about 4 to 5 quarters after the shock occurs. Meanwhile, the economy experiences a boom. Real GDP and inflation increase. In response to this boom, the monetary authority raises the interest rate. It is worth noting that savers (households) reduce their consumption and residential investment due to the increase in the deposit rate, however, the response of borrowers is much stronger such that aggregate consumption and residential investment still rise.

Next, we review the consequences of the credit supply shock under the four different policy regimes. Comparing outcomes under the KRS baseline interest rate rule (blue line) with those under the KRS baseline & macroprudential rule (red line), we find that the additional use of macroprudential policy contributes to stabilizing the economy. Real GDP and inflation increase less under the KRS baseline & macroprudential rule than under the KRS baseline rule alone. The macroprudential rule is quite effective in dampening the credit cycle and the increase in nominal debt growth. As a consequene, the central bank need not raise the nominal interest rate as much as under KRS baseline rule. Hence, macroprudential policy can complement monetary policy in the case of a credit supply shock.

An alternative regime includes a reaction to credit growth in the interest rate rule while keeping the macro-prudential rule constant. It turns out that this KRS baseline & leaning rule (green line) stabilizes real GDP and inflation more effectively than the KRS baseline & macroprudential rule (red line) for the given scenario. Responses of real GDP under the former rule are nearly one-third smaller than those in the latter rule, and almost half the size compared to the KRS baseline rule alone. Lastly, the original Taylor rule (blue line) also performs quite well. It stabilizes real GDP just as effectively as the baseline rule with credit growth, although Taylor's rule does not include credit growth. With respect to inflation, it is as effective as KRS baseline & macroprudential rule, even though the macro-prudential instrument is held constant.

Table 4: Performance of Policy Regimes (Standard Deviations)

	Inflation	Output gap
KRS baseline interest rate rule	1.901	0.372
KRS baseline & macroprudential rule	1.835	0.361
KRS baseline & leaning rule	1.525	0.341
Taylor's rule	1.452	0.339

Notes: Inflation (π_t^a) is year-on-year rate of inflation. The output gap (q_t) is defined quarterly. Detailed definitions are explained in notes of Table 3.

Table 4 reports the unconditional standard deviations of inflation and the output gap taking into the covariance matrix of all economic shocks in the NK_KRS12 model. In addition to the credit supply shock, the model also features a technology and a housing demand shock. The dynamic processes of the three shocks are calibrated to match the second moments of seven key macroeconomic variables. We find a clear ordering of policy rules in terms of macroeconomic stabilization. Taylor's rule performs best. When central bank sets its policy rate according to the Taylor rule, the lowest standard deviations of both inflation and output gap can be achieved. The KRS baseline & leaning rule follows on second place, while the KRS baseline rule implies the highest degree of fluctuations in inflation and the output gap.

This simulation exercise suggests that macro-prudential policy can complement monetary policy in stabilizing the real economy. Similarly, leaning against credit growth in monetary policy can help reduce macroeconomic fluctuations. Yet, it also suggests that it may more important how monetary policy responds to standard macroeconomic variables such as inflation and the output gap.

Of course, we have just compared four simple policy regimes without any effort to optimize policy responses. In such a "second-best" world, it may not be surprising that it is possible to identify cases where a simple rule such as Taylor's rule dominates a more complex monetary regime with counter-cyclical macro-prudential policy. A natural next step is to optimize the various regimes by choosing the response coefficients in order to minimize output and inflation variations. One could even compute more generally optimal rules that are not limited to the specific functional form with up to four response variables. Such optimizations, however, remain conditional on the particular model. Under model uncertainty, it is quite often the case that a rule that is only "second-best" delivers more robust stabilization performance across a range of models (see, for example, Kuester and Wieland (2010) and Orphanides and Wieland (2013)). Thus, it would be of great interest to consider a variety of macro-financial models in a comparison exercise aiming to identify such robust rules that would perform well under different specifications of financial frictions and other modeling assumptions and estimation methods.

7 Conclusions

- Brief summary and outlook to be added.

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