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# A New Comparative Approach to Macroeconomic Modeling and Policy Analysis <sup>\*</sup>

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## Abstract

Macroeconomic model comparison projects have helped produce some very influential insights such as the Taylor rule. However, they have been infrequent and costly, because they require the input of many teams of researchers and multiple meetings to obtain a limited set of comparative findings. This paper provides a new comparative approach to model-based research and policy analysis that enables individual researchers to conduct model comparisons easily, frequently, at low cost and on a large scale. Using this approach a model archive is built that includes many well-known empirically estimated models that may be used for quantitative analysis of monetary and fiscal stabilization policies. A computational platform is created that allows straightforward comparisons of models' implications. Its application is illustrated by comparing different monetary and fiscal policies across selected models. Researchers can easily include new models in the data base and compare the effects of novel extensions to established benchmarks thereby fostering a comparative instead of insular approach to model development.

*Keywords:* Macroeconomic Models, Model Uncertainty, Policy Rules, Robustness, Monetary Policy, Fiscal Policy, Model Comparison.

*JEL-Codes:* E52, E58, E62, F41

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# 1 Introduction

According to Lucas (1980) the objective of macroeconomic model building is

*" to provide fully articulated, artificial economic systems that can serve as laboratories in which policies that would be prohibitively expensive to experiment with in actual economies can be tested out at much lower cost. [...] Our task as I see it [...] is to write a FORTRAN program that will accept specific economic policy rules as 'input' and will generate as 'output' statistics describing the operating characteristics of time series we care about, which are predicted to result from these policies."*

Since then, many new models that aim to explain the behavior of the main aggregates of the world's economies have been developed. Model builders include not only academics but also researchers at many central banks, treasuries and international organizations. Not surprisingly, the models differ in terms of economic structure, estimation methodology and parameter estimates.

If one model were to be found to dominate all others in terms of theoretical appeal and empirical fit, this model could be used exclusively to develop policy recommendations. Or, if no model's structure is considered completely satisfactory from a theoretical perspective, and if many of the competing models describe historical data of key aggregates reasonably well, one could use these models to establish "robustness" of policy recommendations.<sup>1</sup> Yet, systematic comparisons of the empirical implications of a large variety of available models are rare. Evaluating the performance of different policies across many models typically is work intensive and costly. The six comparison projects reported in Bryant, Henderson, Holtham, Hooper, and Symansky (1988), Bryant, Currie, Frenkel, Masson, and Portes (1989), Klein (1991), Bryant, Hooper, and Mann (1993), Taylor (1999) and Hughes-Hallett and Wallis (2004) have involved multiple teams of researchers, each team working only with one or a small subset of available models. While these initiatives have helped produce some very influential insights such as the Taylor rule,<sup>2</sup> the range of systematic, comparative findings has remained limited.

This paper provides a new comparative approach to model-based research and policy analysis that enables individual researchers to conduct systematic model comparisons and policy evaluations easily and at low cost. Following this approach it is straightforward to include new models and compare their empirical and policy implications to a large number of established benchmarks.

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<sup>1</sup>Such an approach is recommended by McCallum (1988), McCallum (1999), Blanchard and Fischer (1989), Taylor (1999) and many others. McCallum (1999), for example, proposes *" to search for a policy rule that possesses robustness in the sense of yielding reasonably desirable outcomes in policy simulation experiments in a wide variety of models."* Taylor and Wieland (2009) follow this recommendation and investigate the policy implications of three well-known models of the U.S. economy available in this data base.

<sup>2</sup>Taylor (1993b) credits the comparison project summarized in Bryant et al. (1993) as the crucial testing ground for what later became known as the Taylor rule.

We start by presenting a formal exposition of our approach to model comparison. A general class of nonlinear dynamic stochastic macroeconomic models is augmented with a space of common comparable variables, parameters and shocks. Augmenting models in this manner is a necessary pre-condition for a systematic comparison of particular model characteristics. On this basis, common policy rules can be defined as model input. Then we derive comparable objects that may be produced as model output. These objects are also defined in terms of common variables, parameters and shocks. Examples for such objects are impulse response functions, autocorrelation functions and unconditional distributions of key macroeconomic aggregates. An illustrative example with two well-known small New Keynesian models is provided.

Next, we give a brief overview of the model archive that we have built. This data base includes many well-known empirically-estimated macroeconomic models that may be used for quantitative analysis of monetary and fiscal stabilization policies. These are models of the U.S. and euro area economies and several multi-country models. Some of the models are fairly small and focus on explaining output, inflation and interest rate dynamics (cf. Clarida et al (1999), Rotemberg and Woodford (1997), Fuhrer and Moore (1995), McCallum and Nelson (1999), Coenen and Wieland (2003), etc.). Others are of medium scale and cover many key macroeconomic aggregates (cf. Christiano, Eichenbaum and Evans (2005), Coenen, Orphanides, and Wieland (2004), Smets and Wouters (2003, 2007)). Some models in the data base are fairly large in scale such as the Federal Reserve's FRB-US model of Reifschneider, Tetlow, and Williams (1999), the model of the G7 economies of Taylor (1993a) or the ECB's Area-wide model of Dieppe, Kuester, and McAdam (2005). Most of the models can be classified as New Keynesian models because they incorporate rational expectations, imperfect competition and wage or price rigidities. Many of these New-Keynesian models fully incorporate recent advances in terms of microeconomic foundations. Well-known examples of this class are models by Christiano, Eichenbaum, and Evans (2005), Smets and Wouters (2003, 2007), Laxton and Pesenti (2003) and Adolfson, Laséen, Lindé, and Villani (2007). In addition, we have included models that assign little role to forward-looking behavior by economic agents (cf. the ECB's area-wide model) or none at all (cf. Rudebusch and Svensson (1999) and Orphanides (2003)).

We have created a computational platform that implements our approach to model comparison. It allows users to solve structural models and conduct comparative analysis. Comparisons of impulse response functions of common variables in response to common shocks, or of autocorrelation functions of common variables in response to model-specific shocks, or of unconditional distributions of common variables are generated. It can also be used to conduct a systematic investigation of policy rules across models. Paraphrasing Lucas (1980), *we have completed the task of writing a program that will accept specific economic policy rules as common input for multiple economic models and will generate as output a comparison of statistics describing the operating characteristics of time se-*

ries we care about, which are predicted to result from these policies according to different economic models. The platform admits nonlinear as well as linear models and allows for perturbation-based approximation of nonlinear models with forward-looking variables as well as two-point boundary value-based approximation.<sup>3</sup> New models may easily be introduced and compared to established benchmarks thereby fostering a comparative rather than insular approach to model building.

Finally, the comparative approach to modeling and policy analysis is illustrated with several examples. We compare monetary and fiscal policy shocks under alternative monetary policy rules, and investigate the predictions of different models and different policies for inflation and output persistence. A detailed description of the model comparison software and of the models included in the data base is provided in the appendices A and B, respectively.

## 2 A general approach to model comparison

Macroeconomic models differ in terms of modeling assumptions. They may include different economic concepts and therefore different variables and parameters; they may use different policy rules; and invariably they tend to use different notation and definitions of the same key macroeconomic aggregates. As a consequence, model output is not directly comparable. In the following, we describe formally how to augment any model in a way that renders comparison of policy implications across models straightforward, while keeping the number of necessary modifications of the original models at a minimum.

### 2.1 Augmenting models for the purpose of comparison

We start by introducing the notation for a general nonlinear macroeconomic model of the economy. The letter  $m$  is used to refer to a specific model considered in the comparison. Thus,  $m = (1, 2, 3, \dots, M)$  will appear as a superscript on any variables or parameters that are part of this model.<sup>4</sup> These variables or parameters need not be comparable across models nor follow particular naming conventions across models. Our notation regarding the vectors model-specific variables, parameters, and shocks is summarized in **Table 1**.

We distinguish two types of model equations, policy rules, which we denote by  $g_m(\cdot)$ , and the other equations and identities that make up the rest of the model, that we denote by  $f_m(\cdot)$ . The two types of equations together determine the endogenous model variables, which are denoted by the vector  $x_t^m$ . The model variables are functions of each other, of model-specific shocks,  $(\epsilon_t^m, \eta_t^m)$ , and

<sup>3</sup>This software is written for MATLAB and utilizes DYNARE software for model solution. For further information on DYNARE see Juillard (2001) and Juillard (1996).

<sup>4</sup>In the computational implementation  $m$  may be associated with a particular list of model names rather than a list of numbers.

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 $x_t^m$ )
$\eta_t^m$	policy shocks in model $m$
$\epsilon_t^m$	other economic shocks in model $m$
$g_m(\cdot)$	policy rules in model $m$
$f_m(\cdot)$	other model equations in model $m$
$\gamma^m$	policy rule parameters in model $m$
$\beta^m$	other economic parameters in model $m$
$\Sigma^m$	covariance matrix of shocks in model $m$

of model parameters ( $\beta^m \gamma^m$ ). A particular model  $m$  may then be defined as follows:

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

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

The superscript  $m$  refers to the original version of the respective model as supplied by the developers. 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. This assumption is for notational convenience only and should not be understood as a restriction on the type of model that is admitted.<sup>5</sup>

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

$$E([\eta_t^m \epsilon_t^m]') = 0 \quad (3)$$

$$E([\eta_t^{m'} \epsilon_t^{m'}]' [\eta_t^{m'} \epsilon_t^{m'}]) = \Sigma^m = \begin{pmatrix} \Sigma_\eta^m & \Sigma_{\eta\epsilon}^m \\ \Sigma_{\eta\epsilon}^m & \Sigma_\epsilon^m \end{pmatrix} \quad (4)$$

In the following we refer to innovations interchangeably as shocks. Some model authors instead differentiate between serially correlated economic shocks that are themselves functions of random innovations. This practice does not prevent us from including such models in a comparison. The serially correlated economic shocks of these authors would appear as elements of the vector of endogenous variables  $x_t^m$  and only their innovations would appear as shocks in our notation. Equation (4) distinguishes the covariance matrices of policy shocks and other economic shocks as  $\Sigma_\eta^m$  and  $\Sigma_\epsilon^m$ . The correlation of policy shocks and other shocks is typically assumed to be zero,  $\Sigma_{\eta\epsilon}^m = 0$ .

If one wants to compare the implications of different models, it is necessary to define a limited set of comparable variables, shocks and parameters that will be in common to all models considered

<sup>5</sup>The software implementation does not restrict the lead- and lag-lengths of participating models.

in the comparison exercise. It is then possible to express policies in terms of particular parameters, variables and policy shocks that are identical across models, and study the consequences of these policies for a set of endogenous variables that are defined in a comparable manner across models. Our notation for common endogenous variables, policy instruments, policy shocks, policy rules and parameters is introduced 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 $z_t$ )
$\eta_t$	common policy shocks in all models
$g(\cdot)$	common policy rules
$\gamma$	common policy rule parameters

Any model that is meant to be included in a comparison first has to be augmented with common variables, parameters and shocks. Augmenting the model implies adding equations. These additional equations serve to define the common variables in terms of model specific variables. We denote these definitional equations or identities by  $h_m(\cdot)$ . By their nature they are model-specific. A further step is to replace the original model-specific policy rules with the common policy rules. All the other equations, variables, parameters and shocks may be preserved in the original notation of the model developers. As a consequence, the augmented model consists of three components: (i) the common policy rules,  $g(\cdot)$ , expressed in terms of common variables,  $z_t$ , policy shocks,  $\eta_t$ , and policy rule parameters,  $\gamma$ ; (ii) the model-specific definitions of common variables in terms of original model-specific endogenous variables,  $h_m(\cdot)$ , with parameters  $\theta^m$ ; (iii) the original set of model-specific equations  $f_m(\cdot)$  that determine the endogenous variables. Thus, the augmented model may be represented as follows:

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

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

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

Models augmented in this manner can be used in comparison exercises. For example, it is possible to compare the implications of a particular policy rule for the dynamic properties of those endogenous variables that are defined in a comparable manner across models. An advantage of this approach is that it requires only a limited set of common elements. With regard to the remainder of the model the original notation used by model authors can be left unchanged, in particular the variable names and definitions of endogenous variables,  $x_t^m$ , the other economic shocks  $\epsilon_t^m$ , the equations  $f_m(\cdot)$  with

model parameters  $\beta^m$  and the covariance matrix of shocks  $\Sigma_\epsilon^m$ . The covariance matrix of policy shocks  $\Sigma_\eta$  may be treated as an element of the vector of policy parameters or constrained to zero.

The essential step in introducing a new model in a comparison exercise is to define the common variables in terms of model-specific variables. It involves setting up the additional equations,  $h_m(\cdot)$ , and determining the definitional parameters,  $\theta^m$ . We illustrate this process with an example.

#### *A simple example*

The vector of common variables,  $z_t$ , is assumed to contain six variables that are meant to be comparable across models:

$$z_t = [ i_t^z \quad g_t^z \quad \pi_t^z \quad p_t^z \quad y_t^z \quad q_t^z ]' \quad (8)$$

These variables are characterized in **Table 3**. They are expressed in percentage deviations from steady state values, because the example applies to linear models. The monetary policy instrument is

Table 3: Comparable Common Variables

Notation	Description
$i_t^z$	annualized quarterly money market rate
$g_t^z$	discretionary government spending (share in GDP)
$\pi_t^z$	year-on-year rate of inflation
$p_t^z$	annualized quarter-to-quarter rate of inflation
$y_t^z$	quarterly real GDP
$q_t^z$	quarterly output gap (dev. from flex-price level)

the annualized short-term money market rate in quarter  $t$  denoted by  $i_t^z$ . The fiscal policy instrument is discretionary government spending expressed in terms of its share in GDP and denoted by  $g_t^z$ . Economic outcomes are measured with regard to inflation, real output and the output gap.  $\pi_t^z$  denotes the year-on-year rate of inflation, while  $p_t^z$  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.<sup>6</sup>

Next, we define common monetary and fiscal policy rules. The monetary rule serves to determine the nominal interest rate,  $i_t^z$ . It includes a systematic response to output and inflation, defined in comparable terms, as well as a monetary policy shock. The fiscal rule determines discretionary government spending,  $g_t^z$ . It is simply defined as the product of a random innovation and a policy

<sup>6</sup>The latter concept of potential output is used in whichever way a particular model defines it. Another interesting exercise would be to compare different concepts of potential output and output gaps across models by introducing additional common variables.



parameter:

$$i_t^z = \gamma_i i_{t-1}^z + \gamma_p p_t^z + \gamma_q q_t^z + \eta_t^i \quad (9)$$

$$g_t^z = \gamma_g \eta_t^g \quad (10)$$

The common policy shocks and parameters are denoted by:

$$\eta_t = [ \eta_t^i \quad \eta_t^g ] \quad (11)$$

$$\gamma = [ \gamma_i \quad \gamma_p \quad \gamma_q \quad \gamma_g ] \quad (12)$$

Having defined common variables, shocks and policy parameter, we proceed to consider two simple New-Keynesian models for conducting a model comparison,  $m = \{1, 2\}$ . One model is taken from Clarida, Galí, and Gertler (1999), ( $m = 1$  refers to the model name *NK\_CGG99*), while the other one is from Woodford (2003) and based on Rotemberg and Woodford (1997), ( $m = 2$  refers to *NK\_RW97*). These are well-known benchmarks in the literature. We present the original model equations as published by the authors and then show how to augment them appropriately for a comparison exercise. This step may seem trivial in the case of such simple models, but it is nevertheless important in order to avoid a case of comparing apples and oranges.

Table 4: Model 1 - The hybrid model of Clarida et al. (1999) (*NK\_CGG99*)

Description	Equations and Definitions
<i>Original Model</i>	
variables	$x_t^1 = [ i_t \quad x_t \quad \pi_t ]'$ , $x_t^{1,g} = [i_t]$
shocks	$\epsilon_t^1 = [ g_t \quad u_t ]'$
parameters	$\beta_1 = [ \varphi \quad \theta \quad \phi ]'$ , $\gamma_1 = [ \alpha \quad \gamma_\pi \quad \gamma_x ]'$
model equations	
$g_1(\cdot)$	$i_t = \alpha + \gamma_\pi(\pi_t - \bar{\pi}) + \gamma_x x_t$
$f_1(\cdot)$	$x_t = -\varphi(i_t - E_t \pi_{t+1}) + \theta x_{t-1} + (1 - \theta)E_t x_{t+1} + g_t$
...	$\pi_t = \lambda x_t + \phi \pi_{t-1} + (1 - \phi)\beta E_t \pi_{t+1} + u_t$
<i>Augmented Model</i>	
$z_t, \eta_t, \gamma, g(\cdot)$	as defined by equations (8-12).
$f_1(\cdot)$	as defined above in original model.
$h_1(z_t, x_t^1, E_t x_{t+1}^1, x_{t-1}^1, \theta^1)$	$i_t^z = 4i_t$
...	$\pi_t^z = \pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3}$
...	$p_t^z = 4\pi_t$
...	$q_t^z = x_t$

The Clarida et al. (1999) model is presented in **Table 4**. The model in the authors' notation consists of three equations: (i) a Phillips curve relating quarterly inflation,  $\pi_t$ , to inflation expectations, past inflation, the output gap,  $x_t$ , and a cost-push shock,  $u_t$ ; (ii) an IS equation relating the current output gap to past and expected future gaps, the expected real interest rate,  $i_t - E_t\pi_{t+1}$ , and a demand shock,  $g_t$ ; (iii) and a policy rule relating the quarterly interest rate to inflation and the output gap.<sup>7</sup> Clarida et al. (1999) call it the hybrid model because it involves forward- and backward-looking elements in the Phillips and IS curves.

In the augmented version of the model the original policy rule is replaced with the common rule, equation (7). The other equations from the original model,  $f_m(\cdot) = f_1(\cdot)$ , remain unchanged. The additional equations in the augmented model,  $h_m(\cdot, \theta^m) = h_1(\cdot, \theta^1)$ , provide the appropriate definitions of common comparable variables in terms of model-specific variables.<sup>8</sup>

The Rotemberg and Woodford (1997) model is presented in **Table 5**. For simplicity, the linearized version is used. Of course, the nonlinear version could similarly be augmented for comparison purposes following the approach outlined in this paper. There are some interesting differences to the hybrid model of Clarida et al. (1999). The Rotemberg-Woodford model does not exhibit endogenous persistence due to the inclusion of lagged inflation and output in the Phillips and IS curves. Instead, however, it allows for persistence in the exogenous shocks. Furthermore, it includes government spending, the natural real interest rate and the natural level of output explicitly. The model in the notation of Woodford (2003) consists of eight equations<sup>9</sup>: (i) a policy rule determining the nominal interest rate,  $\hat{i}_t$ ; (ii) a purely forward-looking Phillips curve equation that determines quarterly inflation,  $\pi_t$ ; (iii) a forward-looking IS equation determining the quarterly output gap  $x_t$ ; (iv) a definition of the natural rate of interest,  $\hat{r}_t^n$ ; (v,vi) definitions of serially correlated government spending dynamics,  $g_t$ , and cost-push shocks  $u_t$  with random innovations,<sup>10</sup>  $\epsilon_{g,t}$  and  $\epsilon_{u,t}$ ; (vii,viii) and definitions of output,  $y_t$ , and the natural level of output,  $y_t^n$ .

## 2.2 Conducting a comparison

Given models augmented with common policy rules and comparable variables it is possible to conduct a proper comparison. It requires solving the augmented models, constructing appropriate objects for comparison, and defining a metric that quantifies the differences of interest.

<sup>7</sup>These are equations 6.1, 6.2 and 7.1 in Clarida et al. (1999) respectively.

<sup>8</sup>This model is defined in terms of the output gap relative to a variable called flexible price output without further information on the determination of said variable. Thus, a comparable definition of the level of output is not available in this model. Therefore, this model remains silent on the time series characteristics of the level of output,  $y_t^z$ , in the comparison exercise. It is important that a systematic approach to model comparison identifies such cases so as to avoid comparing apples and oranges. Furthermore, the model does not explicitly include government spending. Therefore, it also remains silent with regard to the common variable  $g_t^z$ .

<sup>9</sup>See Woodford (2003), page 246-247, equations 1.12-1.14, 2.2-2.4.

<sup>10</sup>In the quantitative analysis we rely on estimates of the autoregressive parameters in the shock processes provided by Adam and Billi (2006), while we obtained the structural parameters from Woodford (2003).

Table 5: Model 2 - The New-Keynesian model of Woodford (2003) (NK\_RW97)

Description	Equations and Definitions
<i>Original Model</i>	
variables	$x_t^2 = [ \hat{i}_t \ \pi_t \ x_t \ \hat{r}_t^n \ g_t \ u_t \ y_t \ y_t^n ]'$ , $x_t^{2,g} = [\hat{i}_t]$
shocks	$\epsilon_t^2 = [ \epsilon_{u,t} ]$ $\eta_t^{2,g} = [\epsilon_{g,t}]$
parameters	$\beta^2 = [ \beta \ \kappa \ \sigma \ \rho_g \ \rho_u \ \omega ]'$ , $\gamma_2 = [ \phi_\pi \ \phi_x \ \bar{\pi} \ \bar{x} ]'$
model equations	
$g_2(\cdot)$	$\hat{i}_t = \bar{i}_t + \phi_\pi(\pi_t - \bar{\pi}) + \frac{\phi_x}{4}(x_t - \bar{x})$
$f_2(\cdot)$	$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t + u_t$
...	$x_t = E_t x_{t+1} - \sigma(\hat{i}_t - E_t \pi_{t+1} - \hat{r}_t^n)$
...	$\hat{r}_t^n = \sigma^{-1}[(g_t - y_t^n) - E_t(g_{t+1} - y_{t+1}^n)]$
...	$g_t = \rho_g g_{t-1} + \epsilon_{g,t}$
...	$u_t = \rho_u u_{t-1} + \epsilon_{u,t}$
...	$y_t = x_t + y_t^n$
...	$y_t^n = \frac{\sigma^{-1}}{\omega + \sigma^{-1}} g_t$
<i>Augmented Model</i>	
$z_t, \eta_t, \gamma, g(\cdot)$	as defined by equations (8-12).
$f_2(\cdot)$	as defined above in original model.
$h_2(z_t, x_t^2, E_t x_{t+1}^2, x_{t-1}^2 \theta^2)$	$i_t^z = 4\hat{i}_t$
...	$g_t^z = \epsilon_{g,t}$
...	$\pi_t^z = \pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3}$
...	$p_t^z = 4\pi_t$
...	$y_t^z = y_t$
...	$q_t^z = x_t$

### Model solution

A solution to the general nonlinear model is obtained by solving out the expectations of future variables conditional on the available information. This step requires an assumption of how expectations are formed. So far, we have used the statistical expectation that is appropriate for models with rational expectations. Solution methods for linear and nonlinear models with rational expectations are available and implemented in the computational platform provided with the paper. Most of the models in the data base assume rational expectations. However, other assumptions regarding expectations formation can also be admitted.<sup>11</sup> Existence and uniqueness of equilibrium also need to be

<sup>11</sup>Examples would be the introduction of adaptive learning in the Smets and Wouters (2007) model by Slobodyan and Wouters (2007), or a version of the FRB-US model with VAR-based expectations instead of rational expectations.

checked in the solution step.<sup>12</sup> The solution of the structural nonlinear model may then be expressed in terms of the following nonlinear reduced-form equations:

$$z_t = k_z(z_{t-1}, x_{t-1}^m, \eta_t, \epsilon_t^m, \kappa_z) \quad (13)$$

$$x_t^m = k_x(z_{t-1}, x_{t-1}^m, \eta_t, \epsilon_t^m, \kappa_x) \quad (14)$$

$(\kappa_z, \kappa_x)$  denote the reduced-form parameters, which are complex functions of the structural parameters,  $\beta^m$ , the policy parameters,  $\gamma$ , and the covariance matrix  $\Sigma^m$ .

Solutions of the nonlinear model can be obtained using 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)) or by linearizing it around a deterministic steady state and using the methods of Uhlig (1995) (generalized eigenvalue-eigenvector problem), Klein (2000) (generalized Shur decomposition), Sims (2001) (QZ decomposition), Christiano (2002) (undetermined coefficients) and many others.

In the remainder of this section we consider the first-order approximation to the reduced form solution of the augmented nonlinear model and show how it may be used to obtain particular objects for comparison defined in terms of comparable variables. The first-order that is linear approximation to the nonlinear solution (or the linear solution to originally linear models as in the preceding example) is given by:

$$\begin{pmatrix} z_t \\ x_t^m \end{pmatrix} = K_m(\gamma) \begin{pmatrix} z_{t-1} \\ x_{t-1}^m \end{pmatrix} + D_m(\gamma) \begin{pmatrix} \eta_t \\ \epsilon_t^m \end{pmatrix} \quad (15)$$

where the reduced-form matrices  $K_m(\gamma)$  and  $D_m(\gamma)$  are complicated functions of the structural parameters including the policy parameters,  $\gamma$ . We denote the dependence on the other (model specific) parameters  $\beta^m$  with the subscript  $m$ .

With the linear reduced form in hand one can derive particular objects for comparison, for example, the dynamic response of a particular common variable (an element of  $z$ ) to a policy shock conditional on a certain policy rule. Impulse response functions describe the isolated effect of a single shock on the dynamic system holding everything else constant. Formally the impulse response functions in period  $t + j$  to the common monetary policy shock  $\eta_t^i$  are defined as:

$$IR_{t+j}^m(\gamma; \eta^i) = \begin{pmatrix} E[z_{t+j}|z_{t-1}, x_{t-1}^m, I_t] - E[z_{t+j}|z_{t-1}, x_{t-1}^m] \\ E[x_{t+j}^m|z_{t-1}, x_{t-1}^m, I_t] - E[x_{t+j}^m|z_{t-1}, x_{t-1}^m] \end{pmatrix} = K_m(\gamma)^j D_m(\gamma) I_t \quad (16)$$

where  $I_t$  is a vector of zeros that is augmented with a single entry equal to the size of the common policy shock, for which the impulse response is computed. Using the ordering from equation (8) and

<sup>12</sup>In linear models the Blanchard-Kahn conditions provide the necessary information. In nonlinear models one may have to resort to search by means of numerical methods.

setting  $I_t(1) = -0.01$  the sixth entry of  $IR_{t+j}^1(\gamma; \eta^i)$  gives the impulse response of the output gap in the first model (*NK\_CGG99*) to a surprise interest rate reduction of 1 percent. Similarly, the sixth entry of  $IR_{t+j}^2(\gamma; \eta^i)$  gives the impulse response of the output gap in the second model (*NK\_RW97*) to the same type of shock.

It is then straightforward to compare the impulse responses of common variables to common shocks across models and policy rules. Such a comparison provides interesting insights into the transmission channels of monetary policy. We define a metric  $s$  that measures the distance between two or more models for a given characteristic of economic time series like an impulse response function. For example, the difference in the cumulative sum of the response of the output gap to a monetary policy shock of -1 percent for the models *NK\_CGG99* ( $m = 1$ ) and *NK\_RW97* ( $m = 2$ ) is given by the sixth entry of:

$$s(\gamma, z) = \sum_{j=0}^{\infty} (IR_{t+j}^1(\gamma; \eta^i; z) - IR_{t+j}^2(\gamma; \eta^i; z)). \quad (17)$$

The index  $z$  is meant as a reminder that we can only compare the entries in the impulse response vector for the common variables, but not the model specific variables. For the two models we get  $s(\gamma, 6) = -0.0399$  under the Taylor rule, that is when the policy parameters  $\gamma$  imply an inflation reaction coefficient of 1.5, an output gap reaction of 0.5 and no interest rate smoothing.

Other possible characteristics for comparison are unconditional variances and serial correlation functions. The unconditional contemporaneous covariance matrix  $V_0^m$  for  $([z \ x^m]')$  is given by:

$$V_0^m = \sum_{j=0}^{\infty} K_m^j D_m \Sigma^m D_m' K_m^{j'} \quad (18)$$

The variance is defined by the implicit expression  $V_0^m = K_m V_0^m K_m' + D_m \Sigma^m D_m'$  and is solved for with an algorithm for Lyapunov equations. Given  $V_0^m$  the autocovariance matrices of  $([z \ x^m]')$  are readily computed using the relationship:

$$V_j^m = K_m^j V_0^m \quad (19)$$

Again, we can compute objects for comparison between models in terms of the unconditional variance or the serial correlations and cross-correlations of common variables. Then, suitable metrics for measuring the distance between two or more models may be calculated. For example, the absolute difference of the unconditional variance for the two models given by:

$$\omega = |V_0^1(z) - V_0^2(z)| \quad (20)$$

The sixth entry on the diagonal of  $\omega$  constitutes the difference of the unconditional variance of the output gaps of the two simple New-Keynesian models considered. Its value is given by  $\omega(6, 6) = 10.7919$ .

It is straightforward to construct other metrics that measure the differences between the models. In section 4 of this paper, for example, we will also study autocorrelation functions of comparable variables in different models of the U.S. economy.

### 3 A data base of macroeconomic models

Implementing the approach to model comparison outlined in the preceding section on a broader scale requires an archive of benchmark models. Individual researchers may then expand this model data base by introducing new models and conducting comparative analysis. The data base that we have created includes many well-known empirically-estimated macroeconomic models. The models implemented as of May 2009 are summarized in **Table 6**. A more detailed overview of each model is provided in appendix B. The data base may easily be expanded. The description of the model comparison software in Appendix A also includes an explanation how to incorporate new models in the data base and augment them with comparable variables.<sup>13</sup>

Currently, the data base includes estimated and calibrated models of the U.S. economy and the euro area, as well as several multi-country models. Most but not all models could be classified as New Keynesian because they incorporate rational expectations, imperfect competition and wage or price rigidities. All models are dynamic, stochastic, general equilibrium (DSGE) models if the term general equilibrium is taken to refer to economy-wide models compared to models of a particular sector of the economy. Only a subset of the models could be characterized as monetary business cycle models where all behavioral equations are derived in a completely consistent manner from the optimization problems of representative households and firms. Many authors use the term DSGE model to refer to this particular class of models. Thus, our data base offers interesting opportunities for comparing policy implications of this class of models to a broader set of empirically estimated, dynamic, stochastic, economy-wide macro models. While most of the models assume that market participants form rational, forward-looking expectations, we have also included some models which assume little or no forward-looking behavior.<sup>14</sup> In our view, comparative analysis of these classes of models will be useful to evaluate recently voiced criticisms that the new models are rendered invalid by the experience of the world financial crisis.

The models are grouped in four categories in **Table 6**. The first category includes small, calibrated versions of the basic New-Keynesian model such as the two models discussed in section 2. These models concentrate on explaining output, inflation and interest rate dynamics. Some of them are

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<sup>13</sup>In the future, we plan to develop an interactive software that helps automate the process of including models that model authors have implemented in DYNARE.

<sup>14</sup>For example, the models of Rudebusch and Svensson (1999) and Orphanides (2003) are essentially structural VAR models with some restrictions on some of the coefficients. The ECB's Area-Wide Model is a medium-size structural model but with a relatively limited role for forward-looking behavior compared to the other structural, rational expectations models in the data base.

calibrated to U.S. data. The model taken from Clarida, Gali, and Gertler (2002) is a two-country version of the basic New-Keynesian model.

The second category covers estimated models of the U.S. economy. It includes small models of output, inflation and interest rate dynamics such as Fuhrer and Moore (1995) and Rudebusch and Svenson (1999). Other models are of medium scale such as Orphanides and Wieland (1998) or the well-known models of Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007) that fully incorporate recent advances in terms of microeconomic foundations. The data base includes the version of Christiano, Eichenbaum and Evans model estimated by Altig, Christiano, Eichenbaum and Linde (2004) because it contains other economic shocks in addition to the monetary policy shock studied by Christiano et al (2005). Because of complications in programming the informational timing assumptions on expectations in this model in DYNARE, two versions are included, one version for simulating the consequences of the monetary policy shock and the other version for simulating the consequences of the other economic shocks in the model. Furthermore, we have included an additional version of the Altig et al (2004) model used in Taylor and Wieland (2009) that omits the cost-channel of monetary policy.<sup>15</sup> The largest model of the U.S economy in the data base is the Federal Reserve's FRB-US model of Reifschneider et al. (1999). We have included a linearized version of this model with rational expectations that was previously used in Levin et al (2003).

The third category in **Table 6** covers estimated models of the euro area economy. Four of these models have been used in a recent study of robust monetary policy design for the euro area by Kuester and Wieland (2009): the medium scale model of Smets and Wouters (2003), two small models by Coenen and Wieland (2005) that differ by the type of staggered contracts inducing inflation rigidity, and a linearized version of the Area-Wide Model used at the ECB for forecasting purposes. In addition, we have included an estimated DSGE model of the euro area recently developed at the Sveriges Riksbank.

The fourth category includes estimated and calibrated models of two or more economies. Currently, the largest model in the data base is the estimated model of the G7 economies of Taylor (1993). The estimated model of Coenen and Wieland (2003) with rational expectations and price rigidities aims to explain inflation, output and interest rate dynamics and spill-over effects between the U.S.A., the euro area and Japan. The model of Laxton and Pesenti (2003) is a two-country model with extensive microeconomic foundations calibrated to the economies of the euro area and the Czech republic. The Federal Reserve's SIGMA model is similarly rich in microeconomic foundations. The parameters in the two-country version of this model from Erceg et al (2008) are calibrated to the U.S. economy and a symmetric twin.

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<sup>15</sup>This version was created in Taylor and Wieland (2009) to evaluate the effect of this assumption in comparing the Altig et al (2004) model with the model of Smets and Wouters (2007) that features no such cost channel.

Table 6: MODELS CURRENTLY AVAILABLE IN THE DATA BASE (MAY 2009)

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1. SMALL CALIBRATED MODELS

- 1.1 NK\_RW97 Rotemberg and Woodford (1997)
- 1.2 NK\_LWW03 Levin et al. (2003)
- 1.3 NK\_CGG99 Clarida et al. (1999)
- 1.4 NK\_CGG02 Clarida et al. (2002)
- 1.5 NK\_MCN99cr McCallum and Nelson (1999), (Calvo-Rotemberg model)
- 1.6 NK\_MCN99pb McCallum and Nelson (1999), (P-bar model)

2. ESTIMATED US MODELS

- 2.1 US\_FM95 Fuhrer and Moore (1995a)
- 2.2 US\_OW98 Orphanides and Wieland (1998) equivalent to MSR model in Levin et al. (2003)
- 2.3 US\_FRB03 Federal Reserve Board model linearized as in Levin et al. (2003)
- 2.4 US\_SW07 Smets and Wouters (2007)
- 2.5 US\_ACElm Altig et al. (2005), (monetary policy shock)
- US\_ACELt Altig et al. (2005), (technology shocks)
- US\_ACElswm no cost channel as in Taylor and Wieland (2009) (mon. pol. shock)
- US\_ACElswt no cost channel as in Taylor and Wieland (2009) (tech. shocks)
- 2.6 US\_RS99 Rudebusch and Svensson (1999)
- 2.7 US\_OR03 Orphanides (2003)

3. ESTIMATED EURO AREA MODELS

- 3.1 EA\_CW05ta Coenen and Wieland (2005), (Taylor-staggered contracts)
- 3.2 EA\_CW05fm Coenen and Wieland (2005), (Fuhrer-Moore-staggered contracts)
- 3.3 EA\_AWM05 ECB's area-wide model linearized as in Dieppe et al. (2005)
- 3.4 EA\_SW03 Smets and Wouters (2003)
- 3.5 EA\_SR07 Sveriges Riksbank euro area model of Adolfson et al. (2007)

4. ESTIMATED/CALIBRATED MULTI-COUNTRY MODELS

- 4.1 G7\_TAY93 Taylor (1993a) model of G7 economies
  - 4.2 G3\_CW03 Coenen and Wieland (2002) model of U.S.A, euro area and Japan
  - 4.3 EACZ\_GEM03 Laxton and Pesenti (2003) model calibrated to euro area and Czech republic
  - 4.4 G2\_SIGMA08 The Federal Reserve's SIGMA model from Erceg et al. (2008) calibrated to the U.S. economy and a symmetric twin.
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## 4 Comparing monetary and fiscal policies across models: An example

We have created a computational platform that renders comparisons of impulse response functions of common variables in response to common shocks, comparisons of autocorrelation functions of common variables in response to model-specific shocks and systematic investigations of policy rules across models straightforward. This result may be described by paraphrasing Lucas (1980) as follows: *we have completed the task of writing a program (in MATLAB instead of FORTRAN) that will accept specific economic policy rules as common comparable input for multiple economic models and will generate as output a comparison across models of statistics describing the operating characteristics of time series we care about, which are predicted to result from these policies according to different economic models.* The computational platform utilizes DYNARE software for model solution.<sup>16</sup> New models may easily be introduced and compared to established benchmarks thereby fostering a comparative rather than insular approach to model building. A detailed description of the model comparison software is provided in **appendix A**.

The software implementation and model database discussed in the preceding section contain a generalized interest rate rule that allows for much richer specifications than equation (9). For the comparison exercise in this paper, we consider five parameterizations of this generalized rule that are taken from Taylor (1993b), Levin et al. (2003), Smets and Wouters (2007), Christiano, Eichenbaum and Evans (2005) and Gerdesmeier and Roffia (2004), respectively. The specific formulas are shown in **Table 7**.

Table 7: POLICY RULES

Taylor (1993b):	$i_t^z = \sum_{j=0}^3 0.38p_{t-j}^z + 0.50q_t^z + \eta_t^i$
Levin et al. (2003):	$i_t^z = 0.76i_{t-1}^z + \sum_{j=0}^3 0.15p_{t-j}^z + 1.18q_t^z - 0.97q_{t-1}^z + \eta_t^i$
Smets and Wouters (2007):	$i_t^z = 0.81i_{t-1}^z + 0.39p_t^z + 0.97q_t^z - 0.90q_{t-1}^z + \eta_t^i$
Christiano et al. (2005)	$i_t^z = 0.8i_{t-1}^z + 0.3E_t p_{t+1}^z + 0.08q_t^z + \eta_t^i$
Gerdesmeier and Roffia (2004):	$i_t^z = 0.66i_{t-1}^z + \sum_{j=0}^3 0.17p_{t-j}^z + 0.10q_t^z + \eta_t^i$

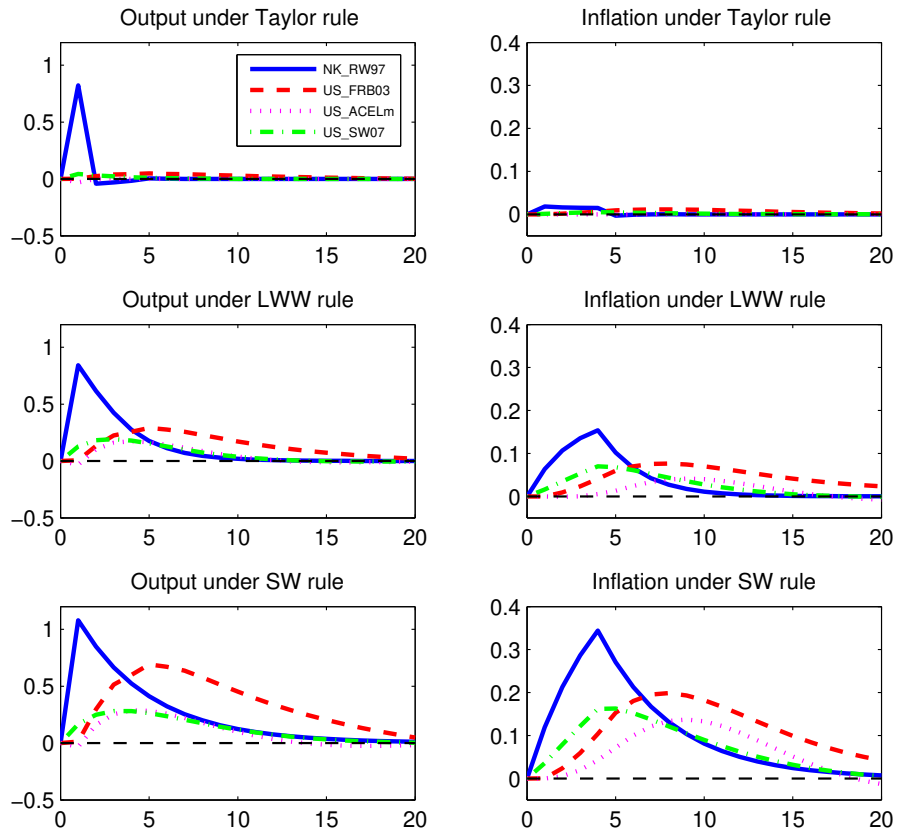
The first rule in the table, that is the simple monetary policy rule of Taylor (1993b) is well-known beyond academic economics and central banks for the following reasons. In the 1990s it became

<sup>16</sup>It admits nonlinear as well as linear models and allows approximating nonlinear models with forward-looking variables with perturbation or two-point-boundary-value methods. For further information on DYNARE see Juillard (2001) and Juillard (1996).

widely known that this rule described Federal Reserve interest rate decisions since 1987 surprisingly well. More recently, the large deviation of Federal Reserve policy from this rule between 2002 and 2006 has been cited as the source of cheap money fueling a housing bubble in the United States that ultimately triggered the world financial crisis. Perhaps little known is that Taylor (1993b) credits the comparison exercise of Bryant et al (1993) as the crucial testing ground that helped select this particular simple rule. Variations of the rule, motivated either by empirical estimation or model performance, abound in the literature. For comparison, we consider a rule originally estimated with U.S. data by Orphanides and Wieland (1998) and simulated in five models of the U.S. economy by Levin et al. (2003) (LWW). Their choice of models is included in our data base. The LWW rule allows for interest-rate smoothing and includes the lag of the output gap in addition to current inflation and the output gap that make up the Taylor rule. Smets and Wouters (2007) (SW) have estimated the same type of rule with interest smoothing, current inflation, current and past output gaps using Bayesian techniques together with the other structural parameters of their model. Christiano, Eichenbaum and Evans (2005) consider a different policy rule that they attribute to Clarida, Gali and Gertler (1999). Their rule includes a response to the forecast of inflation rather than current inflation. It has also been studied in Taylor and Wieland (2009). Furthermore, we add a rule estimated with Euro area data. This rule is due to Gerdesmeier and Roffia (2004) and has been simulated in Kuester and Wieland (2009) in four models of the euro area economy that are also included in our data base.

Finally, the comparative approach to macroeconomic modeling and policy analysis is applied with several examples. We compare monetary and fiscal policy shocks under alternative monetary policy rules and investigate the predictions of different models and different policies for inflation and output persistence. **Figure 1** reports on the effect of a monetary policy shock on output and inflation in four different models of the U.S. economy under the Taylor rule, the LWW rule and the SW rule. The models considered are the calibrated New-Keynesian model of Rotemberg and Woodford (1997) from **Table 2** (NK\_RW97, solid blue line), the Federal Reserve's FRB-US model from Levin et al. (2003) (US\_FRB03, red dashed line), the model of Smets and Wouters (2007) (US\_SW07, green dashed-dotted line) and the model of Altig et al. (2005) (US\_ACELM, pink dotted line). The particular shock considered is a one time unexpected reduction of the nominal interest rate of 1 percentage point. Following the initial shock the nominal interest rate path corresponds to the prescriptions of the policy rule. Three rules are compared by the three rows of panels in **Figure 1**, the Taylor, LWW and SW rules.

Figure 1: NEGATIVE MONETARY POLICY SHOCK

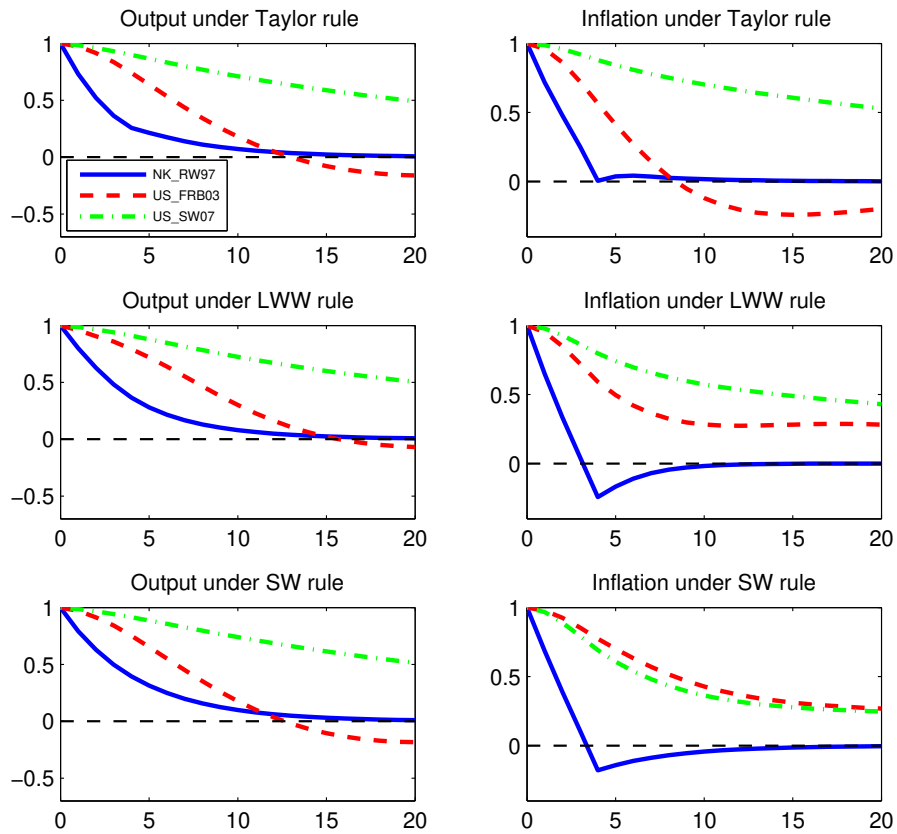


The simulation results exhibit the following findings regarding the transmission of a monetary policy shock. All four models exhibit nominal rigidities and therefore indicate that a monetary shock affects real output as indicated by the left column of panels. Under the Taylor rule, the effect on output is short-lived. In three of the four models the effect is also very small. The exception is the simple calibrated New Keynesian model (NK\_RW97) which indicates a sharp large but temporary boost to output. Under the LWW and SW rules the effect on real output in the US\_SW07, US\_ACELm and FRB\_03 models builds up over time. The reason for the larger and longer-lasting effect on real output lies in the persistent effect of the shock on interest rates due to the near-unity reaction coefficient on the lagged interest rate in these two rules. In NK\_RW97 the effect on real output remains sharp and large but also peters out more slowly. An interesting difference between FRB\_03 and the other models is that the peak effect of the monetary shock on real output in FRB\_03 is reached only in the second year but in the first year in the other models. Thus, the models that incorporate recent advances in microeconomic foundations contradict conventional policy maker wisdom regarding "long" policy

lags of more than one year. The reason for this finding is that these models give more room to the possibility of forward-looking and optimizing behavior by households and firms. The effects of the monetary shock on real output in the two estimated DSGE models with microeconomic foundations are almost identical as already noted by Taylor and Wieland (2009).

The effects of a monetary policy shock on inflation (second column of panels) are more drawn out with the peak effect occurring later than the peak in output, typically in the second or third after the initial shock. Again, the results from the calibrated simple New-Keynesian model (NK\_RW97) appear too extreme relative to the findings from the empirically-estimated models.

Figure 2: AUTOCORRELATION FUNCTIONS



**Figure 2** reports the autocorrelation functions of output and inflation under the Taylor, LWW and SW monetary policy rules. These time series characteristics are derived assuming that shocks are drawn from the empirical distribution of structural shocks of these models. Only the variance of the monetary policy shock is set to zero. The Altig et al. (2005) model is omitted from the comparison because the two non-monetary shocks in that model explain only a relatively small part of the

empirical output and inflation volatility in the U.S. economy (see Taylor and Wieland (2009)). The small calibrated New-Keynesian model (NK\_RW97) exhibits the lowest degree of output and inflation persistence among the three remaining models whichever policy rule is considered. As discussed in section 2 this model does not allow for lagged terms of inflation and output in the New-Keynesian IS and Phillips curves. Only, the exogenous shocks exhibit persistence in that model. The Federal Reserve's estimated model of the U.S. economy, however, implies a larger degree of output and inflation persistence. Thus, better empirical fit is obtained by allowing for a richer set of dynamics and adjustment costs that imply the appearance of one or more lags of endogenous variables in key behavioral equations.

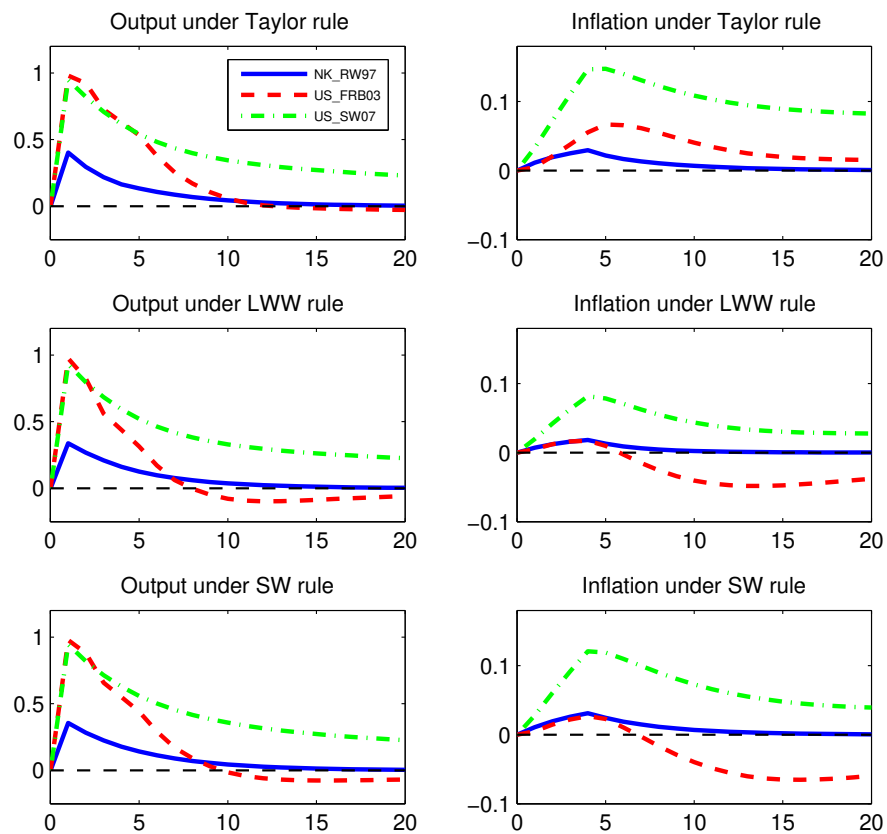
A rather surprising finding is that the estimated DSGE Model of Smets and Wouters (2007) exhibits the highest degree of output persistence under all three policy rules, even under the SW rule that is estimated along with the model. One might have expected that this model with microeconomic foundations would lie somewhere in between the small calibrated model of Rotemberg and Woodford (1997) and the FRB-US model. Much criticism of models such as the Federal Reserve's model was that they introduce too many adjustment costs and therefore too much endogenous persistence. Given our findings one might therefore suspect that Smets and Wouters (2007) have built in too much persistence in their model, a criticism recently voiced by Chari, Kehoe and McGrattan (2009). It would be of interest to further investigate the sources of persistence in this model in future work.

Next, we turn to an evaluation of the consequences of a government spending shock of 1 percent of GDP in the three models. The fiscal policy rule for discretionary government spending is defined as in section 2 by equation (10) with a coefficient  $\gamma_g$  of unity. The estimated degree of persistence of such a shock to government spending differs in each model. Its implications for output and inflation are shown in **Figure 3**. In all three models, the initial shock causes output to increase in the same quarter, followed by a slow drawn-out decline over subsequent years. This profile holds under all monetary policies considered. The magnitude of the effect is rather similar for the monetary rules considered, but differs a lot across models. The impact effect is smallest in the small New-Keynesian model around 0.4 percent of output, compared to about 1 percent of output in the other two models. Thus, private consumption and investment are crowded out immediately in the small model. In the other two models, private consumption and investment also decline from the start but more slowly. Somewhat surprisingly, output declines faster and inflation increases less in the US\_FRB03 model than in the US\_SW07 model.

Comparative evaluations of the consequences of fiscal policy and the robustness of policy recommendations for fiscal stimulus are particularly urgent given the amount of resources to such measures recently. Cogan et al. (2009) provide a first assessment of the American Recovery and Reinvestment of 2009. Their analysis based the Smets and Wouters (2007) model and the Taylor (1993) model

from this data base suggests that the estimates of fiscal multipliers implied by government advisers (cf. Romer and Bernstein (2009)) are far too optimistic and not robust to model uncertainty. The simulation in **Figure 3** suggests that an evaluation using the US\_FRB03 model with rational expectation would result in similar conclusions, while the NK\_RW97 model would provide an even more pessimistic assessment. Interestingly, the US\_FRB03 considers different components of government spending such as federal versus state expenditures and government consumption versus government investment. The shock simulated here is spread across all components according to their steady-state shares in total government spending. Further studies evaluating the non-linear timing and anticipation effects of such fiscal stimulus packages highlighted by Cogan et al (2009) would also be of interest.

Figure 3: FISCAL POLICY SHOCK



## 5 Conclusion

This paper provides a new comparative approach to model-based research and policy analysis that enables individual researchers to conduct model comparisons easily, frequently, at low cost and on

a large scale. Using this approach a model archive is built that includes many well-known empirically estimated models that may be used for quantitative analysis of monetary and fiscal stabilization policies. A computational platform is created that allows straightforward comparisons of models' implications. Its application is illustrated by comparing different monetary and fiscal policies across selected models. Researchers can easily include new models in the data base and compare the effects of novel extensions to established benchmarks thereby fostering a comparative instead of insular approach to model development. Wide application of this approach could help dramatically improve the replicability of quantitative macroeconomic analysis, reduce the danger of circular developments in model-based research and strengthen the robustness of policy recommendations.

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## A How to use the model comparison software (MMB Version 1.0)

Appendix A gives a thorough description of how to install and use the macro model data base (MMB Version 1.0). After reading subsections A.1 and A.2 you should be able to run the program and do your own comparison exercises employing the models and options contained in the data base. Subsections A.3 and A.4 explain the structure of the macro model data base files in more detail. Finally, subsection A.5 discusses how one can add additional models to the data base.

### A.1 Installation and software requirements

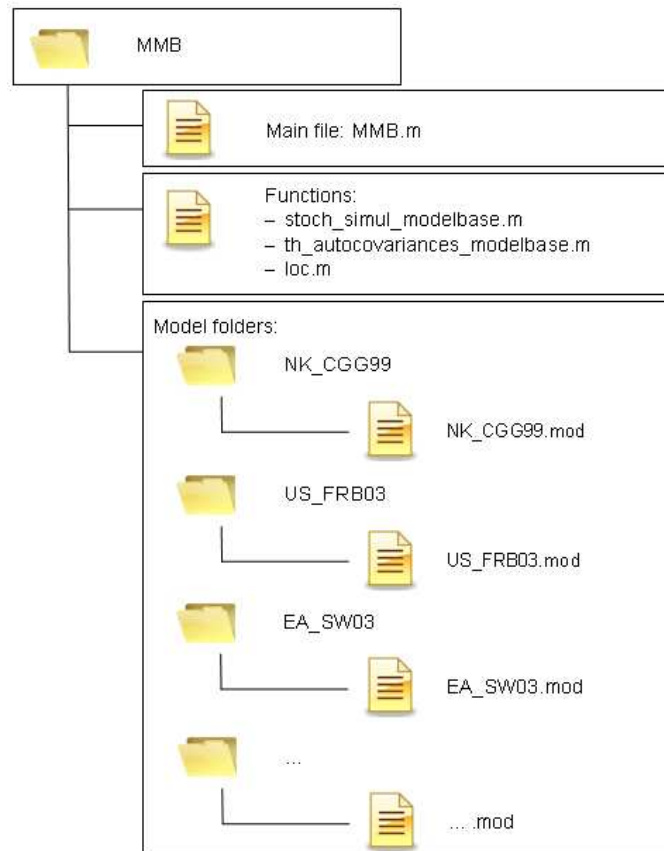
The complete macro model data base is contained in a zip file called *MMB.zip* which you may store to any place on your computer. In order to use the model data base, you have to extract the zip file to retrieve the folder *MMB*. This folder contains the file *MMB.m*, a set of subfolders, one for each model included in the model data base, and a few additional MATLAB function files. Figure 4 illustrates the structure of the model data base. Each model subfolder contains a single Dynare mod-file in which the particular model is specified.

Since the program is written in MATLAB, you need a version of it installed on your computer. For model solution the program utilizes DYNARE version 3, which can be downloaded freely from the web.<sup>17</sup> Double-clicking on the downloaded DYNARE exe-file opens a setup which guides you through the installation. After completion, one has to add the DYNARE path to MATLAB. In order to do so, open Matlab and choose *Set path* from the *File* menu. Use the option *Add folder* and browse to the directory where you have installed DYNARE version 3. The DYNARE subfolder that has to be added is called *matlab*.

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<sup>17</sup>The URL of the DYNARE website is <http://www.cepremap.cnrs.fr/dynare/>. Version 3 of the DYNARE software can be downloaded by choosing *Download* from the main menu and then *Dynare for Matlab* from the submenu of the website.

Figure 4: STRUCTURE OF THE MACRO MODEL DATA BASE



## A.2 Using the macro model data base

*MMB.m* represents the main file which has to be called when using the model data base. In order to run *MMB.m*, you can either open the file in MATLAB, which automatically adjusts the current directory of MATLAB to the correct path, and click the *run* button or you only open MATLAB and adjust the current directory to the path for the *MMB* folder manually. In the latter case you afterwards type *MMB* into the MATLAB command window and press the *Enter* button. In both cases a user interface opens that will guide you through a menu of options from which you can choose. These options include the choice of models you want to use, the selection of a common monetary policy rule used for the analysis as well as the choice of the statistics and visual output that you want to be displayed. By default the output generated by the program will be stored in an excel sheet called *results.xls* in the *MMB* folder. This can be customized by the individual user in the first lines of the *MMB.m* file. Once the file is executed, a list of the models included in the data base and its references

is displayed in the MATLAB command window. The menu structure is illustrated in figure 5. In the following, each menu option is described step by step.

Figure 5: MACRO MODEL DATA BASE MENU: CHOICE OF POLICY RULE AND MODELS

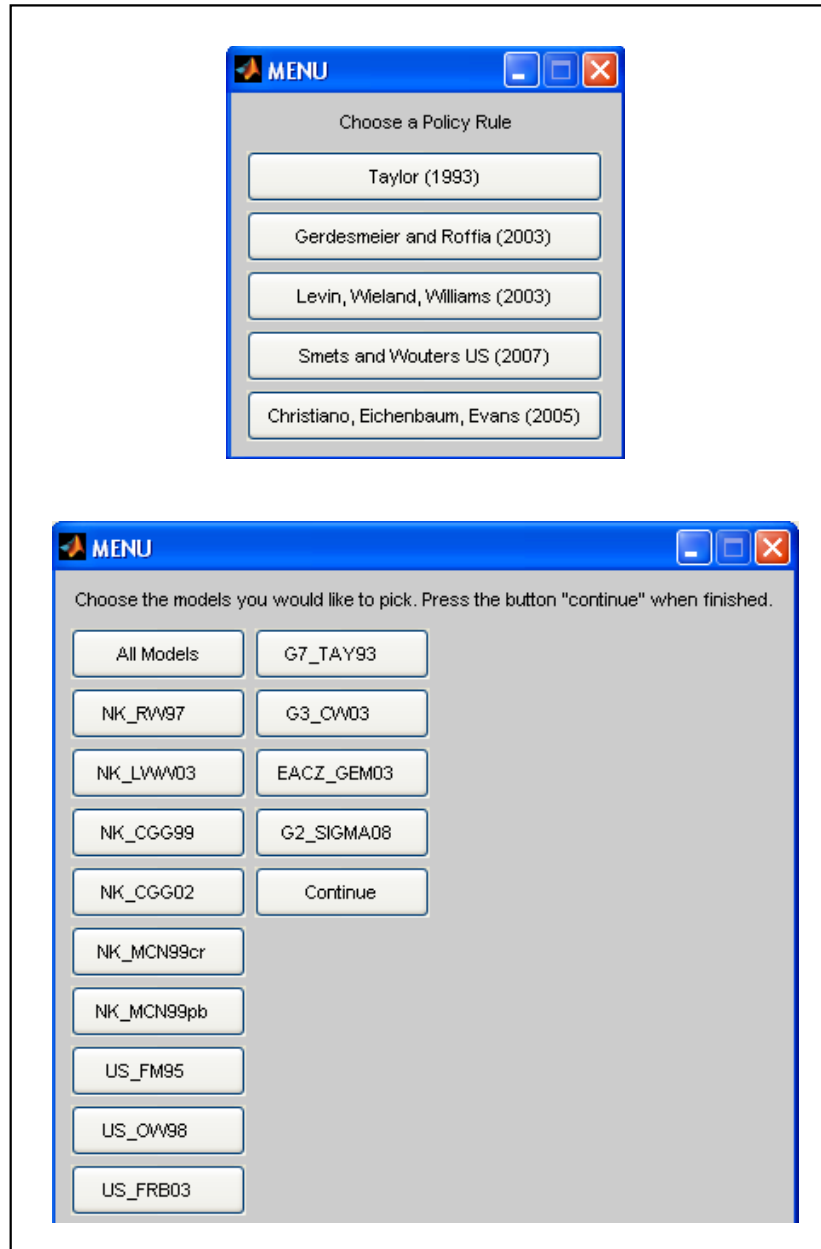
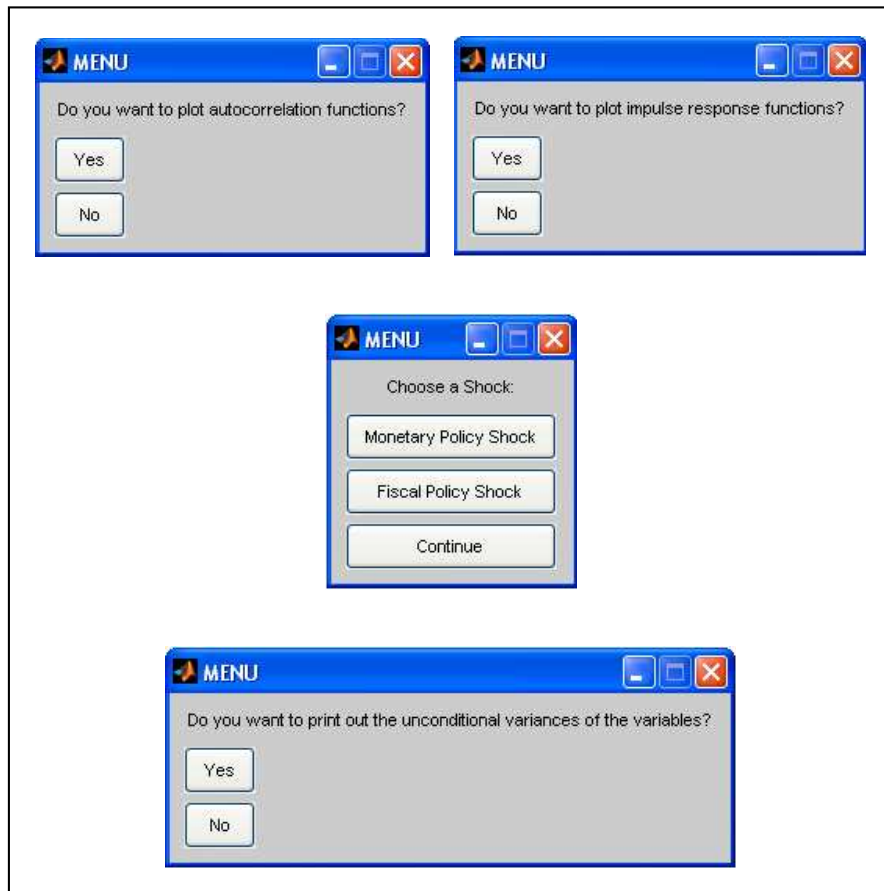


Figure 6: MACRO MODEL DATA BASE MENU: CHOICE OF STATISTICS



#### *Choosing a monetary policy rule*

Once the *MMB.m* file is executed a menu appears that allows you to select a particular interest rate rule. The original interest rate rules of the models in the data base have been replaced with a fairly general monetary policy rule that allows many possible parameterizations. In the MMB Version 1.0 it is possible to choose among the five parameterizations discussed in section 3 of this paper and listed in table 7. A particular rule is chosen by clicking on the respective button in the menu. Only one rule may be selected. The name of the chosen rule will be displayed in the MATLAB command window.

#### *Selecting the models*

Next, a menu with a list of all models included in the data base appears. One can select as many models as desired by clicking on the respective model button. The name of each selected model will be listed in the command window. In order to proceed to the next menu you have to click on the continue button. You can also choose to use all models by clicking on the corresponding button. Be aware that in this case it might take quite some time until all models are solved. Table 6 in the main

part of the paper lists the models contained in the MMB version 1.0. A short description of each of these models is given in appendix B.

### *Choosing statistics and graphical output*

Having chosen the models and a policy rule, the user can make some choices regarding the output to be displayed. First, a menu pops up where the user can decide whether to plot autocorrelation functions of the common variables. Afterwards, one can decide whether to plot impulse response functions. In case only one model is selected, one has the option to shock several innovations contemporaneously. Impulse responses can be plotted for a unit monetary policy shock and a unit fiscal policy shock. In case only one model is selected, one can also choose among the original shocks of the model. Finally, the user can choose to display the unconditional variances of the common variables for each of the selected models. The choices will again be documented in the command window. The numerical results for the selected options will be stored in an excel sheet called *results.xls* in the *MMB* folder.

### **A.3 Structure of the *MMB.m* file**

*MMB.m*, the main file of the model data base, is divided into three parts: An initialization part, where the macroeconomic models are listed, some basic functions of the model data base are described and choices of models, policy rules, shocks and computations are made. In the second part of the file the models are solved using Dynare and impulse response functions and autocorrelation functions are computed. The third part is devoted to the presentation of the results, i.e. setting up graphs of the chosen statistics. As we use cell mode one can easily see where each block starts and ends.<sup>18</sup> The structure of the *MMB.m* file is illustrated in figure 7. All variables used and generated in this file are saved in a structure variable called *modelbase*. For example the number of periods to be plotted can be found by typing *modelbase.horizon*. Table 8 lists the most important variables in the structure variable *modelbase*. In the following, the three separated parts of *MMB.m* are explained in more detail.

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<sup>18</sup>A cell starts with two comment sign, i.e. with *%%*. When setting the cursor in a cell, the background colour of this cell turns to yellow and can thus easily be spotted.

Figure 7: STRUCTURE OF THE *MMB.m* FILE

<b>1. Initialization</b>
Introductory textblock
Defining vectors of models
Specification of general policy rule
Initializing a choice set of policy rules
Programming user menus
<b>2. Solving the model and computing statistics</b>
Storing user choices
Initializing a loop over selected models
Stepwise model solution
Storing model solutions and statistics
<b>3. Plotting the results</b>
Extracting statistics for common variables
Plotting results as chosen by the user



Table 8: KEY VARIABLES OF THE *MMB.m* FILE

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---

modelbase.totaltime	total CPU time (in seconds) used by the modelbase
modelbase.savepath	path for the excel file that contains the output
modelbase.names	names of all models
modelbase.variabledim	dimension of model-specific shocks
modelbase.horizon	number of periods to be plotted
modelbase.mycolor	color vector for the graphs
modelbase.rule	chosen rule
modelbase.models	chosen models
modelbase.option(1)	autocorrelation functions
modelbase.option(2)	impulse response functions
modelbase.option(3)	shock several innovations contemporaneously
modelbase.option(4)	plot impulse responses for original model variables
modelbase.option(5)	unconditional variances of common variables
modelbase.homepath	path of the modelbase folder
modelbase.namesshock	names of shocks contained in the modelbase
modelbase.innos	chosen shocks
modelbase.modeltime	CPU time (in seconds) used for solving each model
modelbase.setpath	paths of the modelfolders of chosen models
modelbase.epsilon	counts the number of loops
modelbase.info	equals 1 if a model has no determinate solution; otherwise 0
modelbase.AUTR	contains the autocorrelation functions
modelbase.AUTlgy_	contains variable names that correspond to the autocorrelation functions
modelbase.IRF	contains the impulse response functions
modelbase.IRF_lgy_	contains variable names that correspond to the impulse response functions

---



---

*Part 1 of MMB.m: Initialization*

This first block of the *MMB.m* file is the only part where the user has to make changes when adding a model. First the most important instructions on how to use the macro model data base and how to add models to it are repeated within a text block of comment lines. Detailed instructions on adding models to the data base can be found in subsection A.5. Afterwards some namevectors for the models are set up. A variable of interest for the user is *modelbase.horizon*. If you want to change the number of periods that are plotted, you need to modify this entry. The vector *names* contains the names of the models. These are used later on to produce proper legends of the graphs. The vector *mycolors* contains a line specification for each model for the graphs that are plotted in part 3 of the file. When adding new models to the data base the number of models might exceed the entries in *mycolors* at some time. In this case the user needs to add some entries to this vector.

A text block follows that describes a very general monetary policy rule that is used for each model and

that nests the policy rules listed in table 7. For each rule it is shown how the original representation is transformed into the respective general rule representation. The parameters in the general policy rule are denoted according to the following scheme: The first three letters are *cof* to indicate a coefficient rather than a variable. The next three letters are *int*, which are the first three letters of *interest* as in this equation the interest rate is pinned down. The next three letters are the first three letters of the variable the coefficient corresponds to, c.f. *cofintout* for the output gap coefficient in the interest rate equation. The next letter is either *f* for coefficients of forward looking variables, *b* for coefficients of backward looking variables and the letter is just left out for contemporaneous variables. A number follows that indicates the number of leads or lags. An example is the coefficient on expected inflation next period: *cofintinfl*.

Below the general policy rule a menu with the name *rule* to choose among the policy rules is programmed. Afterwards, the parameters of the general policy rule are specified according to the specific policy rule chosen and stored in the file *policy\_param.mat*. The parameters are loaded later on in the specific model files to initialize the chosen policy function. If one wants to add an additional policy rule to the macro model data base, one can easily extend the policy rule menu and add an additional specification of the parameters of the general policy rule. It is not necessary to change the model files.

A second menu with the name *model* is set up where the user can choose a subset of the models contained in the model database. The identification numbers of the chosen models are saved in the vector *models*. Menus that let us choose whether to plot autocorrelation functions, impulse response functions and whether to shock monetary or fiscal policy follow. As in the model files the monetary policy shock has the name *interest\_* and the fiscal policy shock has the name *fiscal\_*. This convention is important to address the shocks of the right equations after having solved the model.

### *Part 2 of MMB.m: Solving the model and computing statistics*

Before solving the models using Dynare all choices made so far have to be saved in the file *Modelbase* as Dynare clears the workspace before solving a model. A loop over all models that are saved in the vector *modelbase.models* is initialized. For every cycle of the loop the current directory is changed according to the entries of the vector *modelbase.names* to the subfolder of the specific model that is used during the current cycle. Using the command *dynare* followed by the model abbreviation, c.f. *dynare NK\_CGG99* to solve the model of Clarida et al. (1999), calls the software Dynare to translate the Dynare syntax in a convenient way.

Afterwards the function *stoch\_simul\_modelbase.m* is called to solve the model and compute autocorrelation functions, impulse response functions and unconditional variances. The results are appended to the file *Modelbase* before we return to the beginning of the loop to solve the next model.

### *Part 3 of MMB.m: Plotting the results*

Having solved the models the last part of the *MMB.m* file is devoted to processing and presenting the results. Therefore, figures for impulse response functions of the common variables to each shock and autocorrelation functions are set up and plotted for each model. The common variables can be easily identified within the whole output of each model using the function *loc* that searches for positions of string variables in vectors like *modelbase.IRFly\_*.

#### **A.4 Structure of the model files**

The model files are written in the syntax Dynare and have a common structure. As an example we take the simple New-Keynesian model by Rotemberg and Woodford (1997) to explain the structure of the mod-files, its model specific parts and the common model data base blocks. The mod-file is shown in figures 8 and 9. However, the explanations apply to all models. In the following, the two main parts of a mod-file, the preamble and the model block, are described step by step.

Figure 8: STRUCTURE OF THE MODEL FILES: THE PREAMBLE

```

1 // Model: NK_RW97
2
3 var pi y ynat rnat i x u g g_
4
5 //*****
6 // Modelbase Variables //*
7     interest inflation inflationq outputgap output fispol; //*
8 //*****
9
10 varexo u_
11
12 //*****
13 // Modelbase Shocks //*
14     interest_ fiscal_; //*
15 //*****
16
17 parameters beta sigma alpha theta omega kappa rhou rhog stdinflation_ stdfiscal_
18
19 //*****
20 // Modelbase Parameters //*
21 //*
22     cofintintb1 cofintintb2 ... coffispol; //*
23 //*****
24
25 beta = 1/(1+0.035/4);
26 sigma= 6.25;
27 alpha= 0.66;
28 theta= 7.66;
29 omega= 0.47;
30 kappa= (((1-alpha)*(1-alpha*beta))/alpha)*(((1/sigma)+omega)/(1+omega*theta));
31 rhou=0;
32 stdinflation_=0.154;
33 rhog= 0.8;
34 stdfiscal_=1.524;
35
36 //*****
37 // Specification of Modelbase Parameters //*
38 //*
39 // Load Modelbase Monetary Policy Parameters //*
40     thispath = cd; //*
41     cd('.'); //*
42     load policy_param.mat; //*
43     cd(thispath); //*
44 //*
45 // Definition of Discretionary Fiscal Policy Parameter //*
46 coffispol = 1; //*
47 //*****

```

Figure 9: STRUCTURE OF THE MODEL FILES: THE MODEL BLOCK

```

49 model(linear);
50
51 //*****
52 // Definition of Modelbase Variables in Terms of Original Model Variables //
53
54 interest = i*4; //
55 inflation = (1/4)*(4*pi+4*pi(-1)+4*pi(-2)+4*pi(-3)); //
56 inflationq = pi*4; //
57 outputgap = x; //
58 output = y; //
59 fispol = g_; //
60 //*****
61
62
63 //*****
64 // Policy Rule //
65 // //
66 // Monetary Policy //
67 // //
68 interest = cofintintb1*interest(-1) //
69           + cofintintb2*interest(-2) //
70           ... //
71           + cofintoutf4*outputgap(+4) //
72           + std_r_*interest_; //
73 // //
74 // Discretionary Government Spending //
75 // //
76 fispol = coffispol*fiscal_; //
77 //*****
78
79 // Original Model Code:
80
81 pi = beta * pi(+1)+ kappa*x+ u;
82 u=rhou*u(-1)+u_;
83 x = x(+1) - sigma *( i - pi(+1) - rnat) ;
84 rnat = sigma^(-1)*((g-ynat)- (g(+1)-ynat(+1)));
85 ynate = sigma^(-1)*g / (sigma^(-1)+omega);
86 x = y-ynate;
87 g = rhog*g(-1) + g_;
88 end;
89
90 shocks;
91 var fiscal_ = 1.524^2;
92 var u_ = 0.154^2;
93 end;
94
95 //stoch_simul (irf = 0, ar=100, noprint);

```

### Part 1: The preamble

- Each model file begins with some information about the model. This should include the title, the authors, the publication etc. In front of this description you will find the symbols `//`, which denote a comment in Dynare.
- The file then starts with the initialization of the model variables. In our example given in figure 8 the model-specific endogenous variables are listed in line 3 after the keyword `var`: `pi`, `y`, `ynat`, `rnat`, `i`, `x`, `u`, `g` and `g_`. The latter in fact represents an exogenous government spending shock, however it has to be initialized as endogenous variable for reasons that will be explained below. It follows a Modelbase block in lines 5 to 8 in which the common variables are introduced. In general, Modelbase blocks are separated through `/**/` symbols from the rest of the file.
- Following the keyword `varexo` in line 10 the exogenous variables are initialized. In our example this is `u_`, a cost push shock as well as the common interest rate shock, `interest_` and the common fiscal policy shock, `fiscal_` in line 14. Note that in some models with no treatment of government spending, the latter Modelbase shock may be left out.
- In line 17 following the keyword `parameters` the model-specific parameters are initialized.
- It follows the Modelbase block in which the Modelbase parameters are initialized. In figure 8 line 22 we have for brevity reasons only included three policy parameters. In the actual mod-files there are many more leads and lags. These are the parameters of the general monetary policy function, except for the last one, `coffispol`, which enters the common discretionary government spending equation.
- Afterwards numerical values are assigned to the model-specific parameters in lines 25 to 34.
- Finally a Block called *Specification of Modelbase Parameters* is added. First in lines 39 to 43 the numeric values of the parameters of the selected monetary policy rule are loaded. They are contained in the file `policy_param.mat` in the main folder `MMB`. For models in which the original shocks are expressed in percent/100 the parameter `std_r_` has to be reset to 100 after the parameter-loading command. In our example this would have to be done in line 44. However, the shocks in this model are already expressed in percentage terms. Secondly, the discretionary fiscal policy parameter `coffispol` is defined as a function of the model-specific parameters such that a unit government spending shock has a unit impact on output. The exact implementation of the common fiscal policy shock will be described below. In our example no adjustment is needed and hence `coffispol` is set equal to one.

### Part 2: The model block

- The model block starts in line 49 of figure 9 as indicated by the keyword *model* followed by *linear*, which tells Dynare that the equations are already linearized and thus reduces computing time.
- In the Modelbase block going from lines 51 to 60 the common variables are defined in terms of the original model variables. The variable *interest* denotes the annualized short-term interest rate, *inflation* is annual inflation, *inflationq* represents annualized quarterly inflation, *outputgap* and *output* denote the output gap and output, respectively. The common variable *fispol* represents discretionary fiscal policy. It is set equal to the model-specific government spending shock variable, which in the case of our example is *g\_*. Note again, that this model-specific shock has to be initialized as an endogenous variable. This allows us to keep the original model equation for government spending unchanged.
- It follows the common *Policy Rule* block. In lines 66 to 72 the common monetary policy rule is specified. Again for reasons of brevity we have not displayed the complete general policy rule in figure 9. Below in line 76, the common equation for discretionary government spending is specified.
- The original model equations are then specified in lines 81 to 87. Note in particular that also the government spending equation in line 87 has remained unchanged. The model section ends in line 88 with the required keyword *end*.
- Finally the variance covariance matrix is specified in lines 91 and 92 between the keywords *shocks* and *end*. Importantly, the variance of the original model-specific government spending shock has been assigned to the common fiscal policy shock variable *fiscal\_*. Hence, the common shock *fiscal\_* affects the fiscal policy variable *fispol* through the common discretionary government spending expression in line 76 which is set equal to the model-specific government spending shock *g\_* in line 59.
- The *stoch\_simul* command in line 96 is commented out. Alternatively one can also delete this command.

## A.5 Adding models to the macro model data base

Adding a new model to the data base consists of three steps. First, the original model has to be translated into a Dynare mod-file and the common Modelbase variables have to be defined as functions of the original model variables. Second, the mod-file must be stored under the model name in a folder with exactly the same label. Third, the new model has to be initialized in the file *MMB.m*. In the

following, each of these steps is described in detail.

### *Step 1: Creating the mod-file*

- The first task when adding a new model to the macro model data base is to create a Dynare mod-file. The file should start with a comment section giving some information about the associated reference paper(s) for the model.
- The file must have the usual structure of a Dynare mod-file. That is, one starts with the initialization of variables, shocks and parameters. Then the equations describing the model follow and finally the variance-covariance structure of the shocks is specified.
- However, each of the before mentioned sections has to be augmented by a Modelbase block. This Modelbase block should be visually separated from the original model sections through a comment line `//*****`.
- After the initialization of the original model variables, the common block *Modelbase Variables* follows. It consists of the six common variables *interest*, *inflation*, *inflationq*, *outputgap*, *output* and *fispol*. Those variables will be described below. If output is not specified in the model, then the common variable *output* has to be left out. Furthermore, in some small models, one may have to leave out the *fispol* variable. This common block corresponds to lines 5 to 8 in figure 8.
- The common block *Modelbase Shocks* is added after the initialization of the original model shocks as in lines 12 to 15 of figure 8. It consists of a common monetary policy shock, *interest\_*, and of a common fiscal policy shock, *fiscal\_*.
- The third common block is the *Modelbase Parameters* section. Following the initialization of the original model parameters, the common Modelbase parameters are preset, consisting of the monetary policy rule parameters and the discretionary fiscal policy parameter *coffispol*.
- It follows the numeric specification of the parameters. This is done first for the model-specific parameters and then separately for the common Modelbase parameters in the block called *Specification of Modelbase Parameters*. First, the parameter values of the selected monetary policy rule are loaded. They are contained in the file *policy\_param.mat* in the main folder *MMB*. For models in which the original shocks are expressed in percent/100 the parameter *std\_r\_* has to be reset to 100 after the parameter-loading command. This specification is required for the proper calculation of impulse response functions. In our example this would have to be done in line 44. However, the shocks in the example are already expressed in percentage terms. Secondly, the discretionary fiscal policy parameter *coffispol* is defined as a function of the model-specific



parameters such that a unit government spending shock has a unit impact on output. In our example no adjustment is needed and hence *coffispol* is set equal to one.

- Following the beginning of the model section, i.e. before the original model equations are specified, a *model-specific* Modelbase block has to be added in order to define the common Modelbase variables in terms of original model variables. This is done in lines 52 to 59 in our example. The variable *interest* is defined as the annualized short-term interest rate set by the policy maker and expressed in percent. The variable *inflation* denotes the year-on-year inflation rate in percent and *inflationq* denotes the annualized quarter-to-quarter inflation rate in percent. If for instance the original model variable representing quarterly inflation is not annualized, then *inflationq* would have to be specified as four times the original quarter-to-quarter inflation variable. The common variables *outputgap* and *output* represent the output gap and output, respectively.
- The variable *fispol* specifies the common discretionary fiscal policy variable. For implementation of the discretionary fiscal policy variable, one does not have to change the original model equations. The original shock that should represent the common fiscal policy shock has to be initialized as endogenous variable, i.e. following the command *var* instead of *varexo*. In our example the original government spending shock *g\_* is initialized in this way. Furthermore, in the section in which the shock variances are specified, this original shock has to be replaced by the common shock *fiscal\_*. The *fispol* variable has to be set equal to the original shock variable. If there does not exist a fiscal policy shock in the original model, *fiscal\_* and *fispol* should not be initialized.
- Afterwards the common *Policy Rule* block is added to the mod-file, specifying the general monetary policy rule, like it is done in lines 68 to 72 in figure 9. For the sake of brevity we have not displayed the complete general policy rule in our example. The original monetary policy rule has to be commented out in the original model code. In case the model contains a fiscal policy shock, common discretionary government spending is also specified in the *Policy Rule* block, expressing *fispol* as a function of the *fiscal\_* shock, as in line 76 of figure 9. Hence, the common shock *fiscal\_* affects the fiscal policy variable *fispol* through this common discretionary government spending expression and *fispol* is set equal to the model-specific government spending shock *g\_* in line 59. The original model equations following this block remain unchanged.
- The variances of the two common shocks are specified together with the variances/covariances of the model-specific shocks. Specifically, the variance of the monetary policy shock *interest\_* is set equal to zero and therefore it does not have to show up explicitly. For the fiscal policy

shock *fiscal\_* one adopts the original covariance specification of the replaced shock if available. Otherwise one sets the variance of the fiscal policy shock equal to zero.

- Finally, one has to delete or out-comment the commands for finding the steady state and solving the model as it is done in line 95 of our example.

#### *Step 2: Storing the mod-file*

- Next, the file has to be stored as mod-file under the model name. In the example, the *NK\_RW97* model is stored as *NK\_RW97.mod*. The name of small calibrated New Keynesian models should start with *NK*, models of the US economy should start with *US* and models of the Euro area should start with *EA*. The full model name should allow for the identification of the specific model among the other Modelbase models. The file must be stored in a folder that has to be created under exactly the same model name and that is positioned in the main folder *MMB*.

#### *Step 3: Initializing the model in the MMB.m file*

- In the final step, one initiates the model in the main file *MMB.m*. For this task, one has to open *MMB.m*. After some lines of comments on how to add a model, a textblock with a table of models currently implemented in the Modelbase follows. This table is also shown in the workspace when the program is run. The new model has to be added to this table by itemizing the model name followed by the reference. For instance, the model named *NK\_RW97* is added as *NK\_RW97: Rotemberg, Woodford (1997)*.
- Next, the model name has to be added at the corresponding position to the vector *modelbase.names* and to the vector *modelbase.namesplot*. The entries in these two vectors only differ in that the sign *\_* is preceded by a backslash in the *modelbase.namesplot* vector to guarantee proper model name print outs.
- Finally, a new entry has to be added at the corresponding position to the vector *modelbase.variabledim*. This entry has to be *1* if the model-specific shocks are expressed in percent and it has to be *2* if the model-specific shocks are expressed in percent/100.

## **B A detailed overview of available models**

This section describes the structure and the most important features of the different models in the macro model data base.

Most models assume that expectations of future realizations of model variables such as for example future exchange rates, prices, interest rates, wages and income are formed in a model-consistent, rational manner. A few models assume backward-looking expectations formation, in particular the models from Rudebusch and Svensson (1999) and Orphanides (2003). Most, but not all models are linear, or linear approximations of nonlinear models. In this case the variables appear as percentage deviations from their steady state values. There are many differences in model structure, in terms of size, in terms of countries covered, or the extent of microeconomic foundations considered.

### **B.1 Small Calibrated Models**

#### **B.1.1 NK\_RW97: Rotemberg and Woodford (1997)**

The model and the estimation strategy is discussed in detail in Rotemberg and Woodford (1997). The equations of this model can be derived from the behavior of optimizing agents. The expectational IS equation and the policy rule together can be viewed as determining aggregate demand, while the New-Keynesian Phillips curve equation determines aggregate supply. The Phillips curve equation can be obtained as a log-linear approximation to the first-order condition of optimizing firms with either Calvo-style staggered price contracts (Yun, 1996) or convex costs of price adjustment (Rotemberg, 1982). The IS equation can be obtained as a log-linear approximation of the representative household's first-order equation in a model in which consumption, leisure, and real money balances are each additively separable in the utility function, and total consumption demand (private and government consumption) is equal to aggregate output.

- Aggregate Demand: Standard New Keynesian IS curve.
- Aggregate Supply: Standard New Keynesian Phillips Curve.
- Shocks: A cost-push shock following an AR(1) process, the common monetary policy shock, a government spending shock representing the common fiscal policy shock.
- Calibration/Estimation: Rotemberg and Woodford (1997) match the empirical impulse response functions to a monetary policy shock in a VAR (detrended real GDP, inflation, funds rate) and the empirical variances with the variances and the theoretical impulse responses from the model to all three shocks. Quarterly U.S. data for the period 1980:1–1995:2 is used. The estimated parameters are taken from Woodford (2003) table 6.1. However, we do not have

information on the calibration of the shock processes. Hence, we employ the estimation results from Adam and Billi (2006) for the NK\_RW97 shock specifications.

### **B.1.2 NK\_LWW03: Levin et al. (2003)**

This model is used for comparison in the robustness analysis of monetary policy rules by Levin et al. (2003). Its structure is similar to the NK\_RW97 model presented above, but without explicit treatment of government spending.

- Aggregate Demand: Standard New Keynesian IS curve.
- Aggregate Supply: Standard New Keynesian Phillips Curve.
- Shocks: A cost-push shock, a shock to the real interest rate and the common monetary policy shock.
- Calibration/Estimation: In calibrating the model, the parameter values of Woodford (2003) adjusted for annualized variables as in Levin et al. (2003) are used.

### **B.1.3 NK\_CGG99: Clarida et al. (1999), hybrid model**

The model is similar to NK\_RW97 but it features a hybrid Phillips curve with endogenous persistence in inflation. Also, government spending is not treated explicitly. The model and its implications for monetary policy are discussed in detail in Clarida et al. (1999) from page 1691 onwards.

- Aggregate Demand: Hybrid New Keynesian IS curve.
- Aggregate Supply: Hybrid New Keynesian Phillips Curve.
- Shocks: A cost-push shock, a demand shock and the common monetary policy shock.
- Calibration/Estimation: We use the same parametrization as in in NK\_RW97, however expected inflation enters the Phillips Curve with a weight of 0.52 and lagged inflation with a weight of 0.48. In the IS curve the expected output gap has a weight of 0.56 and the lagged output gap has a weight of 0.44.

### **B.1.4 NK\_CGG02: Clarida et al. (2002), 2-country model**

Clarida et al. (2002) derive a small-scale, two-country, sticky-price model to analyse optimal monetary policy. The two countries are symmetric in size, preferences and technology.

- **Aggregate Demand:** Households maximize their lifetime utility, where the utility function is separable in consumption and leisure, subject to an intertemporal budget constraint. They own the firms, are a monopolistically competitive supplier of labor to the intermediate firms and additionally hold their financial wealth in the form of one-period, state-contingent bonds, which can be traded both domestically and internationally.
- **Aggregate Supply:** Domestic production takes place in two stages. First there is a continuum of intermediate goods firms, each producing a differentiated material input under monopolistic competition using a production function that is linear in labor input and includes an exogenous technology parameter. They set nominal prices on a staggered basis à la Calvo and receive a subsidy in percent of their wage bill to achieve an undistorted steady state. Final goods producers then combine these inputs into output, which they sell to households under perfect competition. Wages are perfectly flexible. Thus, all workers will charge the same wage and work the same amount of hours. Clarida et al. (2002) introduce an exogenous time-varying elasticity of labor demand to vary the wage-mark-up over time. The system of equations is collapsed into an IS equation and a Phillips Curve, which determine the output gap and inflation, conditional on the path of the nominal interest rate both for the domestic and the foreign economy.
- **Foreign sector:** Producer currency pricing is assumed so that the Law of one price holds for the final consumption good and the CPI based real exchange rate is unity. Together with the assumption of complete markets this ensures that the consumption levels are equal in both countries at any point in time.
- **Shocks:** A cost push shock and the common monetary policy shock.
- **Calibration/Estimation:** We take the parametrization of the small open economy model in Galí and Monacelli (2005) to calibrate the model. Galí and Monacelli (2005) calibrate the stochastic properties of the exogenous driving forces by fitting AR(1) processes to log labor productivity in Canada, which is their proxy for the domestic country, and log U.S. GDP, which they use as proxy for world output. The sample period comprises 1963:1–2002:4.

### **B.1.5 NK\_MCN99: McCallum and Nelson (1999)**

The model in McCallum and Nelson (1999) is used to monitor the performance of operational monetary policy rules. Two distinct variants of the model are used, mainly differing in the choice of the aggregate supply setup. In the first setup, aggregate supply is based on a standard Calvo-Rotemberg (NK\_MCN99cr) specification of the Phillips curve where inflation is linked to expected inflation and

the output gap. In the second setup of the model, the authors introduce the so-called P-bar price adjustment (NK\_MCN99pb) where price changes occur in order to gradually eliminate deviations of actual from market clearing values of output.

- Aggregate Demand: Standard New Keynesian IS and LM curve.
- Aggregate Supply: Two setups: (i) Standard New Keynesian Phillips Curve (NK\_MCN99cr), (ii) P-bar price adjustment (NK\_MCN99pb).
- Shocks: A shock to the IS curve which follows an AR(1) process, a shock to the LM curve, an investment shock, a shock on capacity output and the common monetary policy shock.
- Calibration/Estimation: The model equations are estimated individually by ordinary least squares and instrumental variable estimation for U.S. data. The sample period comprises 1955–1996.

## **B.2 Estimated U.S. Models**

### **B.2.1 US\_FM95: Fuhrer and Moore (1995a)**

The model is described in Fuhrer and Moore (1995a) and Fuhrer and Moore (1995b). We employ the parametrization used in Levin et al. (2003). Fuhrer and Moore introduce a new wage contracting model where agents care about relative real wages in order to match the strong inflation persistence observed in U.S. data.

- Aggregate Demand: The US\_FM95 model represents aggregate spending by a single reduced-form equation corresponding to an IS curve. The current output gap depends on its lagged values over the past two quarters and the lagged value of the long-term real interest rate, which is defined as a weighted average of ex-ante short-term real interest rates with a duration of 40 quarters.
- Aggregate Supply: The aggregate price level is a constant mark-up (normalized to one) over the aggregate wage rate. The aggregate wage dynamics are determined by overlapping wage contracts. In particular, the aggregate wage is defined to be the weighted average of current and three lagged values of the contract wage rate. The real contract wage, that is the contract wage deflated by the aggregate wage, is determined as a weighted average of expected real contract wages, adjusted for the expected average output gap over the life of the contract. This specification yields a hybrid Phillips Curve that depends additionally on current and past demand and expectations about future demand.
- Shocks: An ad hoc supply shock and the common monetary policy shock.

- Calibration/Estimation: Full-information maximum likelihood estimation on U.S. data from 1966–1994.
- Replication: We replicated the impulse response functions for annualized quarterly inflation and the output gap to a 100 basis point innovation to the federal funds rate in Figure 2 of Levin et al. (2003).

### **B.2.2 US\_OW98: FRB Monetary Studies, Orphanides and Wieland (1998)**

This is a small open economy model described in Orphanides and Wieland (1998) and used to investigate the consequences of the zero bound on nominal interest rates.

- Aggregate Demand: The US\_OW98 model disaggregates real spending into five components: private consumption, fixed investment, inventory investment, net exports, and government purchases. The aggregate demand components exhibit partial adjustment to their respective equilibrium levels, measured as shares of potential GDP. Partial adjustments reflect habit persistence. Equilibrium consumption and fixed investment are functions of permanent income (discounted at 10 percent) and depend on the long-term real rate. The long-term nominal interest rate is an average of expected future nominal short-term rates. The long-term real rate is determined by the Fisher equation. Inventory investment depends on three lags of output. Government spending is an AR(1) process.
- Aggregate Supply: The structure is similar to the US\_FM95 model. In US\_FM95 and US\_OW98, the aggregate price level is a constant mark-up over the aggregate wage rate.
- Foreign Sector: Net exports depend on domestic output, world output, the real exchange rate and lagged net exports. The exchange rate is determined by an UIP condition.
- Shocks: Five demand shocks including the common fiscal policy shock in the government spending equation, an ad hoc cost push shock to the nominal wage contracts and the common monetary policy shock.
- Calibration/Estimation: The model is estimated for the period 1980–1996 using U.S. data. The demand block is estimated via IV-estimation equation-by-equation. For the supply side simulation-based indirect inference methods are used.
- Replication: We replicated the impulse response functions for annualized quarterly inflation and the output gap to a 100 basis point innovation to the federal funds rate in Figure 2 of Levin et al. (2003).

### **B.2.3 US\_FRB03: FRB-US model**

The FRB model is a large-scale model of the U.S. economy with a relatively detailed representation of the supply side of the economy. The version US\_FRB03 was linearized by Levin et al. (2003).

- **Aggregate Demand:** Real spending is divided into five components: private consumption, fixed investment, inventory investment, net exports and government purchases. The broad components are disaggregated further i.e. spending on fixed investment is separated into equipment, nonresidential structures and residential construction. Government spending is divided into six sub-components, each of which follows a simple reduced-form equation that includes a counter-cyclical term. The specification of most non-trade private spending equations follows the generalized adjustment cost model due to Tinsley (1993).
- **Aggregate Supply:** Potential output is modeled as a function of the labor force, crude energy use, and a composite capital stock, using a three-factor Cobb-Douglas production technology. The equilibrium output price is a mark-up over a weighted average of the productivity-adjusted wage rate and the domestic energy price. The specification of the wage and price dynamics follows the generalized adjustment cost framework used in the aggregate demand block. Wage inflation depends on lagged wage inflation over the previous three quarters, as well as expected future growth in prices and productivity, and a weighted average of expected future unemployment rates. Price inflation depends on its own lagged values over the past two quarters, as well as expected future changes in equilibrium prices and expected future unemployment rates. In addition, both wages and prices error-correct to their respective equilibrium levels. A vertical long-run Phillips curve is imposed in estimation. The model contains a detailed accounting of various categories of income, taxes, and stocks, an explicit treatment of labor markets, and endogenous determination of potential output. Long-run equilibrium in the model is of the stock-flow type; the income tax rate and real exchange rate risk premium adjust over time to bring government and foreign debt-to-GDP ratios back to specified (constant) levels.
- **Foreign sector:** The full model includes detailed treatments of foreign variables. Twelve sectors (countries or regions) are modeled, which encompass the entire global economy. In the model used in the Modelbase the full set of equations describing the foreign countries is replaced by two reduced form equations for foreign output and prices, to reduce computational cost.
- **Shocks:** The model exhibits a large range of shocks to which we add the common monetary policy shock and a fiscal shock that equally affects all three components of federal government spending such that a unit fiscal policy shock affects output by 1 percent.



- Replication: We replicated the impulse response functions for annualized quarterly inflation and the output gap to a 100 basis point innovation to the federal funds rate in Figure 2 of Levin et al. (2003).

#### **B.2.4 US\_SW07: Smets and Wouters (2007)**

Smets and Wouters (2007) develop a medium-scale closed economy DSGE-Model and estimate it for the U.S. with Bayesian techniques. The model features a deterministic growth rate driven by labor-augmenting technological progress, so that the data do not need to be detrended before estimation.

- Aggregate Demand: Households maximize their lifetime utility, where the utility function is nonseparable in consumption and leisure, subject to an intertemporal budget constraint. Smets and Wouters (2007) include external habit formation to make the consumption response in the model more persistent. Households own firms, rent capital services to firms and decide how much capital to accumulate given certain capital adjustment costs. They additionally hold their financial wealth in the form of one-period, state-contingent bonds. Exogenous spending follows a first-order autoregressive process with an iid-normal error term and is also affected by the productivity shock.
- Aggregate Supply: The final goods, which are produced under perfect competition, are used for consumption and investment by the households and by the government. The final goods producer maximizes profits subject to a Kimball (1995) aggregator of intermediate goods, which introduces monopolistic competition in the market for intermediate goods and features a non constant elasticity of substitution between different intermediate goods, which depends on their relative price. A continuum of intermediate firms produce differentiated goods using a production function with Cobb-Douglas technology and fixed costs and sell these goods to the final-good sector. They decide on labor and capital inputs, and set prices according to the Calvo model. Labor is differentiated by a union using the Kimball aggregator, too, so that there is some monopoly power over wages, which results in an explicit wage equation. Labor packers buy the labor from the unions and resell it to the intermediate goods producer in a perfectly competitive environment. Sticky wages à la Calvo are additionally assumed. The Calvo model in both wage and price setting is augmented by the assumption that prices that can not be freely set, are partially indexed to past inflation rates.
- Shocks: A total factor productivity shock, a risk premium shock, an investment-specific technology shock, a wage and a price mark-up shock and two policy shocks: the common fiscal policy shock entering the government spending equation and the common monetary policy shock.

- Calibration/Estimation: The model is estimated for the U.S. with Bayesian techniques for the period 1966:1–2004:4 using seven key macroeconomic variables: real GDP, consumption, investment, the GDP deflator, real wages, employment and the nominal short-term interest rate.
- Replication: We replicated the impulse response functions to a positive one standard deviation monetary policy shock in Figure 6 of Smets and Wouters (2007). The variables include output, hours, quarterly inflation and the interest rate.

### **B.2.5 US\_ACEL: CEE/ACEL by Altig et al. (2005)**

The purpose of the authors is to build a model with optimizing agents that can account for the observed inertia in inflation and persistence in output (Christiano et al., 2005). In the version by Altig et al. (2005) firm-specific capital is introduced to get a Calvo parameter consistent with the microeconomic evidence of price re-optimizations on average once every 1.5 quarters. The Modelbase contains four different specifications of the CEE/ACEL model, labeled by m = monetary policy shock, t = technology shock and sw = SW assumptions, i.e. no cost channel and no timing constraints as in Taylor and Wieland (2009).

- Aggregate Demand: The representative household’s utility is separable in consumption and leisure and allows for habit formation in consumption. Expected-lifetime utility is maximized, choosing optimal consumption and investment, as well as the amount of capital services supplied to the intermediate firms (homogenous capital model) and portfolio decisions. Investment adjustment costs are introduced. Furthermore, the household determines the wage rate for its monopolistically supplied differentiated labor services whenever it receives a Calvo signal. In those periods, in which it does not receive a signal, the wage is increased by the lagged inflation rate augmented by the steady state growth rate of a combination of the neutral technology shock and the shock to capital embodied technology. Labor services are sold to a competitive firm that aggregates the differentiated services and supplies the resulting aggregated labor to the intermediate goods firms.

In the firm-specific capital model, the capital stock is owned by the firms.

- Aggregate Supply: The final consumption good is produced under perfect competition using differentiated intermediate goods as inputs. Each intermediate good is produced by a monopolist employing capital (which is firm-specific in one variant of the model) and labor services. The production function is augmented by a technology shock. Capital is pre-determined. Hence, if capital is firm-specific, marginal costs depend positively on the firm’s output level. Furthermore, it is assumed that the monopolistic firms have to pay the wage bill in advance which requires borrowing from a financial intermediary. Nominal frictions are introduced in

the form of Calvo sticky prices. Non-reoptimizing firms index their prices to previous periods inflation.

- Shocks: The common monetary policy shock, a neutral technology shock and an investment specific technology shock.
- Calibration/Estimation: The model has been estimated by matching the empirical impulse response functions to a monetary policy shock in a ten variable VAR with the theoretical impulse responses from the model to a monetary policy shock. Quarterly U.S. data from 1959:2–2001:4 is used.
- Replication: Using the US\_ACELM model we replicated the impulse response functions for annualized quarterly inflation, output, annualized quarterly money growth and the annualized quarterly interest rate to a one standard deviation monetary policy shock.

#### **B.2.6 US\_RS99: Rudebusch and Svensson (1999)**

Rudebusch and Svensson (1999) set up a simple linear model of the U.S. economy which is used to examine the performance of different policy rules taking into account an inflation targeting monetary policy regime. The model equations are backward looking.

- Aggregate Demand: An IS curve relates the output gap to its own lags and the difference between the average federal funds rate and the average inflation rate over the current and three preceding quarters.
- Aggregate Supply: Phillips Curve of the accelerationist form.
- Shocks: A cost-push shock, a demand shock and the common monetary policy shock.
- Calibration/Estimation: The model equations are estimated individually by ordinary least squares for U.S. data. The sample period comprises 1961:1-1996:2.

#### **B.2.7 US\_OR03:Orphanides (2003)**

Orphanides (2003) conducts a counterfactual analysis based on the historical experience of the United States economy to give an example of the difficulties in identifying robust policy strategies. The counterfactual analysis gives an insight how inflation and the output gap would have evolved from the 1960s to the 1990s if the Federal Reserve had actually followed two distinct activist monetary policy rules taking into account the difference between realistic and non-realistic assumptions on the availability of information on the output gap.

- Aggregate demand: The demand side of the structural model of the economy is represented by an IS equation which relates the output gap to its own lags, lags of inflation and the federal funds rate.
- Aggregate supply: The supply side is represented by an accelerationist form of the Philips curve with an adaptive representation of inflation expectations.
- Shocks: A cost-push shock, a demand shock and the common monetary policy shock.
- Calibration/estimation: The Aggregate Demand and Aggregate Supply equation are estimated in a setup that can be interpreted as a mildly restricted structural vector autoregression (VAR) of up to four lags estimated using quarterly data from from 1960 to 1993.

### **B.3 Estimated Euro Area Models**

#### **B.3.1 EA\_CW05: Coenen and Wieland (2005)**

Coenen and Wieland (2005) develop a small-scale macroeconomic model for various staggered pricing schemes. We use a version with the nominal contract specification of Taylor (1980), labeled EA\_CW05ta, and a version with the relative real wage contract specification of Fuhrer and Moore (1995a), labeled EA\_CW05fm.

- Aggregate Demand: The aggregate demand equation is backward looking: two lags of aggregate demand (should account for habit persistence in consumption, adjustment costs and accelerator effects in investment) and one lag of the long-term interest rate (allows for a transmission lag of monetary policy). The long-term nominal interest rate is an average of expected future nominal short-term rates. The long-term real rate is determined by the Fisher equation.
- Aggregate Supply: As in US\_FM95 and US\_OW98.
- Shocks: A demand shock, a contract wage shock and the common monetary policy shock.
- Calibration/Estimation: The model has been estimated on data from the ECB Area Wide Model data set from 1974:1–1998:4. The contract wage specifications have been estimated by a limited information indirect inference technique while the IS equation has been estimated by means of the GMM.
- Replication: We replicated the impulse response functions of annual inflation and the output gap to a 100bps temporary unanticipated rise in the nominal short term rate in the upper panel of Figure 7 of Kuester and Wieland (2005) for both versions of the model.

### **B.3.2 EA\_AWM05: Area Wide model linearized by Dieppe, Kuester and McAdam (2005)**

The model is described in Fagan, Henry, and Mestre (2005). It was one of the first models to treat the Euro area as a single economy. In the Modelbase we use the linearized version from Dieppe, Kuester and McAdam (2005) that is also used in Kuester and Wieland (2005). The EA\_AWM05 is an open economy model of the Euro area. Expectation formation is largely backward-looking. Activity is demand-determined in the short-run but supply determined in the long-run with employment having converged to a level consistent with the exogenously given level of equilibrium unemployment. Stock-flow adjustments are accounted for, e.g., the inclusion of a wealth term in consumption.

- **Aggregate Demand:** Demand is disaggregated into private consumption, government consumption, investment, variation of inventories, exports, and imports. The term structure (12-year bond) is forward-looking. Private consumption is specified as a function of households' real disposable income and wealth, where the latter consists of net foreign assets, public debt and the capital stock. The change in the log of the investment/output ratio depends on the real interest rate, the real GDP/capital stock ratio and the lagged investment/output ratio. The authors stress that this investment equation represents the key channel through which interest rates affect aggregate demand. Government consumption is treated as exogenous.
- **Aggregate Supply:** Output follows a whole economy production function. Short-run employment dynamics are driven by output growth and real wages. The deflator for real GDP at factor costs, which according to Fagan et al. (2005) is the key price index of the model, is a function of unit labor costs, import prices, the output gap and inflation expectations. The growth rate of wages depends on consumer price inflation, productivity and the unemployment gap, defined as the deviation of the current unemployment rate from the NAIRU.
- **Foreign sector:** Besides extra-area flows, exports and imports also include intra-area flows. World GDP and world GDP deflator are treated as exogenous variables. The exchange rate is a forward-looking variable determined by uncovered interest rate parity.
- **Shocks:** Employment shock, factor cost-push shock, private consumption cost-push shock, gross investment cost-push shock, gross investment shock, exports cost-push shock, imports cost-push shock, private consumption shock, term structure shock, common fiscal policy shock and common monetary policy shock.
- **Calibration/Estimation:** Estimation on Euro area data equation by equation from 1970:1–1997:4, whereas the estimation period of some equations starts later, but not later than 1980:1.
- **Replication:** We replicated the impulse response functions of annual inflation and the output

gap to a 100bps temporary unanticipated rise in the nominal short term rate in the upper panel of Figure 7 of Kuester and Wieland (2005).

### **B.3.3 EA\_SW03: Smets and Wouters (2003)**

The EA\_SW03 model of Smets and Wouters (2003) is a medium-scale closed economy DSGE model with various frictions and estimated for the Euro area with Bayesian techniques.

- **Aggregate Demand:** Households maximize their lifetime utility, where the utility function is separable in consumption, leisure and real money balances, subject to an intertemporal budget constraint. Smets and Wouters (2003) include external habit formation to make the consumption response in the model more persistent. Households own firms, rent capital services to firms and decide how much capital to accumulate given certain capital adjustment costs. They additionally hold their financial wealth in the form of cash balances and one-period, state-contingent bonds. Exogenous spending is introduced by a first-order autoregressive process with an iid-normal error term.
- **Aggregate Supply:** The final goods, which are produced under perfect competition, are used for consumption and investment by the households and by the government. The final goods producer maximizes profits subject to a Dixit-Stiglitz aggregator of intermediate goods, which introduces monopolistic competition in the market for intermediate goods and features a constant elasticity of substitution between individual, intermediate goods. A continuum of intermediate firms produce differentiated goods using a production function with Cobb-Douglas technology and fixed costs and sell these goods to the final-goods sector. They decide on labor and capital inputs, and set prices according to the Calvo model. Labor is differentiated over households using the Dixit-Stiglitz aggregator, too, so that there is some monopoly power over wages, which results in an explicit wage equation. Sticky wages à la Calvo are additionally assumed. The Calvo model in both wage and price setting is augmented by the assumption that prices that can not be freely set, are partially indexed to past inflation rates.
- **Shocks:** Ten orthogonal structural shocks are introduced in the model. Three preference shocks in the utility function: a general shock to preferences, a shock to labor supply and a money demand shock. Two technology shocks: an AR(1) process with an iid shock to the investment cost function and a productivity shock to the production function. Three cost push-shocks: shocks to the wage and price mark-up, which are iid around a constant and a shock to the required rate of return on equity investment. And finally two monetary policy shocks: a persistent shock to the inflation objective and a temporary common monetary policy shock. In addition, the common fiscal policy shock is added in the form of a government spending shock. Since

government spending is expressed in output units, we set the coefficient which scales the shock to unity to achieve a shock size of one percent of GDP.

- **Calibration/Estimation:** The model is estimated using Bayesian techniques on quarterly Euro area data. The data set used is comprised of seven key macroeconomic variables consisting of real GDP, real consumption, real investment, the GDP deflator, real wages, employment and the nominal interest rate over the period 1970:1–1999:4.
- **Replication:** We replicated the impulse response functions of annual inflation and the output gap to a 100bps temporary unanticipated rise in the nominal short term rate in the upper panel of Figure 7 of Kuester and Wieland (2005).

#### **B.3.4 EA\_SR07: Euro Area Model of Sveriges Riksbank, Adolfson et al. (2007)**

Adolfson et al. (2007) develop an open economy DSGE model and estimate it for the Euro area using Bayesian estimation techniques. They analyse the importance of several rigidities and shocks to match the dynamics of an open economy.

- **Aggregate Demand:** Households maximize lifetime utility subject to a standard budget constraint. Preferences are separable in consumption, labor and real cash holdings. Persistent preference shocks to consumption and labor supply are added to the representative utility function. Internal habit formation is imposed with respect to consumption. Aggregate consumption is specified as a CES function, being composed of domestically produced as well as imported consumption goods. Households rent capital to firms. Capital services can be increased via investment and via an increase in the capital utilization rate, where both options are involved with costs. Total investment in the domestic economy is represented by a CES aggregate consisting of domestic and imported investment goods. Households are assumed to be able to save through acquiring domestic bonds and foreign bonds in addition to holding cash and accumulating physical capital. A premium on foreign bond holdings assures the existence of a well-defined steady state. Households monopolistically supply a differentiated labor service. Wage stickiness is introduced in the form of the Calvo model augmented by partial indexation. Government consumption of the final domestic good is financed via taxes on capital income, labor income, consumption and payroll. Any surplus or deficit is assumed to be carried over as a lump-sum transfer to households.
- **Aggregate Supply:** The final good is produced via a CES aggregator using a continuum of differentiated intermediate goods as inputs. The production of intermediate goods requires homogeneous labor and capital services as inputs and is affected by a unit-root technology shock representing world productivity as well as a domestic technology shock. Fixed costs

are imposed such that profits are zero in steady state. Due to working capital, (a fraction of) the wage bill has to be financed in advance of the production process. Price stickiness of intermediate goods is modeled as in the Calvo (1983) model. In addition, partial indexation to the contemporaneous inflation target of the central bank and the previous periods inflation rate is included for those firms that do not receive a Calvo signal in a given period. This results in a hybrid new Keynesian Phillips curve.

- Foreign sector: Importing firms are assumed to buy a homogeneous good in the world market and differentiate it to sell it in the domestic market. Similarly, exporting firms buy the homogeneous final consumption good produced in the domestic economy and differentiate it to sell it abroad. Specifically, the differentiated investment and consumption import goods are aggregated in a second step via a CES function, respectively. The same applies to the export goods. Calvo pricing is also assumed for the import and export sector, allowing for incomplete exchange rate pass-through in the short run. The foreign economy is described by an identified VAR model for foreign prices, foreign output and the foreign interest rate.
- Shocks: Unit root technology shock, stationary technology shock, investment specific technology shock, asymmetric technology shock, consumption preference shock, labor supply shock, risk premium shock, domestic mark-up shock, imported consumption mark-up shock, imported investment mark-up shock, export mark-up shock, inflation target shock, the common monetary policy shock, shocks to the four different tax rates and a government spending shock which represents the common fiscal policy shock and which we have adjusted so that we achieve a shock size of one percent of GDP.
- Calibration/Estimation: The model is estimated using Bayesian estimation techniques for the Euro area using quarterly data from 1970:1–2002:4 in order to match the dynamics of 15 selected variables. According to the authors, they calibrated those parameters that should be weakly identified by the 15 variables used for estimation.
- Replication: We replicated the impulse response functions for annualized quarterly inflation, output, employment and the annualized interest rate to a one standard deviation monetary policy shock in Figure 3 of Adolfson et al. (2007).

## **B.4 Estimated/calibrated Multi-Country Models**

### **B.4.1 G7\_TAY93: Taylor (1993a) G7 countries**

Taylor (1993a) describes an estimated international macroeconomic framework for policy analysis in the G7 countries: USA, Canada, France, Germany, Italy, Japan and the UK. The model consists of



98 equations and a number of identities. This model was the first to demonstrate that it is possible to construct, estimate, and simulate large-scale models for real-world policy analysis (Yellen, 2007). Taylor (1993a) argues that a multicountry model is appropriate for the evaluation of policy questions like the appropriate mix of fiscal and monetary policy or the choice of an exchange rate policy.

- **Aggregate Demand:** The IS components are more disaggregated than in the US\_OW98 model. For example, spending on fixed investment is separated into three components: equipment, nonresidential structures, and residential construction. The specification of these equations is very similar to that of the more aggregated equations in the US\_OW98 model. The aggregate demand components exhibit partial adjustment to their respective equilibrium levels. In G7\_TAY93, imports follow partial adjustment to an equilibrium level that depends on U.S. income and the relative price of imports, while exports display partial adjustment to an equilibrium level that depends on foreign output and the relative price of exports. Uncovered interest rate parity determines each bilateral exchange rate (up to a time-varying risk premium); e.g., the expected one-period-ahead percent change in the DM/U.S.\$ exchange rate equals the current difference between U.S. and German short-term interest rates.
- **Aggregate Supply:** The aggregate wage rate is determined by overlapping wage contracts. In particular, the aggregate wage is defined to be the weighted average of current and three lagged values of the contract wage rate. In contrast to the US\_FM95 model and the US\_OW98 model, G7\_TAY93 follows the specification in Taylor (1980), where the current nominal contract wage is determined as a weighted average of expected nominal contract wages, adjusted for the expected state of the economy over the life of the contract. This implies less persistence of inflation than in the US\_FM95 and the US\_OW98 model. The aggregate price level is not set as a constant mark-up over the aggregate wage rate as in US\_FM95 and US\_OW98. Prices are set as a mark-up over wage costs and imported input costs. This mark-up varies and prices adjust slowly to changes in costs. Prices follow a backward-looking error-correction specification. Current output price inflation depends positively on its own lagged value, on current wage inflation, and on lagged import price inflation, and responds negatively (with a coefficient of -0.2) to the lagged percent deviation of the actual price level from equilibrium. Import prices adjust slowly (error-correction form) to an equilibrium level equal to a constant mark-up over a weighted average of foreign prices converted to dollars. This partial adjustment of import and output prices imposes somewhat more persistence to output price inflation than would result from staggered nominal wages alone.
- **Foreign sector:** G7\_TAY93 features estimated equations for demand components and wages and prices for the other G7 countries at about the level of aggregation of the U.S. sector. Finan-

cial capital is mobile across countries.

- Shocks: Interest rate parity shock, term structure shock, durable consumption shock, non-durable consumption shock, services consumption shock, total consumption shock, aggregate consumption shocks for Germany and Italy, for the other countries disaggregated, nonresidential equipment investment shock, nonresidential structures investment shock, residential investment shock, inventory investment shock, fixed investment shock, inventory investment shock, real export shock, real import shock, contract wage shock, cost-push shock, import price shock, export price shock, fiscal policy shock, where we have adjusted the size of the fiscal policy shock for the U.S. - the common fiscal shock - so that a unit shock represents a 1 percent of GNP shock and a monetary policy shock where again the common Modelbase monetary policy shock enters the monetary policy rule for the U.S..
- Calibration/Estimation: The model is estimated with single equation methods on G7 data from 1971–1986.
- Replication: We replicated the impulse response functions for annualized quarterly inflation and the output gap to a 100 basis point innovation to the federal funds rate in Figure 2 of Levin et al. (2003).

#### **B.4.2 G3\_CW03: Coenen, Wieland (2002, 2003) G3 countries**

In this model different kinds of nominal rigidities are considered in order to match inflation and output dynamics in the U.S., the Euro area and Japan. Staggered contracts by Taylor (1980) explain best inflation dynamics in the Euro area and Japan and staggered contracts by Fuhrer and Moore (1995a) explain best U.S. inflation dynamics. The authors evaluate the role of the exchange rate for monetary policy and find little gain from direct policy response to exchange rates.

- Aggregate Demand: The open-economy aggregate demand equation relates output to the lagged ex-ante long-term real interest rate and the trade-weighted real exchange rate and additional lags of the output gap. The demand equation is very similar to the G7\_TAY93 model without any sectoral disaggregation. Lagged output terms are supposed to account for habit persistence in consumption as well as adjustment costs and accelerator effects in investment. The lagged interest rate allows for lags in the transmission of monetary policy. The exchange rate influences net exports and thus enters the aggregate demand equation. The long term nominal interest rate is an average of expected future nominal short-term rates. The long-term real interest rate is determined by the Fisher equation.
- Aggregate Supply: For the U.S., relative real wage staggered contracts by Fuhrer and Moore

(1995a) are used (see the US\_FM95 model for a detailed exposition). For the Euro area and Japan the nominal wage contracts by Taylor (1980) are used. Note that Taylor contracts, with a maximum contract length exceeding two quarters, result in Phillips Curves that explicitly include lagged inflation and lagged output gaps. Thus, the critique that with Taylor contracts inflation persistence is solely driven by output persistence (Fuhrer and Moore, 1995a) is mitigated.

- Foreign sector: All three countries are modeled explicitly. The Modelbase rule replaces monetary policy for the U.S.. For the Euro area and Japan the original interest rules remain. Foreign output does not affect domestic output directly, but indirectly via the exchange rate in the demand equation. The bilateral exchange rates are determined by UIP conditions.
- Shocks: Contract wage shocks, demand shocks and the common monetary policy shock which is added for the U.S..
- Calibration/Estimation: Euro area data, (fixed GDP weights at PPP rates from the ECB area-wide model database), U.S. data and Japanese data. For the U.S. and Japan OECD's output gap estimates are used. For the Euro area log-linear trends are used to derive potential output. The estimation is robust to different output gap estimations. Demand block: GMM estimation where lagged values of output, inflation, interest rates, and real exchange rates are used as instruments. Supply side: simulation-based indirect inference methods. Estimation period: U.S. 1980:1–1998:4, Euro area 1980:1–1998:4 and Japan 1980:1–1997:1.
- Replication: We replicated the impulse response functions to 0.5 percentage points demand shocks in the United States, the Euro Area and Japan plotted in Figure 3 of Coenen, Wieland (2003). Variables include the output gap, annual inflation and the short-term nominal interest rate of the United States, the Euro Area and Japan.

#### **B.4.3 EACZ\_GEM03: IMF model of Euro Area and Czech Republic, Laxton and Pesenti (2003)**

The model is a variant of the IMF's Global Economy Model (GEM) and consists of a small and a large open economy. The authors study the effectiveness of Taylor rules and inflation-forecast-based rules in stabilizing variability in output and inflation. They check if policy rules designed for large and relatively closed economies can be adopted by small, trade-dependent countries with less developed financial markets and strong movements in productivity and relative prices and destabilizing exposure to volatile capital flows. In contrast to Laxton and Pesenti (2003) we focus on the results for the large open economy (Euro area) rather than the small open economy (Czech Republic).

- **Aggregate Demand:** Infinitely lived optimizing households; government spending falls exclusively on nontradable goods, both final and intermediate. Households face a transaction cost if they take a position in the foreign bond market.
- **Aggregate Supply:** Monopolistic intermediate goods firms produce nontradeable goods and tradable goods. It exists a distribution sector consisting of perfectly competitive firms. They purchase tradable intermediate goods worldwide (at the producer price) and distribute them to firms producing the final good (at the consumer price). Perfectly competitive final good firms (Dixit-Stiglitz aggregator) use nontradable and tradeable goods and imports as inputs. Households are monopolistic suppliers of labor and wage contracts are subject to adjustment costs. Households own domestic firms, nonreproducible resources and the domestic capital stock. Markets for land and capital are competitive. Capital accumulation is subject to adjustment costs. Labor, capital and land are immobile internationally. Households trade a short-term nominal bond, denominated in foreign currency. All firms exhibit local currency pricing, thus exchange rate pass-through is low.
- **Shocks:** Risk premium shock, productivity shock, shock to the investment depreciation rate, shock to the marginal utility of consumption, government absorption shock where the one affecting the large foreign economy represents the common fiscal policy shock, shock to the marginal disutility of labor, preference shifter. We add the common monetary policy shock to the policy rule of the large economy.
- **Calibration/Estimation:** Calibrated to fit measures of macro-variability of the Euro area (1970:1–2000:4) and Czech Republic (1993:1–2001:4).
- **Notes:** Due to the symmetric setup of the model, we use the same policy rule in both countries.
- **Replication:** We replicated the standard deviations of annual inflation, the output gap and the first difference of the interest rate under the optimal Taylor rule implied by the loss function specification 2 of Laxton and Pesenti (2003) as listed in the second row of Table 4 in their paper.

#### **B.4.4 G2\_SIGMA08: FRB-SIGMA by Erceg et al. (2008)**

The SIGMA model is a medium-scale, open-economy, DSGE model calibrated for the U.S. economy. Erceg et al. (2008) in particular take account of the expenditure composition of U.S. trade and analyse the implications for the reactions of trade to shocks compared to standard model specifications.

- **Aggregate Demand:** There are two types of households: households that maximize a utility function separable in consumption, with external habit formation and a preference shock,

leisure and real money balances, subject to an intertemporal budget constraint (forward-looking households) and the remainder that simply consume after-tax disposable income (hand-to-mouth households). Households consume, own the firms and accumulate capital, which they rent to the intermediate goods producers. Erceg et al. (2008) introduce investment adjustment costs a la Christiano et al. (2005), where it is costly for the households to change the level of gross investment. Households also choose optimal portfolios of financial assets, which include domestic money balances, government bonds, state-contingent domestic bonds and a non-state contingent foreign bond. It is assumed that households in the home country pay an intermediation cost when purchasing foreign bonds, which ensures the stationarity of net foreign assets. Households rent their labor in a monopolistic market to firms, where forward-looking households set their nominal wage in Calvo-style staggered contracts analogous to the price contracts and hand-to-mouth households simply set their wage each period equal to the average wage of the forward-looking households.

- **Aggregate Supply:** Intermediate-goods producers have an identical CES production function and rent capital and labor from competitive factor markets. They sell their goods to final goods producers under monopolistic competition and set prices in Calvo-style staggered contracts. Firms, who don't get a signal to optimize their price in the current period, mechanically adjust their price based on lagged aggregate inflation. Final good producers in the domestic and foreign market assemble the domestic and foreign intermediate goods into a single composite good by a CES production function of the Dixit-Stiglitz form and sell the final good to households in their country. Erceg et al. (2008) introduce quadratic import adjustment costs into the final goods aggregator, which are zero in steady state. It is costly for a firm to change its share of imports in a final good relative to their lagged aggregate shares. Thus the import share of consumption or investment goods is relatively unresponsive in the short-run to changes in the relative price of imported goods even while allowing the level of imports to jump costlessly in response to changes in overall consumption or investment demand. Government purchases are assumed to be a constant fraction of output. Government revenue consists of income from capital taxes (net of the depreciation write off), seignorage income and revenue from lump-sum taxes (net of transfers). The government issues bonds to finance the difference between government revenue and expenditure. Lump-sum taxes are adjusted both in response to deviations of the government debt/GDP ratio from a target level and to the change in that ratio.
- **Foreign sector:** Local currency pricing is assumed. Intermediate goods producers price their product separately in the home and foreign market leading to an incomplete exchange rate pass-through. Erceg et al. (2008) point out, that empirically imports and exports in the U.S. are

heavily concentrated, with about 75 percent in capital goods and consumer durables, but the production share of capital goods and consumer durables is very low. To account for this fact in the two-country model they allow the import share in the final good aggregator for investment goods to be higher than the import share in the final good aggregator for consumption goods.

- Shocks: Since we have no information about the variances of the shock terms, we set all shock variances equal to zero. The government spending shock of the home country represents the common fiscal policy shock. The common monetary policy shock is added for the home country.
- Calibration/Estimation: The model is calibrated at a quarterly frequency. Parameters of the original monetary policy rule are estimated using U.S. data from 1983:1–2003:4.
- Replication: We replicated the impulse response functions for real exports, real imports and the exchange rate to a foreign investment demand shock represented by a decline in the foreign capital income tax rate as plotted in Figure 3 (disaggregated trade case) of Erceg et al. (2008).